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1 **How to increase the joint provision of ecosystem services by agricultural** 2 **systems. Evidence from coffee-based agroforestry systems**

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11 Keywords: Ecosystem services, agroforestry systems, agroecological transition, technical levers

12 **Abstract**

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

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

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

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

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

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

45

46 **Highlights**

47 - Agroforestry systems can jointly provide high yields and high levels of cultivated biodiversity,
48 carbon sequestration and water quality preservation

49 - Quantifying ecosystem services for analyzing their relationships and determinants is key to find
50 technical levers to jointly enhance their provision

51 - The choice of associated tree species and their density is crucial for enhancing the joint provision of
52 ecosystem services in agroforestry systems

53

54 **1. INTRODUCTION**

55 Agroforestry systems (AFS) are generally considered to provide more ecosystem services (ES) than
56 monocrop systems (De Beenhouwer et al., 2013; Santos et al., 2019). Potentially harboring high
57 floristic biodiversity (Deheuvels et al., 2012; Valencia et al., 2014), AFS provide permanent shelter
58 due to the perennial nature of the trees they contain, which can in turn accommodate highly diverse
59 wildlife capable of regulating pests and diseases (Cardinale et al., 2012; Ratnadass et al., 2011).
60 Furthermore, this diversity and density of associated trees can potentially sequester high levels of
61 carbon biomass (Cerda et al., 2017; Saj et al., 2013; Somarriba et al., 2013), both above and
62 belowground (Albrecht and Kandji, 2003; Montagnini and Nair, 2004; Niether et al., 2019), and
63 potentially increase soil fertility through litter deposition and nitrogen fixation (Durand-Bessart et al.,
64 2020; Saj et al., 2021; Sauvadet et al., 2018; Souza et al., 2012), while limiting soil erosion (Meylan et
65 al., 2013). It can also enhance economic resilience by diversifying sources of income through other
66 productions in farm plots (Cerda et al., 2014; Schroth and Ruf, 2013; van Asten et al., 2011), and
67 ecological resilience by maintaining a suitable climate for the cropping system despite global
68 warming (Souza et al., 2012).

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

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

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

99 We selected four services, three of environmental interest, water quality, carbon sequestration and
100 tree biodiversity conservation, and one of private economic interest, coffee production. These
101 services were chosen because they are essential: "water quality" to the quality of life of people who

102 directly use and drink river water (Elfikrie et al., 2020); “carbon sequestration” to limit global
103 warming (Albrecht and Kandji, 2003); “tree biodiversity conservation” to maintain a diverse wildlife
104 community (Bhagwat et al., 2008) and, more broadly, for the sustainability of ecosystems,
105 particularly cropping systems (Balima et al., 2020); “coffee production” because it is the main cash
106 crop providing income for farm households.

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

115 **2. MATERIAL AND METHODS**

116 **2.1. Site description**

117 Our study was carried out in Nicaragua’s Matagalpa department, where coffee production accounts
118 for 28% of national coffee production, with an average production of 777 kg.ha⁻¹.yr⁻¹ (FAO, 2015). We
119 analyzed coffee AFS plots located east of La Dalia (13° 08’ 00” N and 85° 44’ 00” W), in the vicinity of
120 the Peñas Blancas Massif and scattered over an area of approximately 200 km². All plots were
121 situated between 700 and 1,100 meters above sea level (m.a.s.l.), under a subtropical humid climate,
122 with mean annual precipitation of around 1,400 mm.year⁻¹, a mild five-month dry season (December-
123 April) and an average temperature of around 21°C.

124 **2.2. Coffee plot network and experimental design**

125 The survey of ES quantification was implemented in two phases (Table 1). In the first step, a sample
126 of 82 coffee growers was selected using the snowball method (Thompson, 2002) without prioritizing
127 any particular type of farm (area, production diversity, etc.). In this sample of 82 farmers, we
128 collected data on coffee production and agrochemical product use in the previous year (2013). There
129 was no mechanical tillage for soil management, nor intercropping with soil cover plants. To our
130 knowledge, the practice of pruning coffee trees was homogeneous in the study area. We estimated
131 biodiversity and carbon sequestration on one 1,000 m² (20 m x 50 m) experimental coffee plot that
132 was assumed to be representative of on-farm coffee plots.

133 As coffee productivity at the plot scale is usually not recorded by farmers and is highly variable, we
 134 decided to conduct a second survey to estimate this service and its relationships to coffee plantation
 135 structure and management. Because measuring coffee yields is relatively time-consuming, the farm
 136 sample was reduced to 27 farms from the initial 82 farmers. The selection was based on the strong
 137 interest shown in the study by the 27 selected producers. In this subsample, we estimated coffee
 138 productivity by counting beans on coffee trees located in three 100 m² squares within the initial
 139 1,000 m² observation plot (Figure 1). Other management and state variables of AFS plots that could
 140 influence coffee yield were ascertained by questioning farmers or measured, as described below
 141 (Section 2.4.).

