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1 PARTICIPATIVE DESIGN OF THE SPATIAL AND TEMPORAL DEVELOPMENT OF IMPROVED
2 COCOA AGROFORESTRY SYSTEMS FOR YIELD AND BIODIVERSITY

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1 PARTICIPATIVE DESIGN OF THE SPATIAL AND TEMPORAL DEVELOPMENT OF IMPROVED 2 COCOA AGROFORESTRY SYSTEMS FOR YIELD AND BIODIVERSITY

3 1. Introduction

4 Cocoa is mostly produced by small-scale farmers within agroforestry systems (AFS) in which cocoa
5 trees are cropped together with ligneous and non-ligneous species (Schroth and Mota, 2014). The
6 combination of these species can provide provisioning services, such as the production of fruit and
7 wood, and provide a large range of environmental services in relation with biodiversity (Malézieux *et*
8 *al.*, 2009). Products can be sold or used for farmers' household consumption. This is the case in the
9 Dominican Republic, where all cocoa-based cropping systems are AFS, most of them organic. Average
10 yields for the last few years are rather good compared to the other main producing countries,
11 respectively 537 kg.ha⁻¹ and 413 kg.ha⁻¹ of dry cocoa beans (FAOSTAT, 2019) but, given the high cost
12 of living, more than a third of households making a living through cocoa production remain below
13 the poverty line (Notaro *et al.*, 2020). Increasing farmers' revenues from cocoa-based AFS is
14 therefore a precondition for the sustainability of the sector, and a key question is to determine what
15 technical changes can contribute to this.

16 Technical improvements can be made on both the strategic and tactical components of AFS
17 management. In particular, innovations may relate to the structure of AFS, which vary greatly in
18 terms of the choice of crop species combined with cocoa and their spatial arrangement (Deheuvels *et*
19 *al.*, 2012; Jagoret *et al.*, 2018b; Sanial, 2018; Salazar-Díaz and Tixier, 2019). The diversity of crop
20 species generates a diversity of phenological, morphological and physiological characteristics, the
21 combination of which influences the agroecological functioning of AFS through facilitation or
22 competition effects (Beer, 1987). It affects the provision of both agricultural products and
23 environmental services (Andreotti *et al.*, 2018) and this evolves over the years according to the
24 development pattern and management of the different cultivated species (Jagoret *et al.*, 2018a;
25 Nijmeijer *et al.*, 2019). Some authors have observed a trade-off between yields and biodiversity
26 within cropping systems (Rapidel *et al.*, 2015), while others have observed a synergy between them

27 (Salazar-Díaz and Tixier, 2019). We made the hypothesis that thoughtful decisions on the crop
28 species to be combined and their spatial arrangement in the plot and management over time should
29 make it possible to maintain a high level of biodiversity while ensuring high yields and therefore
30 better living conditions for farming families.

31 Agricultural innovations may originate from farmers themselves (Catalogna *et al.*, 2018), from public
32 or private extension services, from technical institutes or from research (Reau and Doré, 2008). In
33 some cases, the adoption of these innovations may be difficult. The “top-down” approach still often
34 used by technical consulting organizations has shown weaknesses (Faure *et al.*, 2009). Technical
35 recommendations are either not applied, because they are too expensive or time-consuming to set
36 up (Valdivia *et al.*, 2012), or take time to be accepted by farmers. A different approach involving
37 farmers themselves emerged in the 1990s, as demonstrated by Salembier *et al.* (2018) in their work
38 on the genealogy of design reasoning in agronomy. Participatory design methods deal with the
39 sometimes contradictory objectives of different stakeholders, for example in response to ecological
40 issues in contexts of environmental degradation or conflicting natural resources management
41 (Abrami *et al.*, 2012; Meylan *et al.*, 2013; Speelman *et al.*, 2014; Ravier *et al.*, 2015). Within the
42 framework of the design of cropping and farming systems, the prototyping proposed by Vereijken
43 (1997) initiated the co-design movements of the past 20 years. Nowadays, the design process can
44 aim either at constructing novel cropping or farming systems (*de novo* design) or improving existing
45 systems (*step-by-step* design) by involving farmers in the co-design process (Meynard *et al.*, 2012;
46 Navarrete *et al.*, 2018). Prototypes are assessed experimentally, allowing improvements to be made
47 in a new design cycle if required (Rapidel *et al.*, 2009; Le Bellec *et al.*, 2011; Husson *et al.*, 2015). To
48 facilitate communication among stakeholders, several types of artifacts have been employed:
49 conceptual models (Lamanda *et al.*, 2012; Meylan *et al.*, 2013), pebble distribution methods (Sheil *et*
50 *al.*, 2004), serious games (Martin *et al.*, 2011), mapping games (d'Aquino *et al.*, 2003; Speelman *et*
51 *al.*, 2014), and companion modeling (Borodina *et al.*, 2018). To estimate the expected level of success
52 of prototypes, *ex ante* evaluation methods have been developed, based, for example, either on

53 simulation models such as APSIM (Keating *et al.*, 2003) and BANAD (Blazy *et al.*, 2010) or multiple
54 criteria assessment tools such as MASC (Sadok *et al.*, 2009; Ravier *et al.*, 2015) and DEXIPM (Pelzer *et*
55 *al.*, 2012). Their use in participatory workshops facilitates the selection of the most effective
56 innovations before testing them in on-farm trials.

