How to increase the joint provision of ecosystem services by agricultural systems. Evidence from coffee-based agroforestry systems

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Abstract

CONTEXT Agricultural systems can provide ecosystem services (ES) beneficial for both the sustainability of farms and the quality of life for humans. Agriculture is regularly criticized for focusing technical management of cropping systems more on production services than on support or regulation services. To achieve the agroecological intensification of cropping systems, a joint provision of multiple ES is required.

OBJECTIVE Our aim was to (i) understand the determinants of the provision of ES and (ii) analyze the relationships between these services in order to (iii) identify agroecological intensification pathways. We focused our study on four ES, which are (1) coffee production, (2) water quality preservation, (3) carbon sequestration and (4) biodiversity conservation, provided by coffee agroforestry systems in a small region in Nicaragua.

METHODS A two-phase sampling scheme was implemented to measure and elucidate the provision of these services. First, we selected a large sample (82 coffee plots) to gain insight into and quantify the four ES. Secondly, we extracted a sub-sample (27 plots) showing variability in the provision of the four ES, to closely examine the determinants of the service most useful to farmers, coffee production.

RESULTS AND CONCLUSION The results showed that carbon sequestration (in average 36 $t.ha^{-1}.yr^{-1}$) was not correlated with coffee yield (in average 1,127 $kg.ha^{-1}.yr^{-1}$) and depended more on the presence of a few big trees in farm plots (Ø>0.9m) than on tree density. Yield increased with tree biodiversity up to a threshold (Sh_{index} = 1.5), after which it clearly declined. The use of the most harmful pesticides to human health at higher doses than recommended did not lead to the highest yields. The most important determinants of coffee production were soil nitrogen content, soil pH, solar radiation, disease and weed incidence. Although reducing the shade tree density increased

coffee production, this reduction was not necessarily related to a decrease in shade tree biodiversity and carbon sequestration, or an increase in water contamination potential. A few farmers actually achieved such high joint ES provision, in particular by selecting adequate shade trees grown at moderate densities.

SIGNIFICANCE The novelty of this article lies on an original method that consists in analyzing the ES provided by cropping systems in order to identify management strategies that are effective in providing a higher combined level of ES than those currently provided. We emphasize the importance of linking agricultural practices to the ES delivered, in order to gain an in-depth understanding of which technical levers are positively correlated with the determinants of the expected services.

Highlights

- Agroforestry systems can jointly provide high yields and high levels of cultivated biodiversity, carbon sequestration and water quality preservation
- Quantifying ecosystem services for analyzing their relationships and determinants is key to find technical levers to jointly enhance their provision
- The choice of associated tree species and their density is crucial for enhancing the joint provision of ecosystem services in agroforestry systems

1. INTRODUCTION

Agroforestry systems (AFS) are generally considered to provide more ecosystem services (ES) than monocrop systems (De Beenhouwer et al., 2013; Santos et al., 2019). Potentially harboring high floristic biodiversity (Deheuvels et al., 2012; Valencia et al., 2014), AFS provide permanent shelter due to the perennial nature of the trees they contain, which can in turn accommodate highly diverse wildlife capable of regulating pests and diseases (Cardinale et al., 2012; Ratnadass et al., 2011). Furthermore, this diversity and density of associated trees can potentially sequester high levels of carbon biomass (Cerda et al., 2017; Saj et al., 2013; Somarriba et al., 2013), both above and belowground (Albrecht and Kandji, 2003; Montagnini and Nair, 2004; Niether et al., 2019), and potentially increase soil fertility through litter deposition and nitrogen fixation (Durand-Bessart et al., 2020; Saj et al., 2021; Sauvadet et al., 2018; Souza et al., 2012), while limiting soil erosion (Meylan et al., 2013). It can also enhance economic resilience by diversifying sources of income through other productions in farm plots (Cerda et al., 2014; Schroth and Ruf, 2013; van Asten et al., 2011), and ecological resilience by maintaining a suitable climate for the cropping system despite global warming (Souza et al., 2012).

The artificialization of agrosystems since the so-called industrial revolution (Salembier et al., 2018), has gradually deteriorated the environmental footprint of these ecosystems. As a result, the ecological support and regulation functions of agro-ecosystems have been greatly reduced (Maraux et al., 2013). For about three decades, many research and development projects were led to find solutions to greening and redesigning agriculture without negatively impacting productivity and profitability. These solutions rely on agroecological principles and elements that can be articulated in different ways to form diverse transition pathways (Wezel et al., 2020). They may consist in optimizing a set of ES (i.e. provisioning, as well as regulation and support services) provided by cropping systems (Duru et al., 2015; Robertson and Swinton, 2005). But the methods used in the field to identify the management practices that pave the way for optimization, i.e technical levers, remain to be worked on.

Depending on their nature, ES can be related in various ways to their ecosystems and with other ES and related services. One service can contain (Bennett et al., 2009) or, on the contrary, contribute to the provision of another service (Kandziora et al., 2013). Several authors (Lescourret et al., 2015; Rapidel et al., 2015) have highlighted the importance of gaining insight into the determinants of each targeted ES, how these services are produced and how they are related to each other in order to be able to meet farmers' expectations when designing cropping systems. Situations of trade-offs, independence or synergies can be observed between ES (Kearney et al., 2019; Tschora and Cherubini, 2020). Essentially, the aim is to find out how it is possible to limit trade-offs and foster synergies among ES. Cropping system design and management practices consequently influence different services, e.g. crop selection in a cropping system (including mixed crops) can influence biogeochemical cycles, pest regulation and soil fertility (Gaba et al., 2014).

We assume that this approach for analyzing the ES provided by cropping systems would help to identify management strategies that are effective in providing a higher combined level of ES than those currently provided. Within these services, and the relationships among services, we assume that there are synergies that could be used to increase their overall provision, i.e. potential cropping system modifications that would be harmless or even good for agricultural production (provisioning services), while enhancing the provision of other services (e.g. environmental services). Finally, we hypothesize that greater knowledge on how combinations of cropping practices affect relations between ES could help make better decisions.

We selected four services, three of environmental interest, water quality, carbon sequestration and tree biodiversity conservation, and one of private economic interest, coffee production. These services were chosen because they are essential: "water quality" to the quality of life of people who directly use and drink river water (Elfikrie et al., 2020); “carbon sequestration” to limit global warming (Albrecht and Kandji, 2003); “tree biodiversity conservation” to maintain a diverse wildlife community (Bhagwat et al., 2008) and, more broadly, for the sustainability of ecosystems, particularly cropping systems (Balima et al., 2020); “coffee production” because it is the main cash crop providing income for farm households.

This paper aims to provide insight into how these four ES are produced in coffee AFS and how these services relate to each other. We assume that the determinants of the provision of ecosystem services and the relationships between them have to be understood to ensure this joint provision. We expect that a thorough understanding of the determinants of ES and their relationships is an essential step towards identifying sustainable practices for establishing agroecological intensification pathways in coffee agroforestry systems. In the first phase, we quantified the four ES and identified their determinants. We then explored possible agroecological intensification pathways providing a balanced provision of all services.

2. MATERIAL AND METHODS

2.1. Site description

Our study was carried out in Nicaragua’s Matagalpa department, where coffee production accounts for 28% of national coffee production, with an average production of 777 $kg.ha^{-1}.yr^{-1}$ (FAO, 2015). We analyzed coffee AFS plots located east of La Dalia (13° 08′ 00″ N and 85° 44′ 00″ W), in the vicinity of the Peñas Blancas Massif and scattered over an area of approximately 200 km^2. All plots were situated between 700 and 1,100 meters above sea level (m.a.s.l.), under a subtropical humid climate, with mean annual precipitation of around 1,400 $mm.year^{-1}$, a mild five-month dry season (December-April) and an average temperature of around 21°C.