142

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

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

146

147 **2.3. Research approach: from the quantification of service to the formulation of promising**
 148 **management approaches**

149 The work carried out sought to highlight the technical levers that can be mobilized to foster a high
 150 level of service provision at the cropping system scale, following a methodology similar to that
 151 developed by Bhattarai et al. (2017) and Cerda et al. (2020). Technical levers refer to management
 152 practices that substantially increase the provision of a given service. First, we measured the provision
 153 of the four services studied, investigated the relationships among them, and characterized their

154 determinants. Then we identified the situations providing a good level of the four services and
155 highlighted the explanatory factors and possible levers to reach these successful situations.

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

160

161

162 **2.4. Data collection and assessment**

163 *2.4.a. Assessment of ecosystem services*

164 *α) Water quality*

165 During the first stage of the survey, we asked farmers about the agrochemical products they applied
166 to coffee plants and the doses they used for each application. Two interviews were carried out, the
167 first in April-May 2014 and the other in October 2014 and specifically focused on the agrochemical
168 products used during the previous year (2013) in all coffee plots and during the last crop season
169 (2014) for the experimental plot.

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

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

- 180 - $\tau_{\frac{1}{2} \text{ soil}}$ = Half-life in soil
- 181 - K_s = Solubility in water at 20°C
- 182 - χ = Leaching potential exclusively based on the agrochemical product's chemical properties
- 183 - $\tau_{\frac{1}{2} \text{ water}}$ = Half-life in water
- 184 - X_n = Harmfulness for mammals: lethal ingested dose for 50% of the rodent population

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

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

$$189 \quad PPIH_j = \sum_{i=1}^n \left((\tau \cdot \frac{1}{2} sol_i + Ks_i + \chi_i + \tau \cdot \frac{1}{2} water_i) * Xn_i \right) * [i] \quad (1)$$

$$190 \quad PPIH_x = \sum_{j=1}^m \left((PPIH_j) * \frac{D_{applied\ j}}{D_{recommended\ j}} \right) \quad (2)$$

191 i: Active ingredient

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

193 n: The last active ingredient constituting the agrochemical product

194 m: The last agrochemical product used by the farmer

195 D: Dose (L.ha⁻¹ or kg.ha⁻¹)

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

$$198 \quad WQ_x = - PPIH_x \quad (3)$$

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

201 *β) Tree biodiversity conservation*

202 We identified and counted all plant species higher than coffee trees present in the 1,000 m²
 203 observation plot with diameters at chest height of more than 10 cm. AFS biodiversity was assessed in
 204 each plot using the Shannon index (Sh) to highlight the abundance and the richness of diversity
 205 (Shannon, 1948). Sh indicates both the diversity of tree species and the distribution evenness of tree
 206 individuals into these species in the experimental plot and is calculated as follows:

$$207 \quad Sh = - \sum_{i=1}^n pi (\ln pi) \quad (4)$$

208 pi is the proportion of species i

209 n: Number of species in the experimental plot

210 *γ) Carbon sequestration*

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

$$214 \quad AGB_j = e^{(-2,977 + \ln(\rho_i DBH_j^2 h_j))} \quad (5)$$

215 AGB_j (g): Aboveground biomass of tree j

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

218 DBH_j (cm): Diameter at chest height of tree j

219 h_j (m): Height of tree j

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

$$222 \quad Seq C = \sum_{j=1}^m AGB_j * 0.5 * 10^{-5} \quad (6)$$

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

224 The factor 10^{-5} corresponds to the conversion of g to Mg while taking into account the conversion
225 factor of $1000m^2$ to hectare.

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

230 *δ) Coffee yield*

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

236 *2.4.b. Assessment of management and state AFS variables to identify determinants of coffee yield*

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

238

239

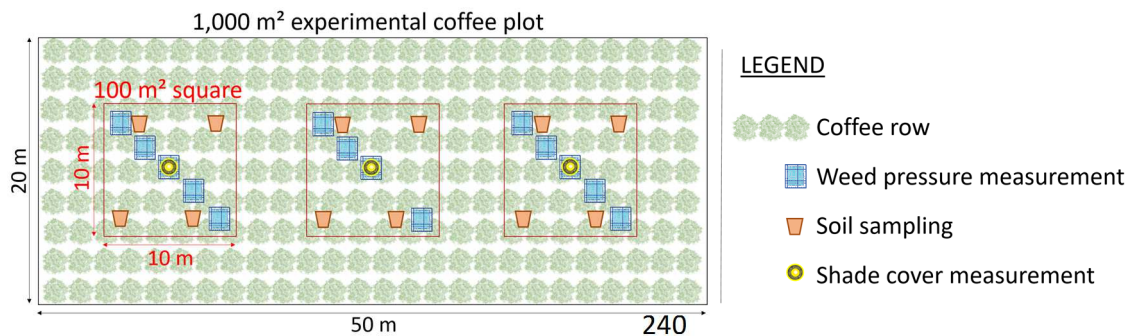


Figure 1. Sampling scheme in coffee plots for ES, management and environmental variables measurement.

241

242

243 ϵ) State variables

244 Four AFS state variables for characterizing the state of systems at a given moment, as defined by
245 Lamanda *et al.* (2012), were considered in the 100 m² squares in the subsample of 27 farmers' plots
246 (Figure 1):

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

250 • Weed pressure (%) was estimated using a 1 m² square frame divided into a grid of 100 identical 1
251 dm²-square cells. A mark of 1 was counted every time a cell included at least one weed. The
252 percentage of cells with 1 mark yielded the weed pressure. This procedure was replicated at five
253 locations in each 100 m² square at two dates (July and October 2014). The average of all the
254 measurements taken for the two dates was used in the statistical analyses.