57 Given the strength of the multi-stakeholder community in developing technical innovations, we have
58 developed a participatory process for designing cocoa AFS prototypes that significantly improve the
59 performance of these systems and thereby farmers' living conditions. Our hypothesis was that the
60 diversity of farmers' and technicians' points of view and skills can be used to design agroforestry
61 systems which are distinctly innovative compared to the current systems described in Notaro *et al.*
62 (2020). We used a participatory approach based on the principles of agroecology: exploring
63 innovations that maximize ecological processes while improving productivity and therefore economic
64 performance (Meynard *et al.*, 2012). The originality of our work lies in (i) the combination in the co-
65 design methodology of different tools extracted from the scientific literature, and (ii) the dynamic
66 nature of the systems designed, from planting to the full development of the species to be combined
67 and spatially distributed. It led to the design of four AFS prototypes, the economic performance of
68 which was assessed *ex ante*.

69 **2. Material and Methods**

70 **2.1. Location**

71 Two zones offering contrasted cocoa-based AFS were selected for the participatory design
72 workshops : the province of Duarte in the north of the Dominican Republic, which is the main and
73 historic cocoa production area with 55,606 ha representing 36.5% of the national cocoa-growing
74 area, and the province of San Cristobal in the south, which is a more extensive cocoa-growing zone
75 with 2,548 ha representing 1.7% of the national cocoa-growing area (Deheuvels, 2015) (Figure 1). In
76 the province of Duarte, the average density and the diversity of associated species are lower than in
77 the San Cristobal area (Notaro *et al.*, 2020). The Duarte zone is more focused on the cultivation of

78 cocoa, with a higher planting density of cocoa trees, the majority of which are produced in nurseries.

79 Physico-chemical properties of the soils in the two areas do not differ significantly (data not shown).

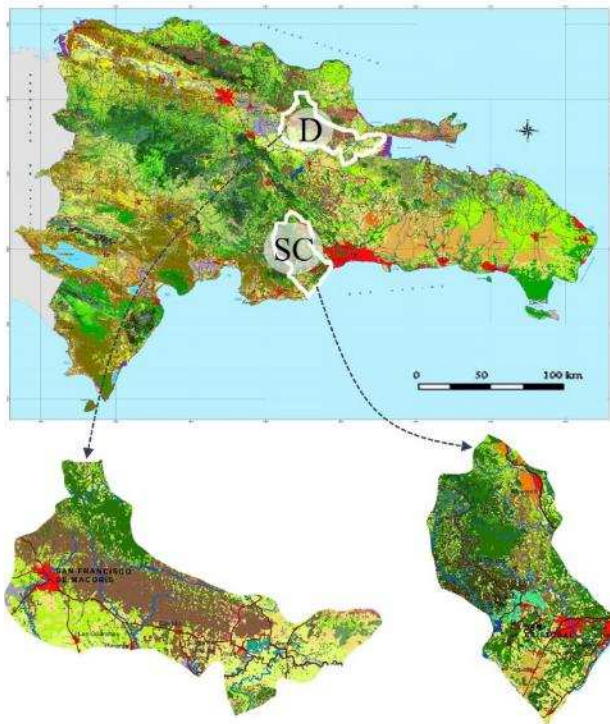


Figure 1. Map of the Dominican Republic showing the location of the two selected provinces, Duarte (D) and San Cristobal (SC) and where cocoa AFS are located (in brown). This map has been adapted from a land use cover map from the Ministry of Environment (Ministerio de Medio Ambiente y Recursos Naturales, 2014).

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91 2.2. Choice of participants

92 Participants with knowledge and skills from different agricultural, scientific and technical
93 backgrounds were invited to enrich the discussions and debates and ensure better acceptance of the
94 innovations by cocoa farmers since they would be directly involved in the design process (Voinov and
95 Bousquet, 2010).

96 In each of the two zones, two different co-design groups were formed: the first was composed of
97 Dominican cocoa farmers and the second of technicians and academics of the cocoa sector. This
98 separation made the farmers feel more comfortable exchanging their views among peers. Mixing all
99 participants from the beginning of the process would certainly have limited the voice of the

100 participants with empirical knowledge, compared to those with academic knowledge (Faure *et al.*,
101 2009). The participatory process did not apparently favor any of the professions represented in these
102 workshops, nor guide the decisions made by the participants.

103 Then a total of four co-design working groups were formed, each containing between 12 and 15
104 participants: farmers from the Province of San Cristobal (FSC), technicians from the Province of San
105 Cristobal (TSC), farmers from the Province of Duarte (FD) and Technicians from the Province of
106 Duarte (TD). Nine women took part in the workshops, with four farmers, four technicians and one
107 researcher, representing 17% of the total sample. To enrich the discussions during the workshops,
108 cocoa-based AFS farmers with different spatial organization and management practices were invited
109 to participate. They were selected from the different groups of a typology of Dominican AFS (Notaro
110 *et al.*, 2020) built on a gradient of density and diversity of associated species.

111 Since more than 55% of Dominican AFS are organic certified, and this proportion is steadily
112 increasing, all the farmers invited to take part in the design process produced certified organic cocoa.
113 The invited technicians all came from cooperatives that were partly financed by the organic certifiers
114 of the farmers' plots, and supplied cocoa to companies concerned with the sustainability of the
115 sector.