2.2. Coffee plot network and experimental design

The survey of ES quantification was implemented in two phases (Table 1). In the first step, a sample of 82 coffee growers was selected using the snowball method (Thompson, 2002) without prioritizing any particular type of farm (area, production diversity, etc.). In this sample of 82 farmers, we collected data on coffee production and agrochemical product use in the previous year (2013). There was no mechanical tillage for soil management, nor intercropping with soil cover plants. To our knowledge, the practice of pruning coffee trees was homogeneous in the study area. We estimated biodiversity and carbon sequestration on one 1,000 m^2 (20 m x 50 m) experimental coffee plot that was assumed to be representative of on-farm coffee plots.

As coffee productivity at the plot scale is usually not recorded by farmers and is highly variable, we decided to conduct a second survey to estimate this service and its relationships to coffee plantation structure and management. Because measuring coffee yields is relatively time-consuming, the farm sample was reduced to 27 farms from the initial 82 farmers. The selection was based on the strong interest shown in the study by the 27 selected producers. In this subsample, we estimated coffee productivity by counting beans on coffee trees located in three 100 m^2 squares within the initial 1,000 m^2 observation plot (Figure 1). Other management and state variables of AFS plots that could influence coffee yield were ascertained by questioning farmers or measured, as described below (Section 2.4.).

Table 1. Services and variables collected, the way they have been collected and the type of results expected from those services (n indicates the sample size). The first stage was carried out in May and June, the second in July and August 2014.

Year of data concerned	Ecosystem service or other variables	Collection method	Object of the study	Expected results
2013 (n = 82, 1st phase)	Water quality	Declaratory survey	Coffee AFS	Characterization of water quality, carbon sequestration, biodiversity services and their determinants
	Carbon sequestration Biodiversity	Measurement	1,000 m^2 experimental coffee plot	
2014 (n = 27, 2nd phase)	Coffee productivity Environmental variables	Measurement	1,000 m^2 experimental coffee plot	Characterization of coffee productivity and its determinants
	Water quality Management variables	Declaratory survey		Possible correlations between the 4 ES taken in pairs, and with management

2.3. Research approach: from the quantification of service to the formulation of promising management approaches

The work carried out sought to highlight the technical levers that can be mobilized to foster a high level of service provision at the cropping system scale, following a methodology similar to that developed by Bhattarai et al. (2017) and Cerda et al. (2020). Technical levers refer to management practices that substantially increase the provision of a given service. First, we measured the provision of the four services studied, investigated the relationships among them, and characterized their determinants. Then we identified the situations providing a good level of the four services and highlighted the explanatory factors and possible levers to reach these successful situations.

To assess the determinants of coffee yield, a conceptual model was built according to the method proposed by Lamanda et al. (2012) with AFS state and management variables (detailed in the next section). Then we tested the hypothetic correlations of the model that led to a statistical model showing the influence of some environmental and management variables on coffee yield.

2.4. Data collection and assessment

2.4.a. Assessment of ecosystem services

α) Water quality

During the first stage of the survey, we asked farmers about the agrochemical products they applied to coffee plants and the doses they used for each application. Two interviews were carried out, the first in April-May 2014 and the other in October 2014 and specifically focused on the agrochemical products used during the previous year (2013) in all coffee plots and during the last crop season (2014) for the experimental plot.

A large number of water quality indicators based on agrochemical product use already exist and have been reviewed (Bockstaller et al., 2009). However, most of them are designed to show the global impact of agrochemical product use on the environment, whereas in our study we focus on showing the potential harm for human health when active ingredients of agrochemical products end up in river water. We developed a simplified, rapid indicator of agrochemical product use that takes into account the features of disintegration, diffusion, dangerousness of the active ingredient contained in the agrochemical product to humans (Lewis et al., 2016), as well as the dose of each agrochemical product used.

The five features used for the calculation of the agrochemical product pressure index on humans (PPIH) are:

- $\tau_{½\,sol}$ = Half-life in soil
- K_s = Solubility in water at 20°C
- χ = Leaching potential exclusively based on the agrochemical product's chemical properties
- $\tau_{½\,water}$ = Half-life in water
- Xn = Harmfulness for mammals: lethal ingested dose for 50% of the rodent population

Each of these features is expressed by a score ranging from 1 to 3 or 1 to 4, with the maximum values indicating a high risk of water contamination. These properties were adapted from the Pesticide Properties DataBase (Lewis et al., 2016).

The PPIH for agrochemical product j (PPIH j) and at the farm level (PPIH x) were calculated as follows:

$$PPIH\ j = \sum_{i=1}^{n}\left(\left(\tau\ ½\ \mathrm{sol_i} + \mathrm{Ks_i} + \chi_\mathrm{i} + \tau\ ½\ \mathrm{water_i}\right) * \mathrm{Xn_i}\right) * [\mathrm{i}]) \qquad (1)$$

$$PPIH\ x = \sum_{j=1}^{m}((\mathrm{PPIHj}) * \frac{\mathrm{D\ applied\ j}}{\mathrm{D\ recommended\ j}}) \qquad (2)$$

i: Active ingredient

[i] : Proportion of the active ingredient in the agrochemical product

n: The last active ingredient constituting the agrochemical product

m: The last agrochemical product used by the farmer

D: Dose ($L.ha^{-1}$ or $kg.ha^{-1}$)

As PPIH corresponds to a nuisance or disservice, water quality index (WQ) of farm x was assessed as the opposite of the PPIHx value (Eq. 3).

$$WQ_x = -\ PPIH_x \qquad (3)$$

The higher the WQ_x (so, closer to 0) of pest control practices, the less harmful they were to the environment.

β) Tree biodiversity conservation

We identified and counted all plant species higher than coffee trees present in the 1,000 m^2 observation plot with diameters at chest height of more than 10 cm. AFS biodiversity was assessed in each plot using the Shannon index (Sh) to highlight the abundance and the richness of diversity (Shannon, 1948). Sh indicates both the diversity of tree species and the distribution evenness of tree individuals into these species in the experimental plot and is calculated as follows:

$$Sh = -\sum_{i=1}^{n} pi\ (\ln pi) \qquad (4)$$

pi is the proportion of species i

n: Number of species in the experimental plot *γ) Carbon sequestration*

Using the tree inventory established as previously described, and adding the total height measured with a laser range finder, we estimated tree aboveground carbon sequestration using the following allometric equation from Chave et al. (2005):

$$AGB_j = e^{(-2{,}977+\ln(\rho i DBH j^2 h j))} \qquad (5)$$

AGB_j (g): Aboveground biomass of tree j

ρi ($g.cm^{-3}$): Wood density at 12% water content, specific to each species i, taken from published data (ICRAF, 2016; Zanne et al., 2009)

DBH j (cm): Diameter at chest height of tree j

h j (m): Height of tree j

Carbon sequestration in aboveground biomass (Seq C) was then expressed in Mg $C.ha^{-1}$ using a constant C/biomass ratio of 0.5 (Dixon et al., 1994):

$$Seq\ C = \sum_{j=1}^{m} AGB_j * 0.5 * 10^{-5} \qquad (6)$$

m: Number of ligneous species other than coffee tree in the experimental plot

The factor 10^{-5} corresponds to the conversion of g to Mg while taking into account the conversion factor of 1000m² to hectare.

We did not find it necessary to perform these measurements on coffee trees given the negligible value of C sequestered by coffee trees found in the literature, ranging from 3 to 19% of the C contained in the total aboveground biomass (Dossa et al., 2008; Ehrenbergerová et al., 2016; Hergoualc'h et al., 2012).

δ) Coffee yield

Average coffee yield at the farm level was estimated from an interview with coffee growers in 2013. In the second phase, we estimated coffee yield in the plots through a tailored equation not described here but similar to the one used by Meylan et al. (2017), comprising the average density of coffee trees per hectare, the average fruit load per coffee tree and the average weight of dried beans. As this estimation is labor intensive, it was only applied to the subsample (27 plots).

2.4.b. Assessment of management and state AFS variables to identify determinants of coffee yield

The following variables were investigated in-depth to better explore coffee yield determinants.