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

$$262 \text{ Disease incidence}(\%) = \frac{\text{number of leaves affected by rust} + \text{number of leaves affected by ALS}}{\text{Total number of leaves for the coffee plant}} \quad (7)$$

263

264 • Soil chemical properties were analyzed by mixing four soil samples extracted in the upper 20 cm
265 with an auger in each square. The resulting composite samples (one per 100 m²-square) were sent
266 for analysis to the soil laboratory at Nicaragua's National Agriculture University (UNA). Organic
267 matter (OM, %), total nitrogen in soil (N_{tot}, ‰) and pH were analyzed.

268 ζ) *Management variables*

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

273

274 2.5. Statistical analyses

275 All analyzes were run using the 'stats' and 'ade4' (Dray, 2007) R statistical packages (R Core Team,
276 2016) with R studio 3.3.1 (Rstudio Team, 2016). In order to sharpen the initial conceptual model built
277 for coffee yield by maintaining only the significant relations, generalized linear models (GLM) were
278 used to estimate the relationships: 1) between coffee yield and all the state variables, and 2)
279 between those variables and the reported agricultural practices. Indeed, the different practices
280 carried out by farmers lead to changes in the state of the systems, which in turn impact yields (Doré
281 et al., 1997; Sebillotte, 1990). **Without using statistical method and analysis software, we performed**
282 **by our own discernment a clustering based on the variability of provision of the four ES to form two**
283 **groups, one of which provided a higher overall level of supply of the four ES than the other. We**
284 **selected for the group of situations providing high levels of services, situations showing high levels of**
285 **provision for at least two of the four services studied.** This differentiation then helped us to identify
286 promising AFS, in terms of state variables and technical management, that provided the most
287 balanced sets of ES.

288

289 3. RESULTS

290 **The 27 coffee cropping systems that have been described in detail in agronomic terms included**
291 **coffee trees with an average age of 13 years (±11.5), planted at an average density of 3,362 coffee**
292 **trees ha⁻¹ (±878) for an average production of 1,127 kg.ha⁻¹.yr⁻¹ (±1,240), generating an average**
293 **turnover of US\$ 1,547 ha⁻¹.yr⁻¹. All cropping systems were managed in agroforestry (AFS) with varying**
294 **densities of species association: on average, 170 banana plants.ha⁻¹ (±160), 108 *Fabaceae* trees.ha⁻¹**
295 **(±96), 48 trees.ha⁻¹ for timber production (±55) and 35 fruit trees.ha⁻¹ (±51). The plants with annual**
296 **production, i.e. banana and fruit trees, generated a turnover equivalent to US\$ 136 ha⁻¹, which was**

297 9% of the total turnover of the AFS. The products of these food crops were for 81% self-consumption
 298 by the farms' household.

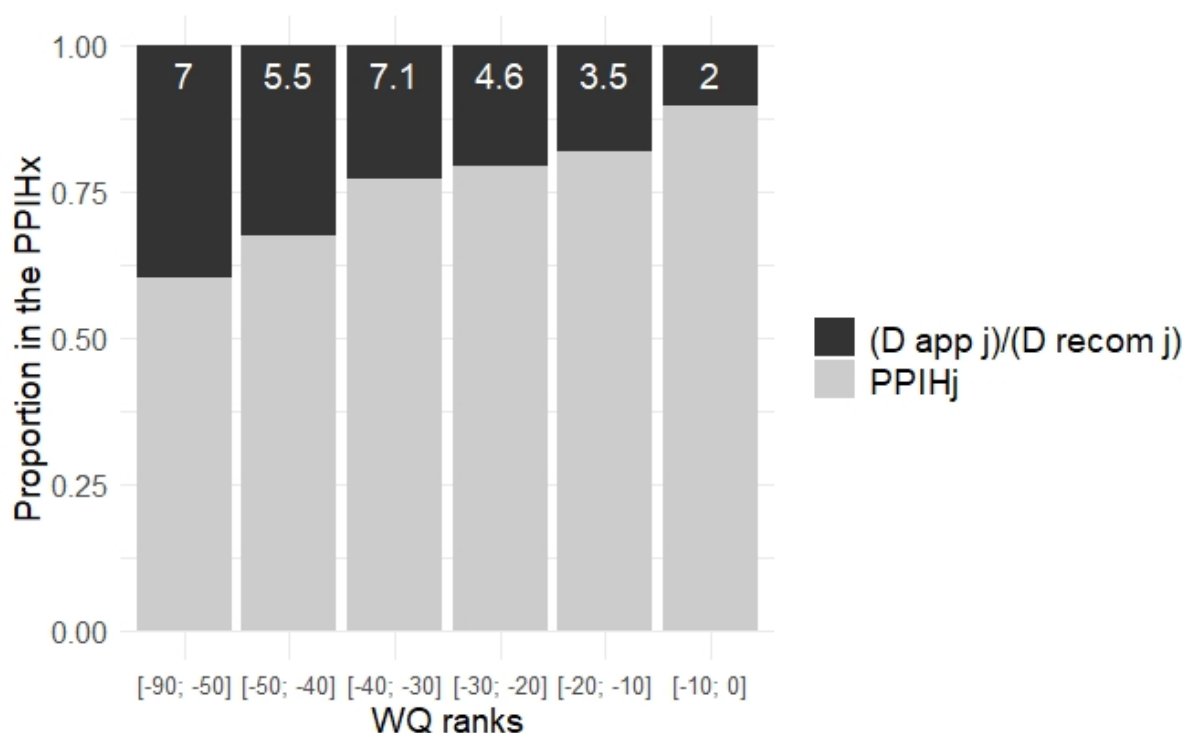
299 The technical management of these AFS took an average of 43 days per hectare per year. Time
 300 requirements of practices were, in decreasing order: an average of 10 (± 6.4) days of manual weeding
 301 with a machete, 7.7 (± 6.8) days of sucker removal, 7.4 (± 5.3) days of pruning shade trees),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