116 **2.3. The different stages of the participatory design process**

117 Each group went through eight meetings, which lasted 3 to 4 hours each. One prototype was
118 elaborated per group, giving a total of four prototypes. All the meetings proceeded in three key
119 stages (**Table 1**):


120 Step 1- The first three meetings laid the groundwork for co-design as participants explained the
121 desired biophysical states of AFS, such as soil characteristics, shading, spatial congestion.

122 Step 2 - The next three meetings focused on the selection of species and varieties to be used in the
123 prototypes, of their spatial arrangement and of the practices to be adopted for their management.

124 Step 3 - The last meeting consisted of simulating the economic performance of the prototypes in
125 order to assess if they matched the initial objective of the project in terms of income.

126

127 Table 1. Synthesis of the different design stages, the topics and the materials used during the workshops. For each issue, the reference to the corresponding section in
 128 Material and Methods (M&M) and the date the workshop was held in each group are given. FSC = farmers' group from San Cristobal province, TSC = technicians' group from

Step	Topic	Means	M&M	Results	Workshop date per group			
					FSC	TSC	FD	TD
(1) Definition of the design framework	Explanation of the issues and objectives	-	2.4	-	23 Aug 2017	21 Aug 2017	18 Oct 2017	17 Oct 2017
	Description of the desired states and associated functions/criteria	Drawings and field trips	2.5	3.1 & 3.2	30 Aug 2017	28 Aug 2017	25 Oct 2017	24 Oct 2017
	Prioritization of these functions/criteria	Sheil method	2.6	3.3 & 3.4	6 Sep 2017	4 Sept 2017	1 Nov 2017	31 Oct 2017
(2) Technical formalization	Selection of species (and varieties)	Sheil method and consensus	2.6	3.3 & 3.4	13 Sep 2017	11 Sep 2017	8 Nov 2017	7 Nov 2017
	Spatial arrangement of species and choice of planting densities	 Prototype schematization game	2.7	3.5	20 Sep 2017	18 Sep 2017	22 Nov 2017	21 Nov 2017
	Selection of management techniques for the species and more generally for the cropping system	Excel table	2.8	3.5	27 Sep 2017	25 Sep 2017	29 Nov 2017	27 Nov 2017
(3) <i>Ex ante</i> assessment	Economic projections to see if targets can be met	Excel table	2.8	3.6	4 Oct 2017	2 Oct 2017	6 Dec 2017	5 Dec 2017

129 San Cristobal province, FD = farmers' group from Duarte province, TD = technicians' group from Duarte province.

130 **2.4. Objectives of the co-design process**

131 The main objective of the co-design process was a significant increase in earnings from AFS. To avoid
132 poverty among Dominican cocoa farmers and their dependents, earnings of US\$ 1,115 yr⁻¹ are
133 required for each dependent cocoa farmer, this being the poverty line in the Dominican Republic
134 (ONE, 2016). According to the analyses of Notaro *et al.* (2020), for at least 75% of farmers to obtain
135 these earnings for each member of their family, sales of AFS products would have to reach US\$ 5,943
136 ha⁻¹ (cf. calculation method in Appendix 1). This corresponds to more than twice farmers' current
137 average earnings (Notaro *et al.*, 2020).

138 In addition, prior to the workshops, we made a commitment with participants that the improvement
139 in economic performance would not be at the expense of the ecological sustainability of the co-
140 designed AFS prototypes. However, in the *ex ante* assessment of the prototypes, we evaluated only
141 their agro-economic performance, and the provision of environmental services was considered to be
142 sufficient, as already documented in the literature for organic farming and multi-species cropping
143 systems (Cerdeira *et al.*, 2017). Therefore, the criterion for maintaining existing plant diversity in
144 Dominican AFS was set at a minimum of three species combined with cocoa trees in the co-designed
145 prototypes, which corresponds to the average observed in existing Dominican AFS by Notaro *et al.*
146 (2020).

147 **2.5. Agroecological levers at the core of the co-design method**

148 Increasing the income from AFS while maintaining at least the same level of plant biodiversity is
149 equivalent to strengthening the agro-ecological character of cocoa farming in agroforestry (Altieri *et al.*
150 *et al.*, 2015). The co-design process aimed to identify the optimal combination of crop species to obtain
151 satisfactory overall yields in the long term. The main technical levers discussed were: (i) the species
152 and varieties to be planted in the AFS, (ii) the planting densities and (iii) spatial arrangement of each.
153 The criteria for selecting the species were provided by the participants or presented by experts when
154 knowledge input was required. This was the case, for example, for the tolerance of cocoa varieties to

155 diseases that are still absent from the island such as *Moniliophthora roreri* and *Crinipellis pernicioso*,
156 but which could one day be there.

157 The emergence of these selection criteria was facilitated through a drawing workshop followed by a
158 field trip (Figure 2 A and B). Initially, the drawings allowed the participants to express themselves on
159 the components of the current AFS as they perceive them according to three levels of importance
160 based on a color code: "green" for essential components, "blue" for less important components, and
161 "black" for neutral or even problematic components. The following field trip made it possible to
162 better explain these criteria, most of which can be described as the functions of certain AFS
163 components needed to achieve the set objectives.