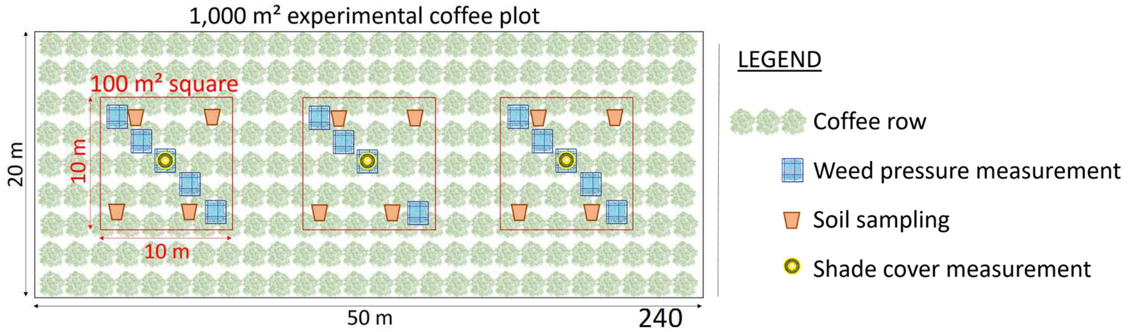


Figure 1. Sampling scheme in coffee plots for ES, management and environmental variables measurement.

ε) State variables

Four AFS state variables for characterizing the state of systems at a given moment, as defined by Lamanda *et al.* (2012), were considered in the 100 m^2 squares in the subsample of 27 farmers' plots (Figure 1):

● Shade cover from AFS associated trees (%) was measured with a concave spherical densitometer (Lemmon, 1956) in the center of each square in four directions. The percentage of transmitted radiation to the coffee canopy was roughly estimated by the complement of shade cover to 100%.

● Weed pressure (%) was estimated using a 1 m^2 square frame divided into a grid of 100 identical 1 dm^2-square cells. A mark of 1 was counted every time a cell included at least one weed. The percentage of cells with 1 mark yielded the weed pressure. This procedure was replicated at five locations in each 100 m^2 square at two dates (July and October 2014). The average of all the measurements taken for the two dates was used in the statistical analyses.

● Disease incidence (%) was evaluated for each plant selected for yield estimation (10 per square), during two periods (July and October 2014), by observing each leaf of the plant and noting if it was infested or not (1/0) by the two most prevalent coffee diseases: coffee leaf rust (caused by *Hemiliea vastatrix*) that broke out in Central America in 2012-2013 (Avelino et al., 2015), and American leaf spot (ALS caused by *Mycena citricolor*), which can severely affect heavily shaded coffee plantations. The disease incidence calculation was then calculated as the sum of the incidence of the two diseases:

$$Disease\ incidence(\%) = \frac{number\ of\ leaves\ affected\ by\ rust + number\ of\ leaves\ affected\ by\ ALS}{Total\ number\ of\ leaves\ for\ the\ coffee\ plant} \qquad (7)$$

● Soil chemical properties were analyzed by mixing four soil samples extracted in the upper 20 cm with an auger in each square. The resulting composite samples (one per 100 m^2-square) were sent for analysis to the soil laboratory at Nicaragua's National Agriculture University (UNA). Organic matter (OM, %), total nitrogen in soil (N_{tot}, ‰) and pH were analyzed.

ζ) Management variables

Agricultural practices were documented at the farm scale for 2013 and at the plot scale for 2014. Through an interview, technical data for analyzing input efficiency (fertilizer and agrochemical product names and application doses) and labor efficiency (labor time and cost for pruning, weeding and fertilizing) were obtained.

2.5. Statistical analyses

All analyzes were run using the 'stats' and 'ade4' (Dray, 2007) R statistical packages (R Core Team, 2016) with R studio 3.3.1 (Rstudio Team, 2016). In order to sharpen the initial conceptual model built for coffee yield by maintaining only the significant relations, generalized linear models (GLM) were used to estimate the relationships: 1) between coffee yield and all the state variables, and 2) between those variables and the reported agricultural practices. Indeed, the different practices carried out by farmers lead to changes in the state of the systems, which in turn impact yields (Doré et al., 1997; Sebillotte, 1990). Without using statistical method and analysis software, we performed by our own discernment a clustering based on the variability of provision of the four ES to form two groups, one of which provided a higher overall level of supply of the four ES than the other. We selected for the group of situations providing high levels of services, situations showing high levels of provision for at least two of the four services studied. This differentiation then helped us to identify promising AFS, in terms of state variables and technical management, that provided the most balanced sets of ES.

3. RESULTS

The 27 coffee cropping systems that have been described in detail in agronomic terms included coffee trees with an average age of 13 years (±11.5), planted at an average density of 3,362 coffee trees ha^{-1} (±878) for an average production of 1,127 $kg.ha^{-1}.yr^{-1}$ (±1,240), generating an average turnover of US$ 1,547 $ha^{-1}yr^{-1}$. All cropping systems were managed in agroforestry (AFS) with varying densities of species association: on average, 170 banana plants.ha^{-1} (±160), 108 *Fabaceae* trees.ha^{-1} (±96), 48 trees.ha^{-1} for timber production (±55) and 35 fruit trees.ha^{-1} (±51). The plants with annual production, i.e. banana and fruit trees, generated a turnover equivalent to US$ 136 ha^{-1}, which was

9% of the total turnover of the AFS. The products of these food crops were for 81% self-consumption by the farms' household.

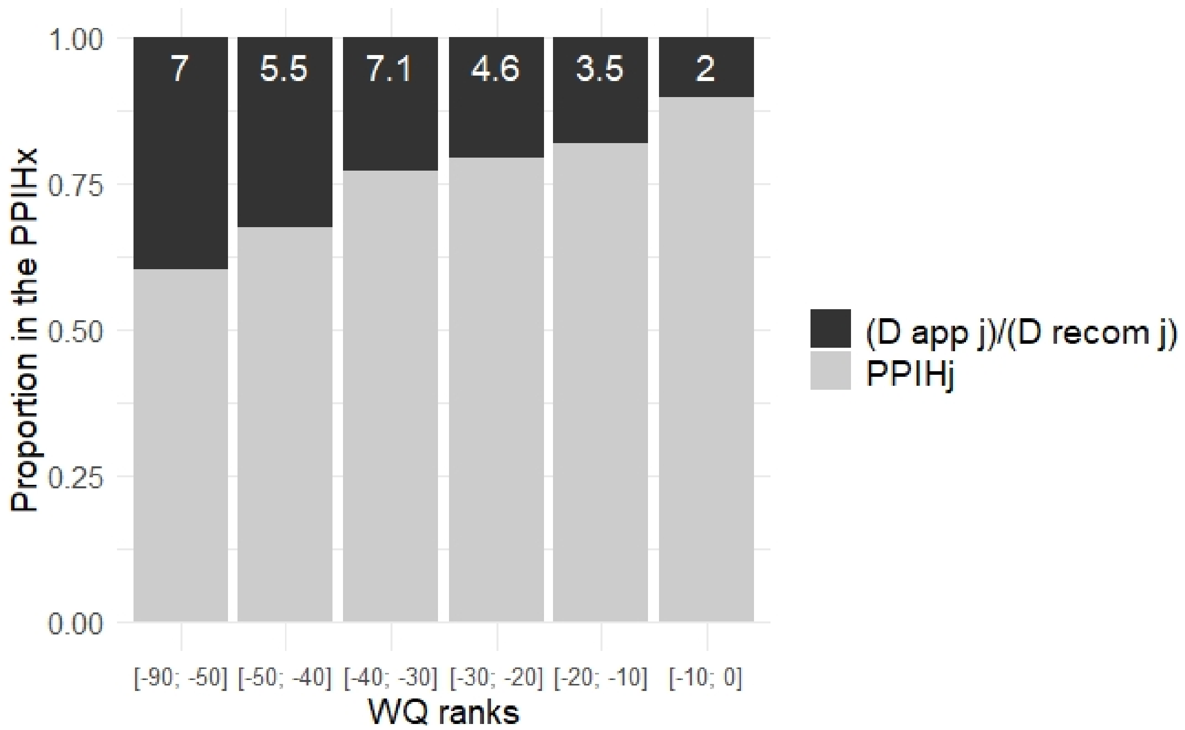
The technical management of these AFS took an average of 43 days per hectare per year. Time requirements of practices were, in decreasing order: an average of 10 (±6.4) days of manual weeding with a machete, 7.7 (±6.8) days of sucker removal, 7.4 (±5.3) days of pruning shade trees), 6.6 (±4.1) days of phytosanitary treatments, 6.1 (±6.3) days of fertilization and 5.2 (±4.0) days of pruning coffee trees. Agrochemicals had an average total cost of US$ 135 ha^{-1}.yr^{-1} (±101), of which 70% is represented by fertilizers. Including the harvesting task, labor costs on average US$ 465 ha^{-1} (±228). The net income, without taking into account post-harvest activities which represent a considerable charge, was US$ 1,083 ha^{-1} (±660).