307 The variability of the four services studied was high: for water quality index (WQ), the minimum was -
 308 88 and the maximum 0 (average of -18). For the Shannon index (Sh), the minimum was 0.22 and the
 309 maximum 2.63 (average of 1.41). For carbon sequestration (seqC), the minimum was 1 t.ha⁻¹.yr⁻¹ and
 310 the maximum 190 t.ha⁻¹ (average 36t.ha⁻¹). Finally, for coffee yield, the minimum was 233 kg.ha⁻¹.yr⁻¹
 311 and the maximum 3,236 kg.ha⁻¹ (average 1,127 kg.ha⁻¹.yr⁻¹).

3.1. ES quantification and determinants

3.1.1. Water quality

314 What mainly explained the PPIHx were the properties of the active molecules that were used to
 315 calculate the PPIH of agrochemical product j, including the dangerousness for mammals. However, it
 316 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).

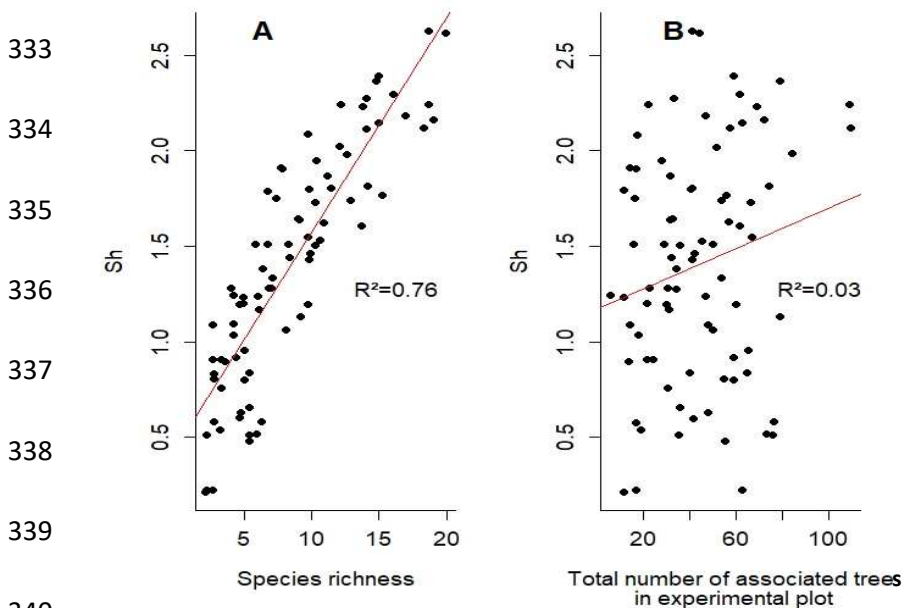
317 applied. The more the WQ decreased from class ([-10; 0]) to class ([-90; -50]), the more it was the
318 dose that was involved in the value of the indicator rather than the PPIHj (Figure 2). There was a
319 significant positive correlation between the number of treatments and WQ ($R^2 = 0.80$). Mann-
320 Whitney statistical tests had shown significant differences (p -value < 0.05) between the number of
321 treatments and the agrochemical product dose at the PPIHx between the most polluting situations ([-
322 90; -50] and [-50; -40]) and the least polluting ([-10; 0]). There was no clear link between WQ and the
323 different types of agrochemical products: insecticides, fungicides and herbicides (data not shown).

324

325 3.1.2. Tree biodiversity conservation

326 111 species were identified in total in the 82 experimental plots. The Shannon index was particularly
327 dependent on species richness ($R^2 = 0.76$, p -value $< 10^{-16}$), but not on the density of associated trees
328 ($R^2 = 0.03$, p -value = 0.08) (Figure 3 A and B). The more species present in the same proportion, the
329 higher the Shannon index is. In the situations we studied, the higher the species richness, the more
330 similar the proportions of species were, given the strong correlation between species richness and Sh
331 (Figure 3).