Figure 2. Drawing session and field trip to explain what is expected from the different resources and entities in the landscape agroforestry systems (A and B). Use of Sheil's method to prioritize the criteria to be used to select cocoa varieties and associated species (C). Workshop for the schematization of cocoa AFS prototypes in order to determine the selected plant species and their spatial arrangement. Photos A, C and D taken in the offices of FUNDOPO, partner farmers' association, and photo B in a farmer's plot in Loma Verde (San Cristobal province), in September and October 2017 (© M. Notaro).

178 **2.6. Selection of cocoa varieties and associated species**

179 The pebble distribution method (Sheil *et al.*, 2004), herein called Sheil's method, was used to
180 facilitate technical choices in the selection of cocoa varieties and other species to be introduced in
181 the prototypes (Figure 2C). This method is very simple and allows certain "concepts" or "objects" to
182 be ranked in order of importance. It consists of distributing the same number of pebbles to each
183 participant. Each participant then places them on representations of the concepts, or objects,
184 according to their relative importance for him. For example, an object that is of no importance to a
185 participant will receive no pebble, whereas an important object may receive several pebbles. The
186 order of importance of the concepts or objects is based on the number of pebbles assigned to each
187 of them.

188 In our case, Sheil's method was used three times and 10 pebbles were given to each participant to
189 classify:

190 (1) the selection criteria for cocoa varieties, where discussions were mainly based on agronomic
191 performance criteria, whose analyses for each variety were carried out in local or international
192 technical or research institutes (Turnbull and Hadley, 2017). These agronomic data came from
193 published scientific results.

194 (2) the selection criteria for associated species, where we only used criteria "evaluated" by the
195 participants, such as those listed in Table 2 in the "Results" section. In addition, the list of plant
196 species that could be associated with cocoa trees was proposed by the participants. In order to rank
197 these species associated with cocoa trees, it was necessary to proceed in two combined steps
198 according to the following formula:

199 (Eq. 1) $Scoring\ species\ E = \sum_{i=1}^n (P_i * P_{i*E})$

200 where

201 i = criterion considered

202 P_i = Importance of criterion i (the number of pebbles it received during the 2nd use of Sheil's method)

203 P_{i*E} = Importance assigned to species E in achieving the criterion i (number of pebbles received in the
204 3rd use of Sheil's method)

205 (3) the plant species of potential interest to meet the objectives.

206 The selection of cocoa varieties and associated plant species was carried out in two separate
207 workshops because the criteria for selecting cocoa varieties were scientifically studied in
208 experimental stations (quantitative data), while the criteria for selecting associated species were
209 evaluated by the farmers themselves (empirical data). The cocoa varieties and associated plant
210 species that came out first in the classification were then selected to be included in the prototypes.
211 The selected cocoa varieties were chosen to meet at least the first three selection criteria. The
212 number of cocoa varieties was decided once all participants were satisfied with the selected
213 varieties. Concerning the associated species, the minimum number of selected species was set at
214 three, as explained above. The final number of species per prototype was established when the
215 participants no longer wished to increase the diversity of associated plants.

216 **2.7. Choice of planting densities and spatial arrangement of species**

217 In each group, the spatial arrangement of the most popular cocoa varieties and associated species in
218 relation to the selected criteria was addressed in a mapping game. It consisted in a rectangular board
219 (80 x 100 cm) and many circular tokens (diameter 5 cm), each token being in one of 10 different
220 colors (Figure 2D). The rectangular board represented the area dedicated to AFS and the circular
221 tokens represented the plants, each color being associated with a single species.

222 To introduce the game and to ensure the participants understood the purpose of the workshop, we
223 started with a schematic representation of existing AFS (Notaro *et al.*, 2020) characterized by the
224 disorganized arrangement of cocoa trees and associated plants. Once this representation was
225 validated by the participants, the discussion turned to the advantages and disadvantages of the

226 spatial arrangement of species in existing AFS, which it was important to clarify in order to move on
227 to the next stage of design.

228 Then, each participant was asked to schematize the spatial arrangement of the different species and
229 the minimum or maximum distances to be respected between two plants of the same species or two
230 plants belonging to different species, by explaining his or her choices. After each participant went
231 through this brainstorming exercise, the broad outlines shared by the majority of the participants
232 were drawn and the basis of the spatial arrangement for the prototype was established. Once the
233 rules of inter- and intra-species spatial arrangement had been agreed upon, the final choice of cocoa
234 varieties and companion species was made. The mapping game made it possible to decide on the
235 specific composition and densities to be used in the prototype.

236 **2.8. Economic projections for the co-designed prototypes**

237 Economic projections for the prototypes are essential to assess their level of success in relation to
238 the original objective, i.e. to generate total earnings (TE, gross product minus expenses), at least
239 equal to US\$ 5,943 ha⁻¹.yr⁻¹ (see calculation method in Appendix 1). We simulated the economic
240 performance of each prototype over a period of 20 years, which we considered sufficient for the
241 optimal expression of the agro-economic performance of the species present in the prototypes. **To**
242 **do so, it was necessary to estimate (i) the total revenue of the prototypes and (ii) the costs**
243 **associated with their management. The total revenue (R_{total}) includes the revenues from the sale of**
244 **cocoa (R_{cocoa}) and from the sale and self-consumption of other products (R_{other}).**

245 To estimate the **revenue** generated from the sale of cocoa (R_{cocoa}), we used:

- 246 (i) the yields of each cocoa variety included in the prototypes, obtained from experimental
247 stations in the Dominican Republic for local varieties and other countries for international
248 varieties (Turnbull and Hadley, 2017),
- 249 (ii) the farm gate sales prices for the past 10 years provided by the Ministry of Agriculture
250 (Ministerio de Agricultura, 2017).