The variability of the four services studied was high: for water quality index (WQ), the minimum was -88 and the maximum 0 (average of -18). For the Shannon index (Sh), the minimum was 0.22 and the maximum 2.63 (average of 1. 41). For carbon sequestration (seqC), the minimum was 1 t.ha^{-1}.yr^{-1} and the maximum 190 t.ha^{-1} (average 36t.ha^{-1}). Finally, for coffee yield, the minimum was 233 kg.ha^{-1}.yr^{-1} and the maximum s 3,236 kg.ha^{-1} (average 1,127 kg.ha^{-1}.yr^{-1}).

3.1. ES quantification and determinants

3.1.1. Water quality

What mainly explained the PPIHx were the properties of the active molecules that were used to calculate the PPIH of agrochemical product j, including the dangerousness for mammals. However, it also clearly depended on the dose of agrochemical products used and the number of treatments



(PPIHx) in 2013. The label corresponds to the number of treatments carried out over the year. The classes have a range of 10 except for the first [-90, -50] which groups three agrochemical product use cases (only one grower had a WQ of -88 and the next two had a WQ between -60 and -50).

applied. The more the WQ decreased from class ([-10; 0]) to class ([-90; -50]), the more it was the dose that was involved in the value of the indicator rather than the PPIHj (Figure 2). There was a significant positive correlation between the number of treatments and WQ (R^2 = 0.80). Mann-Whitney statistical tests had shown significant differences (p-value < 0.05) between the number of treatments and the agrochemical product dose at the PPIHx between the most polluting situations ([-90; -50] and [-50; -40]) and the least polluting ([-10; 0]). There was no clear link between WQ and the different types of agrochemical products: insecticides, fungicides and herbicides (data not shown).

3.1.2. Tree biodiversity conservation

111 species were identified in total in the 82 experimental plots. The Shannon index was particularly dependent on species richness (R^2 = 0.76, p-value < 10^{-16}), but not on the density of associated trees (R^2 = 0.03, p-value = 0.08) (Figure 3 A and B). The more species present in the same proportion, the higher the Shannon index is. In the situations we studied, the higher the species richness, the more similar the proportions of species were, given the strong correlation between species richness and Sh (Figure 3).

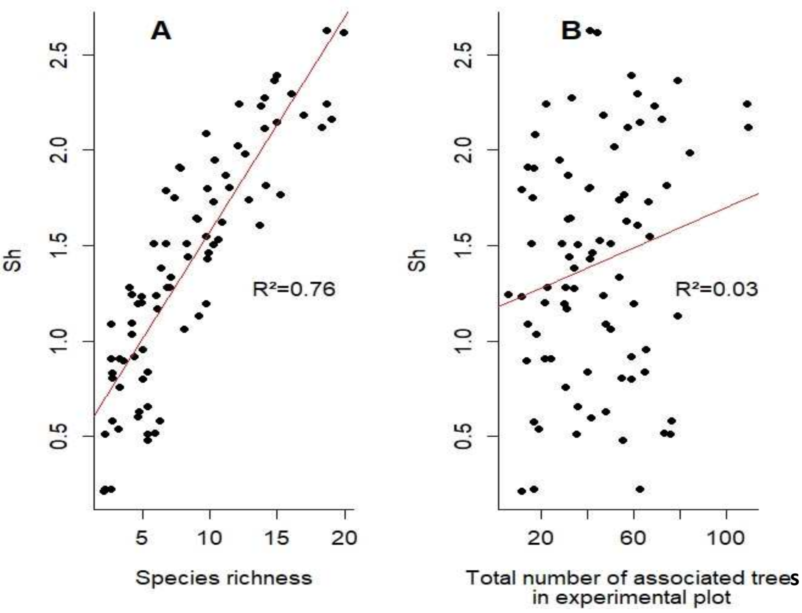


Figure 3. A) Shannon index as a function of the specific richness of the experimental plots.
B) Shannon index as a function of the total number of associated trees in the experimental plots.

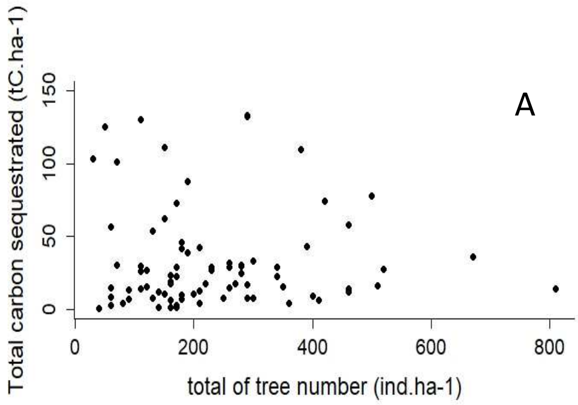
According to farmers, associated trees have four different functions in the plots: fruit production, N fixation, timber production and firewood production, with each species having one major function. The plants most common in coffee AFS according to their function were fruit species (*Musa* spp., *Mangifera indica*, *Persea americana*, *Citrus sinensis*, *Theobroma cacao* and *Psidium guajava*) and Nfixing trees of the *Fabaceae* family (*Inga* spp. and *Erythrina* spp.), with a relative abundance of 60% and 24%, respectively (Table 2).

Table 2. Most frequent plant species in coffee-based agroforestry systems, relative abundance and main function.

Species name	Occurrence on 82 plots (%)	Total number of individuals in the sample	Density when species is present (ha^{-1})	Main expected function
Musa spp.	83	1,705	239	Fruit production
Inga oerstediana	72	277	47	N fixation
Inga punctata	54	322	73	N fixation
Cordia alliodora	45	154	42	Timber production
Mangifera indica L.	35	66	23	Fruit production
Erythrina poeppigiana	32	153	59	N fixation
Theobroma cacao	30	168	67	Fruit production
Persea americana	29	72	30	Fruit production
Lonchocaprus macrophyllus	23	57	30	Firewood production
Trichilia sp.	21	32	19	Firewood production
Brosimum alicastrum	18	25	17	Timber production
Terminalia amazonia	17	18	13	Timber production
Citrus sinensis	15	27	23	Fruit production
Cedrela odorata	15	14	13	Timber production
Guazuma ulmifolia	15	14	12	Firewood production
Nectandra reticulata	13	18	16	Firewood production
Juglans olanchana	12	32	32	Timber production
Erythrina fusca	11	55	61	N fixation
Cordia collococca	11	12	13	Timber production
Psidium guajava	11	15	17	Fruit production

3.1.3. Carbon sequestration

The highest seqC was found in plots with low and intermediate tree densities (Figure 4A). However, there was no negative statistical correlation between carbon sequestration in aboveground biomass and the density of associated trees ($R^2 = 0.01$, p-value = 0.3). Figures 4B and 4C confirm that trees with relatively thin trunks, although in high number, store little carbon. The presence of a few trees with a high DBH is sufficient for a good provision of seqC. Therefore, DBH is the essential determinant of the provision of carbon sequestration.