332



341 *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.*

342 According to farmers, associated trees have four different functions in the plots: fruit production, N
343 fixation, timber production and firewood production, with each species having one major function.
344 The plants most common in coffee AFS according to their function were fruit species (*Musa* spp.,
345 *Mangifera indica*, *Persea americana*, *Citrus sinensis*, *Theobroma cacao* and *Psidium guajava*) and N-

346 fixing trees of the *Fabaceae* family (*Inga* spp. and *Erythrina* spp.), with a relative abundance of 60%
 347 and 24%, respectively (Table 2).

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

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

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351 3.1.3. Carbon sequestration

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

358

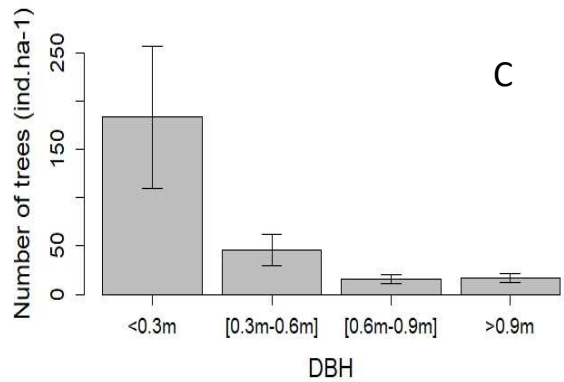
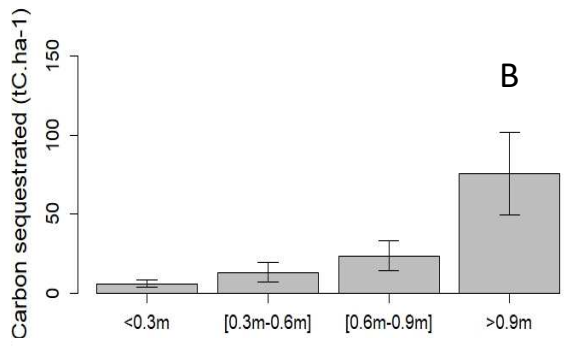
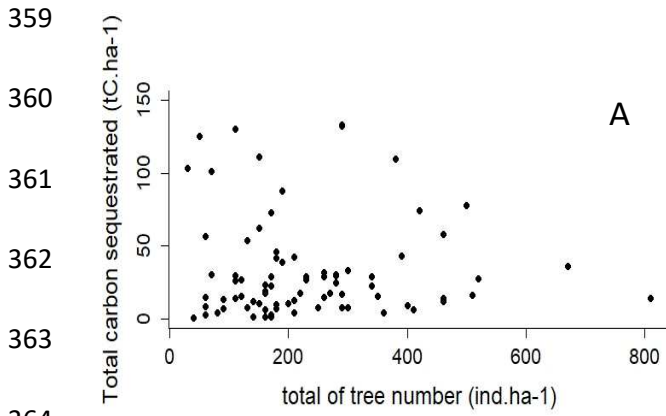
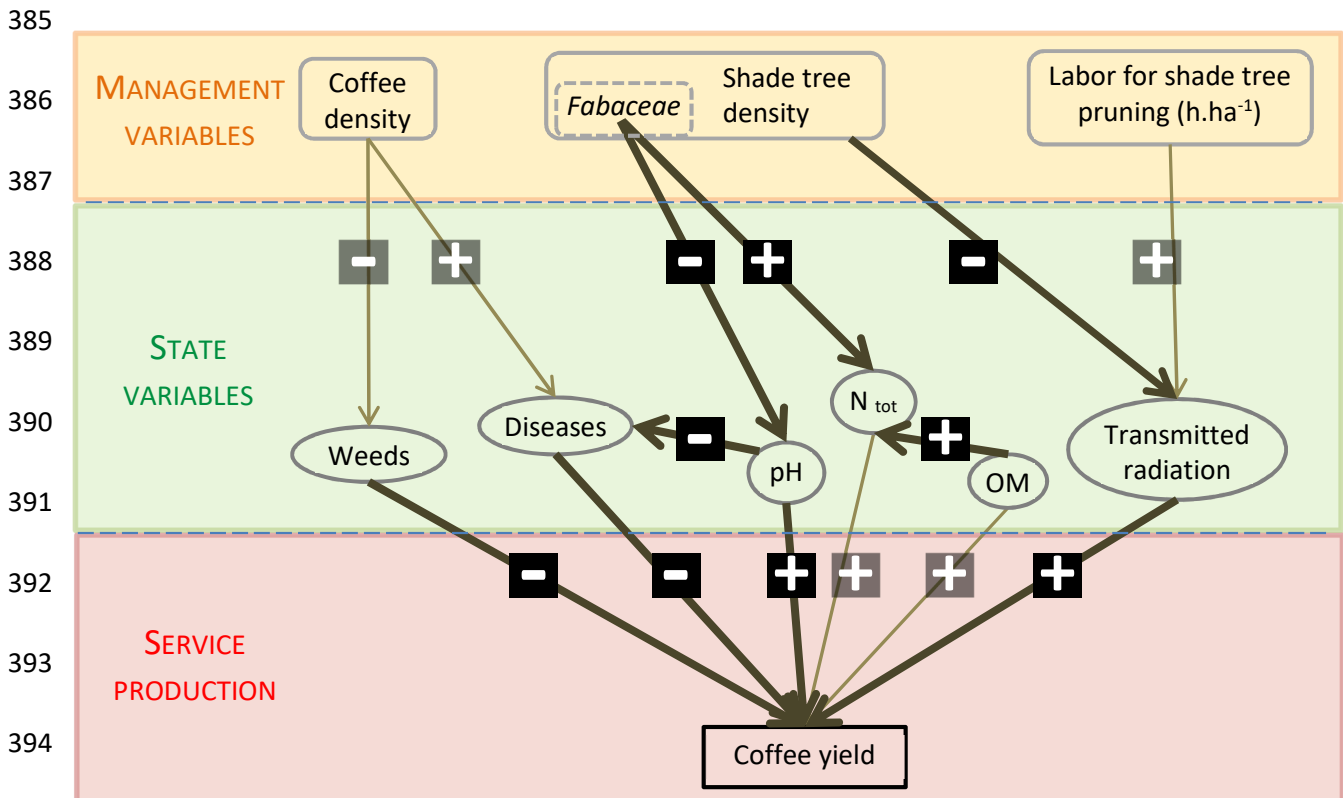