251 To assess the **revenue from** sales and self-consumption of other products (R_{other}), we used:

- 252 (i) the yields of each species (sp.) in the prototypes, **estimated** by the participants themselves,
253 (ii) the farm gate sales prices for each associated species (sp.) provided by the Ministry of
254 Agriculture (Ministerio de Agricultura, 2017).

255 The three indicators described above were calculated as follows:

256 (Eq. 2) $R_{cocoa} = Cocoa\ yield * Cocoa\ price$

257 (Eq. 3) $R_{other} = \sum_{i=1}^n (yield_{sp.i} * price_{sp.i})$

258 (Eq. 4) $R_{total} = R_{cocoa} + R_{other}$

259 R_{cocoa} and R_{other} were calculated according to three yields: minimum, medium and maximum, thereby
260 providing a range of potential R_{total} . In order to mimic the law of supply and demand (though the
261 cocoa market is much more complex), we applied the following rules for calculating R_{cocoa} and R_{other} :
262 minimum yields were multiplied by the maximum price, maximum yields by the minimum price, and
263 average yields by average price.

264 For cocoa productivity per prototype, the minimum, medium and maximum yields corresponded to
265 25%, 50% and 75% of the average yields provided by the International Cocoa Germplasm Database
266 (ICGD) website (Turnbull and Hadley, 2017). These threshold choices were accepted by the
267 participants, all of them being aware of the discrepancy between yields on experimental stations and
268 in their own plots. For the productivity of combined species, minimum, medium and maximum yields
269 were based on a consensus reached by the participants in each group. Lastly, minimum, medium and
270 maximum prices for cocoa and other products were taken from the data for the past 10 years
271 provided by the Ministry of Agriculture (Ministerio de Agricultura, 2017).

272 The evaluation of the costs of labor, tools and plant material were estimated jointly by all the
273 participants who took part in the co-design process. This step required the participants to establish a
274 consensual management plan, that included the different practices to be used (soil preparation,
275 setting up the planting system, planting, pruning, weeding, harvesting, etc.) and the associated
276 workloads and costs. The estimated time requirements and cost of inputs (labor and tools) to carry

277 out the different management practices in the prototypes (including their cultivated biodiversity) is
278 not described in detail, as we focus here on the “structural” design of the prototypes.

279 **3. Results**

280 **3.1. Specification of the desired agroecological functions in the AFS**

281 Before being ready to make technical choices for the prototypes during the co-design process, a first
282 phase of characterization of the current and envisaged future agroforestry systems was necessary.

283 This step led the participants to define desired biophysical states such as plant structure, soil
284 properties, shade level, climate under the canopy, etc. Then these states could be translated into
285 agroecological functions, i.e. their role in improving the ecological functioning of the agroforestry
286 system. Finally, these functions were transcribed into species selection criteria that could be
287 multidimensional (mainly agronomic, biophysical, physiological, commercial, economic), ultimately
288 enabling the selection of cocoa tree varieties and associated plant species.

289 The AFS components examined in both regions by the two groups were identical (Table 2). The
290 desired states and associated functions were described with a very similar lexicon and with
291 converging views. Both farmers and technicians focused on the interest of associated plants for both
292 the provision of ecosystem services (maintenance of soil fertility, pollination, regulation of disease or
293 pest pressure) and the support of cocoa development, and for producing marketable products or
294 products for self-consumption (Table 2).

295 Table 2. Summary of the desired states, associated agroecological functions and corresponding selection criteria of the different components of AFS in different strata for the
 296 Duarte area. The opinion of the technical group is in normal font, the opinion of the farmer group is in italics and opinions shared by the two groups are in bold. As the
 297 desired states and associated functions for the San Cristobal area groups were very similar, they are not presented here.

Stratum	Component	Desired states	Agroecological functions	Selection criteria
Upper	Shade trees	Vertical habit (orthotropic growth) with a trunk twice the height of cocoa trees, and maximum 50% light reduction	Promote aeration of the plot while forming a windbreak , and allow the transmission of sufficient light for the development of cocoa trees	Favorable to the development of cocoa trees Productivity Market access High selling price Hurricane resistant
		<i>Regular shade over the cocoa trees in the intermediate stratum</i>	<i>Keep cocoa trees cool</i>	
	Able to fix nitrogen in soil (Legumes) and lose annual leaves (Caducifoliate) preferably in winter	Fertilize the soil to improve plant development and promote the appearance of flowers on flower pads		
	Tree roots deeper than the roots of cocoa trees	Reduce competition with cocoa trees for soil nutrients (including water)		
	Productive (Food production)	Harvest a significant amount of marketable and profitable products		
	<i>Hurricane resistant</i>	<i>To protect the integrity of cocoa trees</i>		
Intermediate	Cocoa trees	Wide trunk, producing 3 to 5 main branches in the shape of a cup, total height: 4 m	Facilitate the flowering and production of pods as well as their harvesting	Productivity
		Adequate distance between cocoa trees (min 3 x 3 m)	The space between the cacao trees should not be congested to avoid competition between cacao trees (roots and branches) or limit the transmission of light to the ground	