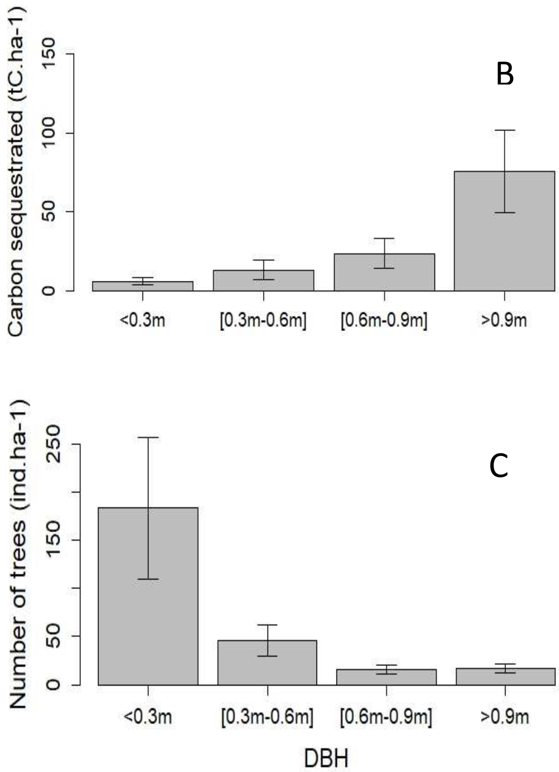


Figure 4. *A) Total carbon sequestration depending on the associated tree density.*
B) Mean seqC per tree depending on tree DBH ranks from less than 0.3m to more than 0.9m.
C) Mean number of trees depending on tree DBH ranks from less than 0.3m to more than 0.9. Error bars correspond to standard

3.1.4. Coffee yield

The data from the first stage of the survey, recorded on a declaratory basis, indicated a mean yield of 1,380 $kg.ha^{-1}.yr^{-1}$, i.e. much higher than the value for the whole department (788 $kg.ha^{-1}.yr^{-1}$) reported by Nicaragua's Ministry of Agriculture in 2013. In 51% of the plots the coffee variety grown was Catimor, while Caturra was grown in 17% and a mixture of the two in 23%. Other varieties were grown in the remaining 9% of plots. No significant difference in coffee yield was found between these different varieties. The mean yield measured in the plots for 2014 was 1,127 $kg.ha^{-1}$, which was not significantly different from the survey's 2013 yield.

To select the explanatory state variables on yield, we then statistically tested causal relationships based on our measurements via GLM, and produced a simple model, where only the significant relationships are reported (Figure 5).

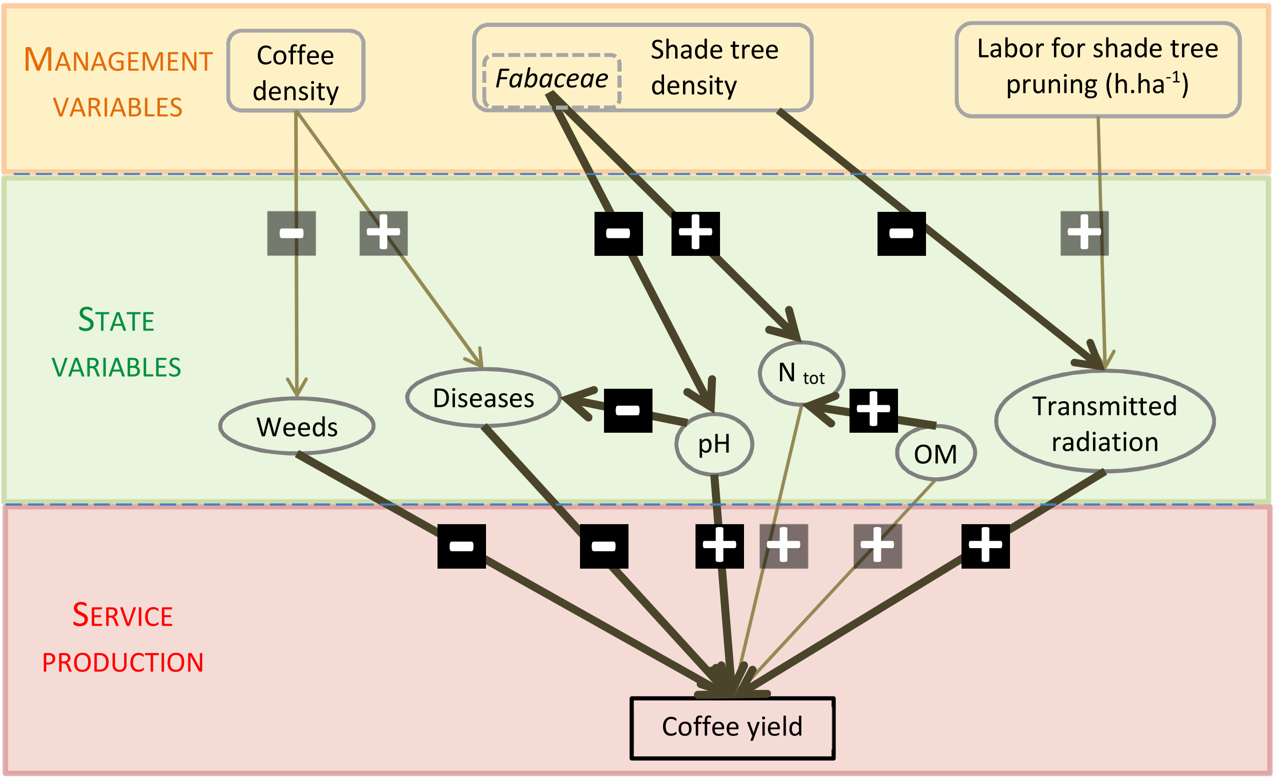


Figure 5. Statistical relationships between coffee yield and its determinants. Elements (state of the cropping system in green and farming practices in orange) that positively (+) or negatively (-), directly or indirectly influenced coffee yield are represented (Pearson correlation tests). Due to a small number of situations (27) we decided to represent the influences until a p-value of 0.15. The influence of the factor on the component is strong for bold arrows (p-value<0.05) and minor for thin arrows (p-value between 0.05 and 0.15).

We did not find any direct influence of agricultural practices on coffee yield. Those practices had direct relationships with the state variables that in turn had effects on coffee yield (Figure 5). Farmers' selection of shade trees and their plantation density had marked impacts on the state variables (soil pH, total soil N and transmitted radiation). *Fabaceae* trees were especially positively correlated to total soil N and negatively to soil pH. Shade tree density obviously positively affected shade cover, thus decreasing radiation transmitted to coffee bushes. The density of coffee plants showed only a limited effect: it inhibited weed development and favored the spread of disease. At the same level of statistical significance, labor spent on pruning shade trees was positively related to light transmitted to coffee plants.

The number of shade trees from the *Fabaecae* family had a contradictory indirect relationship with coffee yield by increasing soil N content, which was positively related to yield, but also by decreasing pH, which had a negative effect on yield and also on coffee disease prevention. Some expected relationships did not appear in the analysis (Figure 5): no practices related to herbicides and pest and disease management had any significant effect on their corresponding environmental variables, i.e. weeds and diseases.

3.2. Clustering among ecosystem services in coffee plantations

Through clustering analysis, we identified a group of farmers who achieved the provision of a better set of ES (Table 3). The analysis was conducted using only values of the four services as determining variables for the differentiation of two groups, with the first having higher provision of the four ES studied and another group with fluctuating ES values. We also extended the comparisons of the two groups formed according to the state variables, as possible sources of these differences in ES, and to management practices, to derive practical conclusions for the management of coffee agroforestry systems.