Figure 4. A) Total carbon sequestration depending on the associated tree density. B) Mean seqC per tree depending on tree DBH ranks from less than 0.3m to more than 0.9m. C) Mean number of trees depending on tree DBH ranks from less than 0.3m to more than 0.9. Error bars correspond to standard

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).



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

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

409 The number of shade trees from the *Fabaceae* family had a contradictory indirect relationship with
 410 coffee yield by increasing soil N content, which was positively related to yield, but also by decreasing
 411 pH, which had a negative effect on yield and also on coffee disease prevention. Some expected
 412 relationships did not appear in the analysis (Figure 5): no practices related to herbicides and pest and

413 disease management had any significant effect on their corresponding environmental variables, i.e.
414 weeds and diseases.

415 **3.2. Clustering among ecosystem services in coffee plantations**

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

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

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

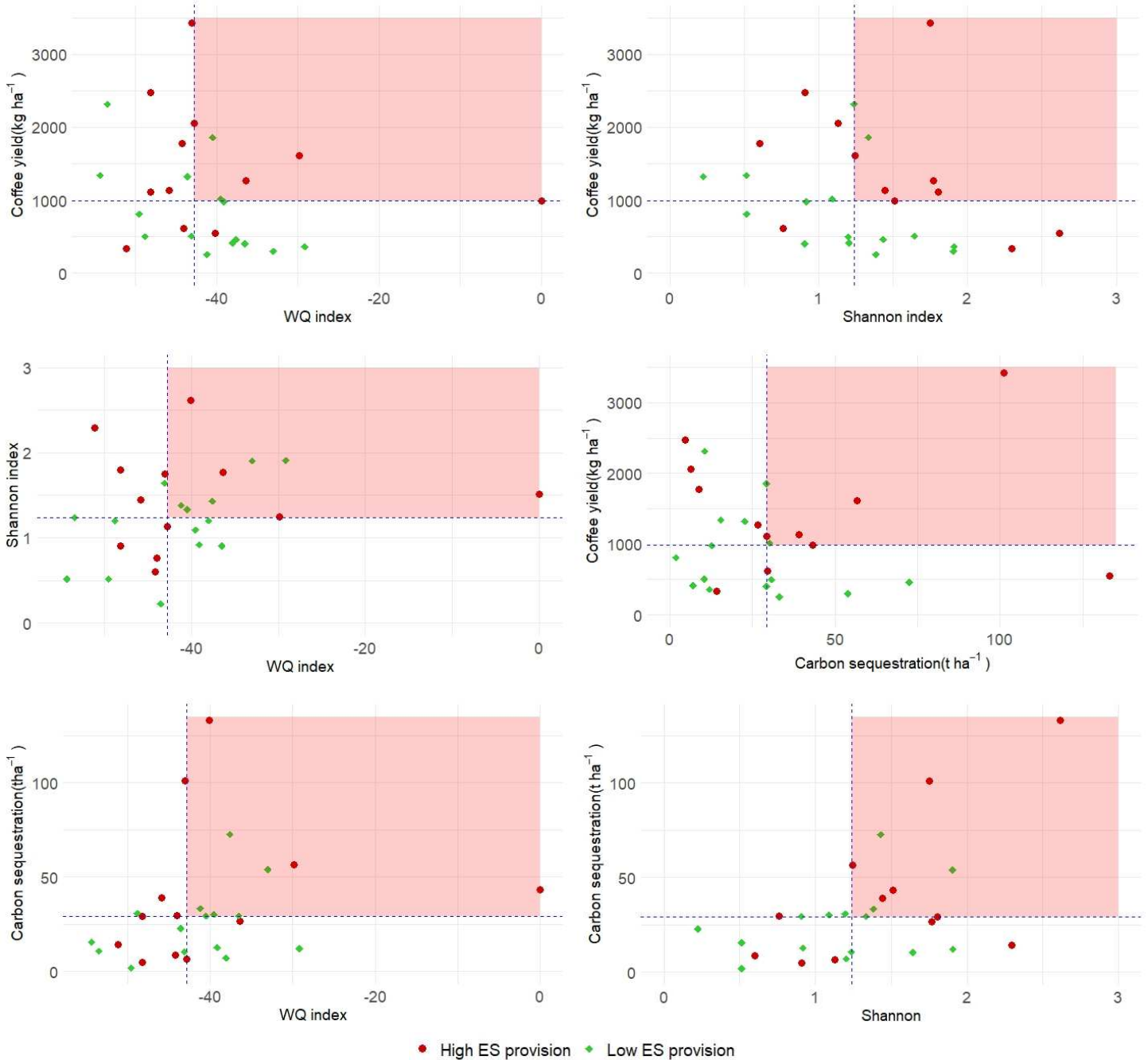
	Comparison element	Unit	High-ES type (n = 12) Mean (±SD)	Low-ES type (n = 15) Mean (±SD)	T-test
ES	Coffee yield	kg.ha ⁻¹ .yr ⁻¹	1,445 ±887	855 ±619	***
	WQ (index)	-	-39.5 ±13.6	-41.2 ±7.2	
	Seq C	t.ha ⁻¹	41 ±39.4	24.8 ±18.8	
	Sh (index)	-	1.49 ±0.60	1.16 ±0.50	
State variables of agroforestry systems	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 <i>Fabaceae</i> 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		