Stratum	Component	Desired states	Agroecological functions	Selection criteria
Intermediate	Cocoa trees	Good organoleptic quality of cocoa beans (white colour desired, Criollo or Trinitario varieties)	Obtain niche markets with better selling prices	High selling price
	Pests and diseases of cocoa trees	Few to no longer present	Maintain the highest possible yield	Tolerance to brown rot, moniliasis and witches' broom
Lower	Staple Crops	Strong under the cocoa trees Low and productive (food)	Prevent weeds growing Avoid competition with cocoa trees for soil resources + provision of products for sale or self-consumption	
	Weeds	<i>Act as a barrier perpendicular to the slope</i> In steeply sloping plots, let some weed species cover the soil (i.e. <i>Mimosa pudica</i> , <i>Arachis pintoi</i> , <i>Commelina nudiflora</i>)	<i>Limit erosion</i> Limit erosion and maintain good soil moisture	Productivity (cocoa and other products)
	Soil	The first 5 cm are rich in decomposing organic matter (<i>black soil</i>) and living soil that is home to many worms. A soil balanced between sand, silt and clay that crumbles easily	Maintain or improve soil fertility levels to ensure good yields	Favorable to the development of cocoa trees
All strata	Pollinators	Present in the plots (hosted by <i>Musaceae</i> and <i>Ananas comosus</i> or attract them by letting some fruits rot, such as citrus fruits)	Pollinate flowers and increase yields	

300 Yet there were some specificities. The two groups of technicians certainly had a more solid
301 knowledge of crop physiology, which is why some of the expected functions were described in more
302 detail (e.g. "to promote sufficient light radiation for the floral cushions of cocoa trees by giving them
303 a cupped shape through pruning and by associating trees that lose their leaves during the cocoa
304 flowering period"). In these two groups, the organoleptic quality of the cocoa beans appeared to be
305 important to ensure good sales contracts between cooperatives and buyers, and to envisage more
306 profitable niche markets. In contrast to technicians, the two producer groups draw attention to the
307 need for regular shade to prevent cocoa trees from suffering from excessive heat. In addition, to limit
308 erosion, they insisted on the need to maintain rows of weeds perpendicular to the slope.

309 **3.2. Identification of criteria for the selection of cocoa varieties and associated plant species**

310 These desired functions were then jointly reformulated into selection criteria (Table 2) that were
311 subsequently used to select cocoa varieties and associated plant species. Some criteria were not
312 used for the selection of cocoa varieties, such as the organoleptic quality of cocoa, as there was no
313 indicator to assess it individually for each variety. We chose to include tolerance of the varieties to
314 fungal diseases moniliasis (*Moniliophthora roreri*) and witches' broom (*Crinipellis perniciososa*), that are
315 still absent from the island of Hispaniola but are geographically close and therefore likely to reach
316 the island in the near future. Tolerance to other diseases already present on the island such as brown
317 rot caused by *Phytophthora palmivora* was also taken into account. A summary table of the agronomic
318 characteristics of the 110 varieties available in the Dominican Republic is presented in Appendix 2. In
319 addition, four other criteria were added following discussions between participants after the field
320 trips: the self-compatibility of pollen for the selection of cocoa tree varieties, the ease of technical
321 management, speed of production and period of production (different from that of cocoa trees) for
322 the selection of associated plants.

323

324

325 **3.3. Choice of cocoa varieties**

326 The criteria for selecting cocoa varieties differed among the groups and provinces (Table 3) and were
327 distinguished as follows:

328 - the two groups in San Cristobal focused on productivity, whereas the two groups in Duarte gave
329 equal importance to productivity and autocompatibility;

330 *Table 3. Results of the Sheil's method (number of points out of a total of 50 points per group) applied to the*
331 *selection criteria of cocoa varieties by the two groups in the two zones (FSC = farmers' group from San Cristobal*
332 *province, TSC = technicians' group from San Cristobal province, FD = farmers' group from Duarte province, TD =*
333 *technicians' group from Duarte province).*

Criteria	FSC	TSC	FD	TD
Productivity	23	23	15	17
Autocompatibility of pollen	7	6	17	14
Tolerance to brown rot	16	7	18	6
Tolerance to moniliasis	2	13	0	11
Tolerance to witches' broom	2	1	0	2

334
335 - both groups of farmers were most concerned by brown rot, whereas both groups of technicians
336 were more concerned by the arrival of moniliasis on the island and the yield losses it would cause, so
337 that they put the criterion for selecting moniliasis-tolerant cocoa varieties ahead of brown rot.

338 Based on these results, the clones were selected collectively, with majority approval in each group.
339 The FSC and TSC groups (San Cristobal) selected four clones, ICS-39, UF-221, ML-4, ML-103 and ICS-
340 95, UF-676, GS-36 and ML-22, respectively. Whereas the FD and TD groups (Duarte) selected 10 and
341 7 clones, ICS-1, ICS-39, RZ-12,RZ-44,RZ-83, RZ-100, IML-44, IML-53, ML-66, ML-103 and ICS-39, UF-
342 296, ICS-95, IML-119, IML-53, ML-22 and ML-105, respectively. Each clone should be grafted onto
343 rootstocks with satisfactory vigor and root development properties to ensure successful plantation.