Clustering identified a group of 12 coffee growers who succeeded in providing a better set of ES (High-ES Type) in comparison to the other 15 farmers (Low-ES Type), but only coffee yield was significantly different between both types. Good ES provision situations were generally found in win-win situations when two services were compared, in the red areas at the top right of the graphs in Figure 6. The highest set of ES provision was achieved through a lower incidence of diseases and weeds, less shade cover and higher pH and total soil N (Table 3). Interestingly, farmers' practices in this group showed a higher diversity of tree species, but lower *Fabaceae* tree density. Surprisingly, there was no significant difference in labor per hectare between these two groups. Labor productivity was significantly higher for the High-ES Type with a production of 57.8 kg coffee.day^{-1} versus 30.5 kg coffee.day^{-1} for the Low-ES Type. No significant difference was observed in fertilization, disease and weed management between the two groups.

*Table 3. Average values for ES, environmental variables and management practice values in coffee agroforestry plots for two Types of AFS derived from the clustering analysis of ES. Standard deviations are indicated; for each variable, t-test significant differences between the two groups are indicated: p-value < 0.05 '***', between 0.05 and 0.15 '*'*

	Comparison element	Unit	High-ES type (n = 12) Mean (±SD)	Low-ES type (n = 15) Mean (±SD)	T-test
ES	Coffee yield	$kg.ha^{-1}.yr^{-1}$	1,445 ±887	855 ±619	***
	WQ (index)	-	-39.5 ±13.6	-41.2 ±7.2	
	Seq C	$t.ha^{-1}$	41 ±39.4	24.8 ±18.8	
	Sh (index)	-	1.49 ±0.60	1.16 ±0.50	
State variables of agroforestry systems	Diseases	% affected leaves	13 ±23	31 ±34	*
	Shade	% plot covered by tree shade	45.8 ±15.2	50.6 ±12.4	*
	Weeds	% ground plot covered	23 ±14.9	30.7 ±16.6	*
	pH	-	6.07 ±0.48	5.83 ±0.24	***
	N soil	mg/L of N in the soil	0.28 ±0.06	0.23 ±0.09	***
	Organic matter	% soil	4.65 ±0.69	4.56 ±0.73	
Management practices and shade tree choices	Nitrogen fertilization	$kg N.ha^{-1}$	24.7 ±31.1	21.5 ±30.1	
	Total volume of fungicides	$L.ha^{-1}.yr^{-1}$	0.9 ±1.2	0.8 ±0.9	
	Total volume of herbicides	$L.ha^{-1}.yr^{-1}$	2.0 ±1.4	1.5 ±1.1	
	Total number of coffee protection treatments	$nb.yr^{-1}$	3.4 ±1.9	2.7 ±1.6	
	Pruning time of shade trees	$days.ha^{-1}$	4.3 ±3.6	5.1 ±3.6	
	Number of tree species	$nb.1000 m^{-2}$	9.5 ±6.1	5.9 ±2.7	*
	Number of fruit trees	$nb.ha^{-1}$	228 ±195	158 ±177	
	Number of firewood/timber trees	$nb.ha^{-1}$	72 ±38	43 ±69	
	Number of *Fabaceae* trees	$nb.ha^{-1}$	**73 ±80**	**143 ±98**	***
	Coffee age	years	12.1 ±11.5	12.9 ±12.4	
	Coffee plantation density	$nb.ha^{-1}$	3,535 ±878	3,213 ±911	
	Management workload	$day.ha^{-1}$	25 ±10.1	28 ±9	

No significant linear correlation was found between the four ES (figure 6), which means that there were no trade-offs nor synergies between these services. This result suggests that there are no barrier to jointly increasing service provision. The design of more agroecological systems (with high service provision) then consists of understanding the determinants of these services and promoting them through technical levers. These technical solutions are then to be explored in situations in the upper right zones of each scatterplot where the provision of each of the two services exceeds their average provision at the scale of the study.

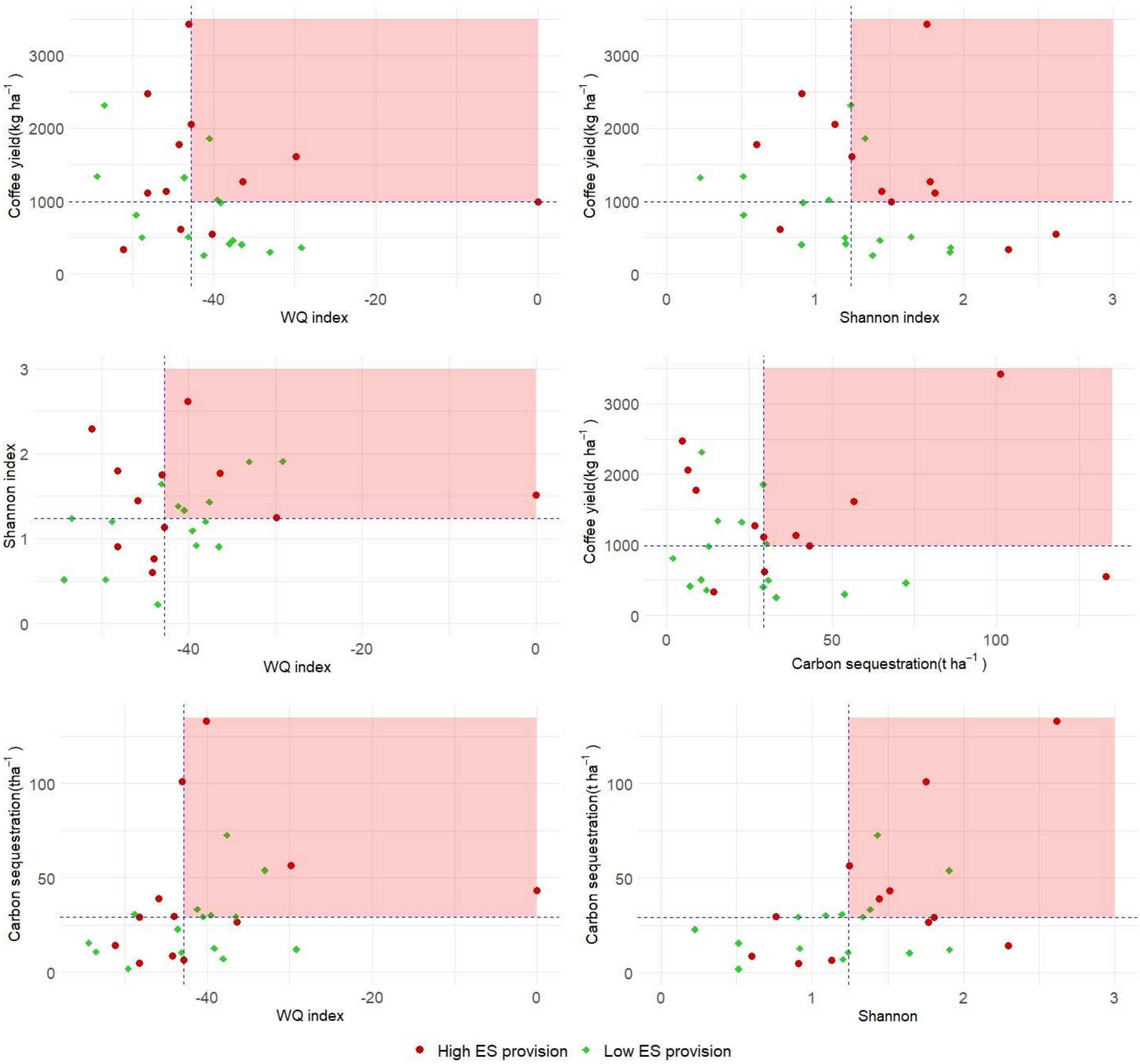


Figure 6. Relationships between ecosystem services in the sub-sample of 27 farmers. The red dots are the situations with the best ecosystem service provision (n = 12). Horizontal and vertical dotted lines represent medians of the services from the y and x axis respectively. The red rectangles are the areas where situations provide good levels of ES.