446

447 No significant linear correlation was found between the four ES (figure 6), which means that there
 448 were no trade-offs nor synergies between these services. This result suggests that there are no
 449 barrier to jointly increasing service provision. The design of more agroecological systems (with high
 450 service provision) then consists of understanding the determinants of these services and promoting

451 them through technical levers. These technical solutions are then to be explored in situations in the
 452 upper right zones of each scatterplot where the provision of each of the two services exceeds their
 453 average provision at the scale of the study.

454 *Figure 6. Relationships between ecosystem services in the sub-sample of 27 farmers. The red dots are the*
 455 *situations with the best ecosystem service provision (n = 12). Horizontal and vertical dotted lines represent*



456 *medians of the services from the y and x axis respectively. The red rectangles are the areas where situations*
 457 *provide good levels of ES.*

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460 3.3. Possible benchmarks for agroecological intensification pathways

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

- 463 - Regarding the practices: (i) The number of tree species differed significantly between the two
464 groups (9.5 and 5.9 on average), which translated into Sh differences, and which could also
465 had an influence on coffee production. (ii) The density of nitrogen-fixing trees was much
466 higher for the Low-ES Type, i.e. almost two-fold higher than for the High-ES Type.
- 467 - Regarding the state variables: (i) For Low-ES Type, soil pH was low (5.83), as was soil N
468 concentration (0.23 mg.L⁻¹), and significantly different from the High-ES Type (6.23 and 0.31
469 mg.L⁻¹, respectively). The link between *Fabaceae* trees, soil nitrogen content, and
470 acidification is well known (Moura et al., 2015). So, there seemed to be a balance about
471 *Fabaceae* density to increase soil nitrogen content while not decreasing pH, i.e.
472 approximately 73 trees per hectare, in line with the current practices of the High-ES Type. (ii)
473 Weed pressure and transmitted radiation differed between the two groups (23% versus
474 30.7% of weeds on the ground and 45.8% versus 50.6% of shade) and these factors were
475 related to coffee yield, as observed in the statistical model (Figure 5). (iii) A significant
476 difference existed in disease pressure (13% vs 31%), with fungi having a much higher effect
477 on Low-ES Type.

478

479 4. DISCUSSION

480 4.1. Coffee AFS with varying levels of ES supply

481 We found a large range of delivery of the services we assessed in this small and relatively
482 homogeneous region. With the exception of coffee yield, the average provision of these services was
483 often much lower than in natural forests but much higher than in monocrop systems (Santos et al.,
484 2019).

485 Carbon sequestration in aboveground biomass (seqC) of shade trees ranged over two orders of
486 magnitude, with a mean of 36.6 t.ha⁻¹, which was slightly above the 28.3 t.ha⁻¹ estimated in the San
487 Ramon coffee plantation (Goodall et al., 2015), close to the study area, but better than the 13.9 t.ha⁻¹
488 in neighboring Costa Rica (Hergoualc'h et al., 2012), and far behind mature forests, even secondary
489 forests, at 99.1 t.ha⁻¹ (Aryal et al., 2014). This sequestered C is obviously in constant evolution,
490 depending on the growth of the trees, the pedoclimatic conditions, and the use of the wood/timber.
491 However, in the region, we can expect its value to increase or be sustained. On one hand, companies

492 dedicated to timber exploitation do not log the trees in the area. On the other hand, wood and
493 timber from the AFS are generally used sparingly by farmers for firewood (often pruning waste) or
494 for houses building. Furthermore, associated trees help to buffer microclimate conditions that
495 decrease soil CO₂ efflux and mitigate global warming (Gomes et al., 2016).