344 **3.4. Choice of associated plant species**

345 The first criterion for the choice of species associated with cocoa trees for both groups of technicians
346 was that they are favorable to the development and production of cocoa trees, particularly for TD.

347 The productivity of these species and the existence of a market for their products were of secondary
 348 importance (Table 4). The differences were greater between the two groups of farmers. In Duarte,
 349 being beneficial to cocoa trees also was an important selection criterion, just behind productivity and
 350 just ahead of market access. In San Cristobal, market access was the most important criterion ahead
 351 of the technical manageability of the associated species. The criteria of hurricane resistance, speed of
 352 production once planted, and the production period being staggered in relation to that of cocoa
 353 trees were of little importance to all four co-design groups.

354 *Table 4. Results of Sheil's method (number of points out of a total of 50 per group) applied to the importance*
 355 *weight Pi given to each selection criterion of the species associated with cocoa trees in the two groups of the*
 356 *two zones (FSC = farmers' group from San Cristobal province, TSC = technicians' group from San Cristobal*
 357 *province, FD = farmers' group from Duarte province, TD = technicians' group from Duarte province).*

Criteria	FSC	TSC	FD	TD
Favorable to the development of cocoa trees	4	12	11	22
Productivity	4	9	12	8
Selling price	7	6	5	2
Market access	13	9	10	8
Production period	3	7	3	0
Ease of technical management	10	5	4	4
Speed of production	6	1	3	4
Hurricane resistant	3	1	2	2

358
 359 Musaceae received the highest score from all four groups (Appendix 3). Musaceae, avocados and
 360 citrus were found in all prototypes because they play an essential role in Dominican dietary habits.
 361 Their fruits can be used as food for the farmer's family or sold to intermediaries connected to local
 362 markets. The other top ranking species were regularly associated with cocoa trees as service plants
 363 (gliricide, erythrin, annatto) or as providers of staple foods (taro, yam, pigeon pea) or fruits
 364 (sapodilla, soursop, coconut palm). In contrast, catalpa and lime trees were rarely associated with
 365 cocoa trees.

366 **3.5. Design of the structure of AFS at planting and full grown**

367 Discussions concerning the structure of the AFS prototypes were a key to discussing the combination
 368 of cocoa trees and associated species and their spatial arrangement. **Each associated species**

369 obtained an E score (Eq. 1), depending on the different criteria presented above, none of which takes
370 into account the possibility of being associated in the plot with plants other than cocoa trees. This
371 explains the fact that sometimes it was not the species with the highest E-score that have been
372 chosen. Indeed, the discussions between participants enabled the exclusion of certain species which,
373 associated with other species with a high E score, would have been detrimental to the good
374 development of the prototypes. In addition, all four groups emphasized the need for short cycle
375 crops as soon as the prototypes were established to ensure revenue, but also to promote further
376 development of the cocoa trees and prevent weeds growing.

377 All four groups wanted to change the arrangement of cocoa trees from the current disorganized
378 arrangements observed in the AFS to a more regular arrangement in rows (see Figures 3 and 4 for
379 the prototypes of San Cristobal and Duarte zones, respectively). The reasons given were (i) to provide
380 exactly the same amount of space for each cocoa tree for its development and to limit competition
381 for resources and (ii) to facilitate the technical management of cocoa trees as well as their harvesting
382 through the creation of inter-row alleys. Depending on the group, the final results were rather
383 contrasted with regard to the density of cocoa trees: the FSC group proposed a density of 640 cocoa
384 trees per hectare while the FD group proposed 1,120 per hectare, which were the minimum and
385 maximum of the four prototypes; the two groups of technicians proposed intermediate densities:
386 864 and 832 cocoa trees ha⁻¹ for TSC and TD, respectively.

387 Concerning the associated plant species, the differences were not as marked as for cocoa tree
388 density. The FD group proposed 192 trees ha⁻¹ and the TD group 288 trees ha⁻¹, the other two groups
389 in the San Cristobal region proposed intermediate densities. None of the groups wished to mix cocoa
390 trees with other tree species in the same row; the latter were therefore located in the inter-row.
391 According to the participants, this ensures a certain continuity in the technical management by row,
392 and makes it possible not to reduce the space allocated for cocoa trees and thus not to reduce cocoa
393 production. In the young phase (phase A) of the prototypes, from planting to approximately 7 years
394 of age, sometimes high densities of tubers (taro, ginger, turmeric), musaceae (dessert banana or

395 plantain) or service trees (Gliricide and Annatto) were proposed (Table 5). In their mature phase
396 (phase B), the prototypes exhibited a **species** richness of plants associated with cocoa trees of four
397 (FD group), six (FSC group) and seven species (TSC and TD groups). Avocado (*Persea americana*) and
398 citrus were introduced in all four prototypes. The farmers' prototypes (FSC and FD) were dominated
399 by fruit trees (Table 5), the FSC prototype being distinguished by the presence of soursop and
400 sapodilla (*Annona muricata* and *Pouteria sapote*) and the FD prototype by the presence of coconut
401 trees (*Cocos nucifera*). In contrast, the two groups of technicians promoted forest trees: the TSC
402 prototype was distinguished by the presence of three forest species (*Catalpa longissima*, *Gmelina*
403 *arborea* and *Swietenia mahagoni*) whereas the TD prototype was distinguished by a significant
404 association of Gliricides (*Gliricidia sepium*), arranged in parallel rows to the cocoa trees and serving
405 as stakes for pepper plants (*Piper nigrum*).