3.3. Possible benchmarks for agroecological intensification pathways

The management practices and the values of the state variables of the 12 coffee plantations in the High-ES Type could be used as benchmarks:

- Regarding the practices: (i) The number of tree species differed significantly between the two groups (9.5 and 5.9 on average), which translated into Sh differences, and which could also had an influence on coffee production. (ii) The density of nitrogen-fixing trees was much higher for the Low-ES Type, i.e. almost two-fold higher than for the High-ES Type.
- Regarding the state variables: (i) For Low-ES Type, soil pH was low (5.83), as was soil N concentration (0.23 $mg.L^{-1}$), and significantly different from the High-ES Type (6.23 and 0.31 $mg.L^{-1}$, respectively). The link between *Fabaceae* trees, soil nitrogen content, and acidification is well known (Moura et al., 2015). So, there seemed to be a balance about *Fabaceae* density to increase soil nitrogen content while not decreasing pH, i.e. approximately 73 trees per hectare, in line with the current practices of the High-ES Type. (ii) Weed pressure and transmitted radiation differed between the two groups (23% versus 30.7% of weeds on the ground and 45.8% versus 50.6% of shade) and these factors were related to coffee yield, as observed in the statistical model (Figure 5). (iii) A significant difference existed in disease pressure (13% vs 31%), with fungi having a much higher effect on Low-ES Type.

4. DISCUSSION

4.1. Coffee AFS with varying levels of ES supply

We found a large range of delivery of the services we assessed in this small and relatively homogeneous region. With the exception of coffee yield, the average provision of these services was often much lower than in natural forests but much higher than in monocrop systems (Santos et al., 2019).

Carbon sequestration in aboveground biomass (seqC) of shade trees ranged over two orders of magnitude, with a mean of 36.6 $t.ha^{-1}$, which was slightly above the 28.3 $t.ha^{-1}$ estimated in the San Ramon coffee plantation (Goodall et al., 2015), close to the study area, but better than the 13.9 $t.ha^{-1}$ in neighboring Costa Rica (Hergoualc'h et al., 2012), and far behind mature forests, even secondary forests, at 99.1 $t.ha^{-1}$ (Aryal et al., 2014). This sequestered C is obviously in constant evolution, depending on the growth of the trees, the pedoclimatic conditions, and the use of the wood/timber. However, in the region, we can expect its value to increase or be sustained. On one hand, companies dedicated to timber exploitation do not log the trees in the area. On the other hand, wood and timber from the AFS are generally used sparingly by farmers for firewood (often pruning waste) or for houses building. Furthermore, associated trees help to buffer microclimate conditions that decrease soil CO_2 efflux and mitigate global warming (Gomes et al., 2016).

Among the multitude of indicators for measuring diversity, we have chosen the Shannon indicator because it is simple to calculate and summarizes complex information. Moreover, it is very widespread and allows many comparisons with other situations. Shade tree diversity (Sh) ranged over more than one order of magnitude in plots, but it was rather high throughout the whole sample, higher than that reported in cacao-based AFS in a neighbouring region (Cerda et al., 2014) but lower than that reported for coffee AFS established in the remnants of primary forests in a biosphere reserve in Chiapas, Mexico (Valencia et al., 2014). The proximity of coffee plots to the Peñas Blancas natural reserve, a possible source for diversified tree species, could partly explain this high biodiversity.

Water quality, as assessed by the quantity and nature of agrochemical products used in plantations, was also relatively variable, although the indicator we developed only gave relative estimates and not absolute measurements. It is therefore difficult to compare these results with other studies. Nevertheless, data collected for 2013 and 2014 show that farmers use very few pesticides (data not shown), i.e. about half as much as the quantities reported by Meylan et al. (2017) in Costa Rica.

Coffee plot productivity is not routinely measured by farmers, although it is the the studied service in which they have the most interest, as harvesting is usually done by hired hands who move between plots in different rounds. Coffee yields ranged from high values (more than 3 $t.ha^{-1}.yr^{-1}$ of green coffee) to much lower values (below 400 $kg.ha^{-1}.yr^{-1}$), and the average (1,127 $kg.ha^{-1}.yr^{-1}$) was far lower than what has been found in Costa Rica (Meylan et al., 2013) where around 400 kg of N per hectare was applied. Disease management, and the recent outbreak of coffee leaf rust (Avelino et al., 2015), is probably another reason for this high variation. In addition, this variability could be the result of varietal adaptation of coffee trees in certain plots, where more rust-tolerant varieties such as Catimor have replaced more susceptible varieties such as Caturra (Libert Amico et al., 2020). Once transformed into an economic service relevant for the household, this production service also varies significantly, with an income from the sale of coffee of US$ 1,561 $ha^{-1}.yr^{-1}$ for High-ES Type compared to only US$ 889 $ha^{-1}.yr^{-1}$ for Low-ES Type. As other productions from species associated with coffee trees in AFS occupy only 9% of the total turnover (data not shown), with little variation among AFS, we did not consider these other productions in our studied services.

4.2. Analyzing ES determinants to identify promising technical levers

The intrinsic source of variation in the delivery of services was estimated for four ES that we could rapidly estimate. Similarly to Cerda et al. (2017), we found that there are no clear trade-offs between the different services, at least for the services we have studied. This means it could be possible to observe and design systems with a higher level of multiple service provision compared to current systems. Carbon sequestration depends on the presence and size of big trees much more than on the total number of trees (Figure 4), as demonstrated in forests and agroforestry systems worldwide (Schroth et al., 2015). Biodiversity depends on species richness more than on tree density (Figure 3). Finally, pesticide water contamination was mainly linked with the doses of the products used rather than the intrinsic physico-chemical properties of active ingredients (Figure 2). To prevent active molecules from leaching out and ending up in surface water, Pavlidis and Tsihrintzis (2018) have shown that the roots of associated trees, particularly certain species, in AFS have the ability to retain these pollutants. Coffee yield variation was related to factors that could be controlled by farmers, particularly shade tree selection and management (Figure 5). Indeed, plant composition and its management have a direct impact on soil quality (nutrient recycling, structure, moisture, competition and facilitation) as well as the photosynthetic active radiation (PAR) received by coffee trees, which are essential parameters for their physiological functioning and productivity. Furthermore, other AFS state variables significantly influenced coffee yield in ways that were in line with current knowledge, i.e. weeds and diseases limited coffee yield.

The causal relationship between AFS management, state variables describing the system environment and productivity were assessed through a conceptual model in which relationships were tested statistically. The idea that productivity is not directly related to practices, but rather includes their effects on the plant environment, is not new by any means as it is one of the cornerstones of modern agronomy (Sebillote, 1974). Conceptual modeling, as proposed by Lamanda et al. (2012) and applied here, is a convincing approach to screen for statistically significant relationships, such as those we found in this study.

The objective of improving the sustainability and performance of coffee AFS is to increase the provision of all services jointly. To meet this challenge, it is necessary to identify the most effective technical levers of ES determinants to use in practice.

4.3. Possible technical levers to improve the sustainability of coffee AFS

Quantifying ES and analyzing their relationships can be a first step in the implementation of sustainable land-use systems (Tsonkova et al., 2012), adopting an approach resembling agroecological engineering (Dalsgaard et al., 1995), as has already been done for cacao AFS with the Pareto frontier algorithm method (Andreotti et al., 2018). Technical choices affect the nature and quantity of ES in an ecosystem (Rodriguez et al., 2006). Interventions can have positive (e.g. rehabilitation of degraded areas) or negative effects (e.g. converting biodiversity rich areas into cropland) on ES (Kovács et al., 2015). For example, replacing agrochemical products with others that are potentially less dangerous, therefore different in their chemical composition but with similar objectives (reduction of weedy grasses and fungal pressure, etc.), could also be an effective solution to improve WQ (Steingrímsdóttir et al., 2018).