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

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

510 Coffee plot productivity is not routinely measured by farmers, although it is the the studied service in
511 which they have the most interest, as harvesting is usually done by hired hands who move between
512 plots in different rounds. Coffee yields ranged from high values (more than 3 t.ha⁻¹.yr⁻¹ of green
513 coffee) to much lower values (below 400 kg.ha⁻¹.yr⁻¹), and the average (1,127 kg.ha⁻¹.yr⁻¹) was far
514 lower than what has been found in Costa Rica (Meylan et al., 2013) where around 400 kg of N per
515 hectare was applied. Disease management, and the recent outbreak of coffee leaf rust (Avelino et al.,
516 2015), is probably another reason for this high variation. In addition, this variability could be the
517 result of varietal adaptation of coffee trees in certain plots, where more rust-tolerant varieties such
518 as Catimor have replaced more susceptible varieties such as Caturra (Libert Amico et al., 2020). Once
519 transformed into an economic service relevant for the household, this production service also varies
520 significantly, with an income from the sale of coffee of US\$ 1,561 ha⁻¹.yr⁻¹ for High-ES Type compared
521 to only US\$ 889 ha⁻¹.yr⁻¹ for Low-ES Type. As other productions from species associated with coffee
522 trees in AFS occupy only 9% of the total turnover (data not shown), with little variation among AFS,
523 we did not consider these other productions in our studied services.

524 4.2. Analyzing ES determinants to identify promising technical levers

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

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

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

553 **4.3. Possible technical levers to improve the sustainability of coffee AFS**

554 Quantifying ES and analyzing their relationships can be a first step in the implementation of
555 sustainable land-use systems (Tsonkova et al., 2012), adopting an approach resembling
556 agroecological engineering (Dalsgaard et al., 1995), as has already been done for cacao AFS with the
557 Pareto frontier algorithm method (Andreotti et al., 2018). Technical choices affect the **nature and**

558 quantity of ES in an ecosystem (Rodriguez et al., 2006). Interventions can have positive (e.g.
559 rehabilitation of degraded areas) or negative effects (e.g. converting biodiversity rich areas into
560 cropland) on ES (Kovács et al., 2015). For example, replacing agrochemical products with others that
561 are potentially less dangerous, therefore different in their chemical composition but with similar
562 objectives (reduction of weedy grasses and fungal pressure, etc.), could also be an effective solution
563 to improve WQ (Steingrimsdóttir et al., 2018).

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

584 **4.4. A method that would benefit from scaling up from the cropping system to the farm level**

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

588 While this may be relevant for seqC, i.e. it is an essentially additive service that can be summed up
589 plot by plot, it is probably not very relevant for the delivery of other services such as WQ provision.
590 Indeed, pollution may be caused by other processes, such as contamination with organic waste from

591 coffee milling at the farm scale, sediments at the watershed scale, etc. Upscaling the analysis of ES
592 from the plot to the scale that is relevant to ES delivery can be much more challenging for some ES
593 than for others.

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

603 **5. CONCLUSION**

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

622

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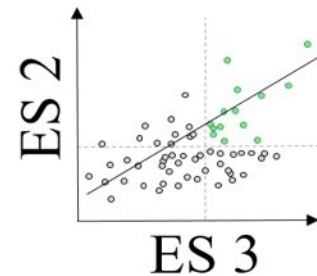
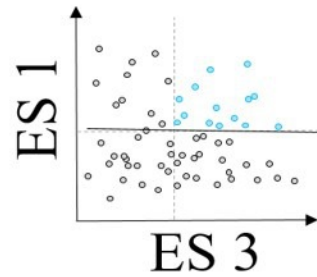
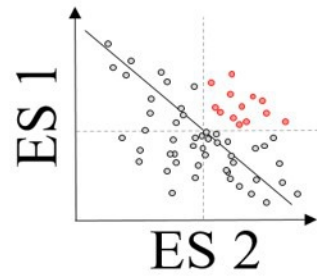
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1

SELECT AND QUANTIFY

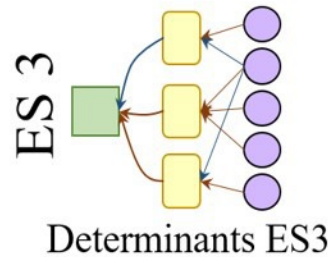
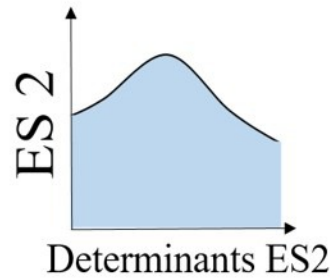
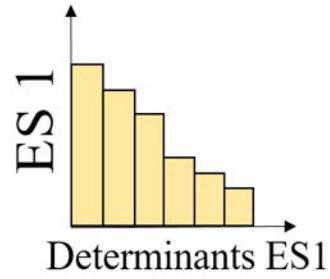
Quantify ecosystem services (ES) that play a major role in the sustainability of cropping systems (CS) and analysis of the relationships between them



2

FIND THE DETERMINANTS

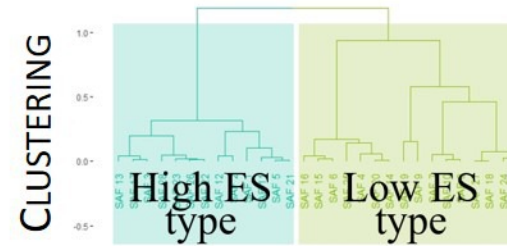
Characterize the determinants of ES provision



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



⊘ Favours 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.

⊘ 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.