Several studies have demonstrated that solutions to provide ES are determined largely by the number of species and the functional diversity of the species in the cropping system (De Beenhouwer et al., 2013; Malézieux et al., 2009; Storkey et al., 2015; Tschora and Cherubini, 2020). For example, to enhance WQ, besides reducing the doses of agrochemical products used and the number of treatments, consideration could be given to the selection of certain plant species that foster the regulation of some coffee pests (Bagny Beilhe et al., 2020; Nesper et al., 2017). In addition to tree species selection, which is in fact a technical choice, management practices such as particular spatial arrangement for the selected tree species help to reduce the dispersal of spores of some coffee plant diseases (Gagliardi et al., 2020). Furthermore, to achieve good levels of carbon sequestration and coffee production, tree selection is also a decisive point. Indeed, the shading of coffee by associated trees, often correlated to their density, has a negative effect on the productivity of coffee trees past a threshold (Durand-Bessart et al., 2020; Sarmiento-Soler et al., 2020). However, according to our findings, it is mainly trees with a high growth capacity (both height and width) that are responsible for high carbon sequestration. To jointly increase ES, it therefore seems interesting (i) to select various associated species that are useful in the biological control of coffee pests and diseases and whose roots have the capacity to limit the leaching of pollutants, including trees with a high carbon storage capacity, (ii) to plant them at densities that do not provide too much shade, and (iii) to manage them in a way adapted to an effective functioning of the AFS (pruning, spacing between plants, etc.) whether these objectives can be jointly met at acceptable management cost remains mostly unknonw.

4.4. A method that would benefit from scaling up from the cropping system to the farm level

We have proposed technical levers to improve the provision of four ES but their identification comes from analyses at the plot scale only. While this choice allowed us to obtain accurate relationships between services, which was our goal, the scale is too small to address two issues.

While this may be relevant for seqC, i.e. it is an essentially additive service that can be summed up plot by plot, it is probably not very relevant for the delivery of other services such as WQ provision. Indeed, pollution may be caused by other processes, such as contamination with organic waste from coffee milling at the farm scale, sediments at the watershed scale, etc. Upscaling the analysis of ES from the plot to the scale that is relevant to ES delivery can be much more challenging for some ES than for others.

The second issue of scale is related to the leeway to change the way coffee plantations are managed. Some elements can be changed at the plot scale because they have few consequences at the farm level, such as the substitution of an agrochemical product with another of similar efficacy but lower pollution potential. Decisions on most practices, however, are taken at the farm scale, where other trade-offs are also considered, e.g. between the best way to allocate labor, funding, etc. For example, shade tree species have different effects on coffee plants, but also require different degrees of labor input for their management. Such issues need to be considered when proposing new cropping systems. This study should be extended to encompass the farm scale and the decisions taken at this scale.

5. CONCLUSION

We proposed and tested an integrated method to assess the multiple ES provision of cropping systems and explored the management options in coffee AFS to increase them. Technical levers for improving the provision of ES and therefore the sustainability of coffee-based agroforestry systems, can be readily determined via the analysis of the ES provided. The application of our method enabled us to come up with some recommendations for cropping practices, in particular that a thoughtful choice of associated trees selected according to their expected functions is a key point when designing AFS that provide high levels of ES. However, other dimensions of intensification pathways have to be included in the analysis, particularly at the farming system scale. For an effective agroecological intensification of coffee systems, participatory approaches for the selection of innovative and acceptable practices, including farmers and their knowledge, should be developed. This work should make it possible to identify species to associate with coffee trees over time and space, to (1) improve coffee yields, and (2) provide other environmental services (e.g. regulation of diseases and pests, nutrient recycling, carbon sequestration, anti-erosion protection). Public policies could be designed to finance these participatory activities, which would be implemented by agricultural development and technical institutes. Furthermore, payment for ecosystem services policies could be strengthened. Finally, research could study the pros and cons of the different novelties that have emerged from participatory approaches in experimental stations under controlled conditions and investigate the underlying biogeochemical processes.

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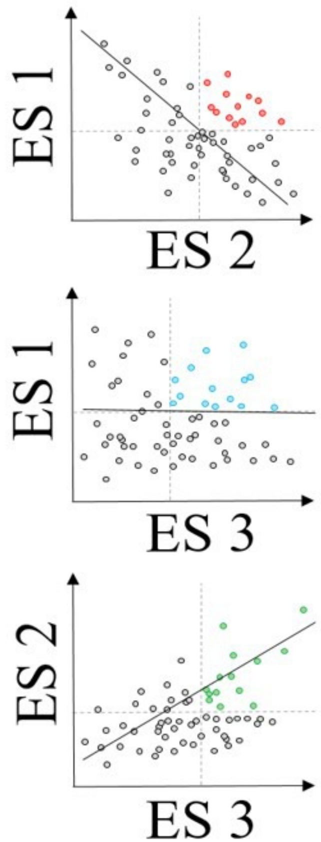
1

SELECT AND QUANTIFY

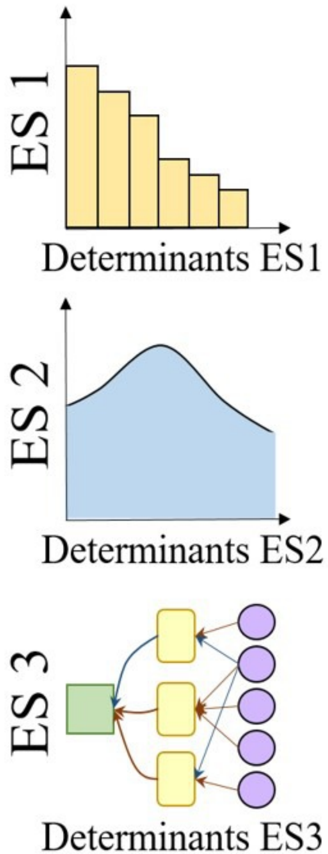
Quantify ecosystem services (ES) that play a major role in the sustainability of cropping systems (CS) and analysis of the relationships between them



2

FIND THE DETERMINANTS

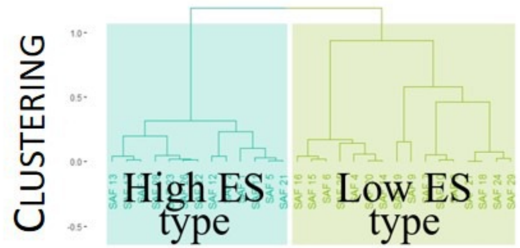
Characterize the determinants of ES provision



3

IDENTIFY PRACTICES

Identify key practices correlated to the determinants of ES by comparing management between CS that provide good levels of ES and those that provide low levels of ES



	High-ES type vs. Low-ES type
ES1	***
ES2	*
ES3	***
Management 1	-
Management 2	***
Management 3	***
Management 4	-
Management n	*

4

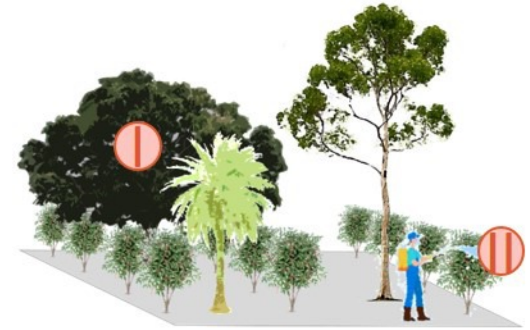
UNDERSTAND AND RECOMMEND

Understand the practices correlated to the determinants to make valuable design advices of CS with high provision of diverse ES in terms of

(i) choice of species

(ii) management practices

MAIN ADVICES IN OUR CASE STUDY



I Favouring a few associated trees with coffee trees:

(1) with a high trunk growth potential in width to increase the carbon stock,

(2) of various species to conserve biodiversity and adapted to promote agroecological functioning to allow a sustainable production of coffee.

II Using agrochemicals at authorized doses, giving priority to those that are less harmful for human health and those with a low potential for transfer to surface water.