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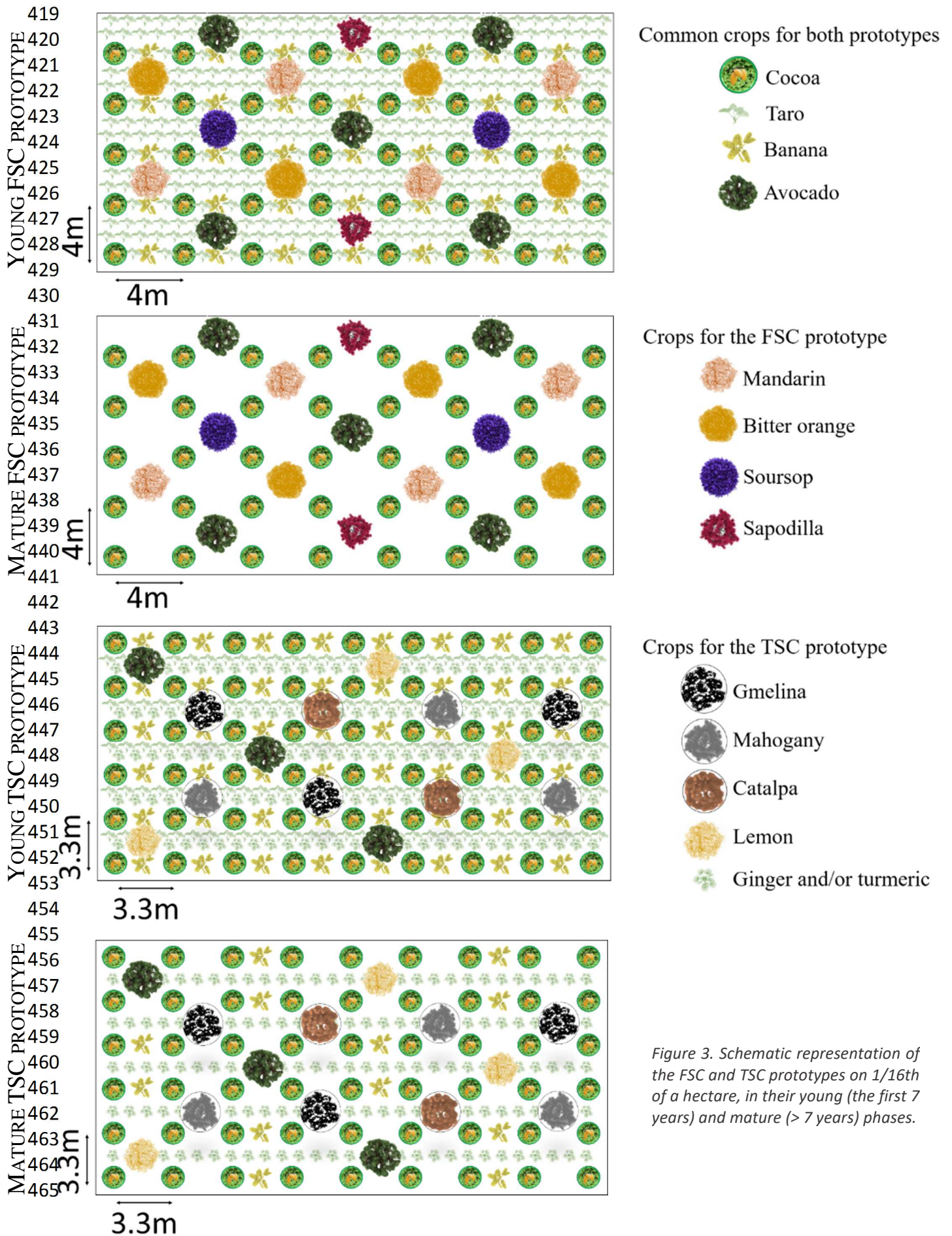
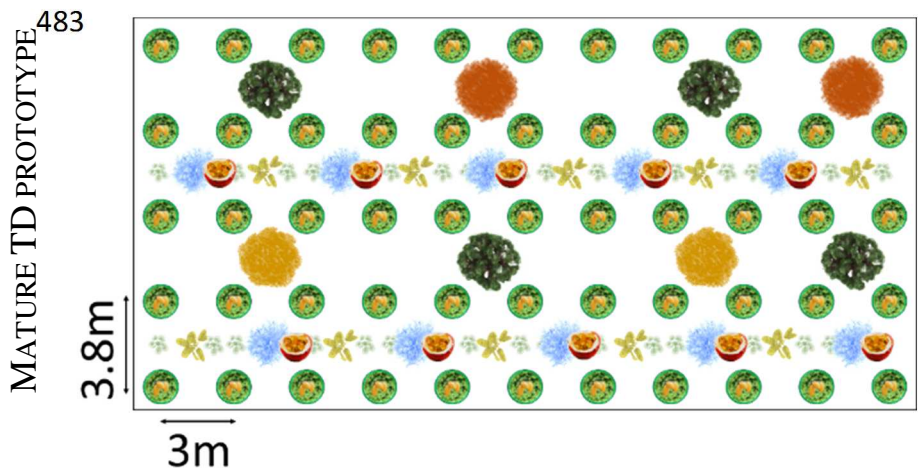
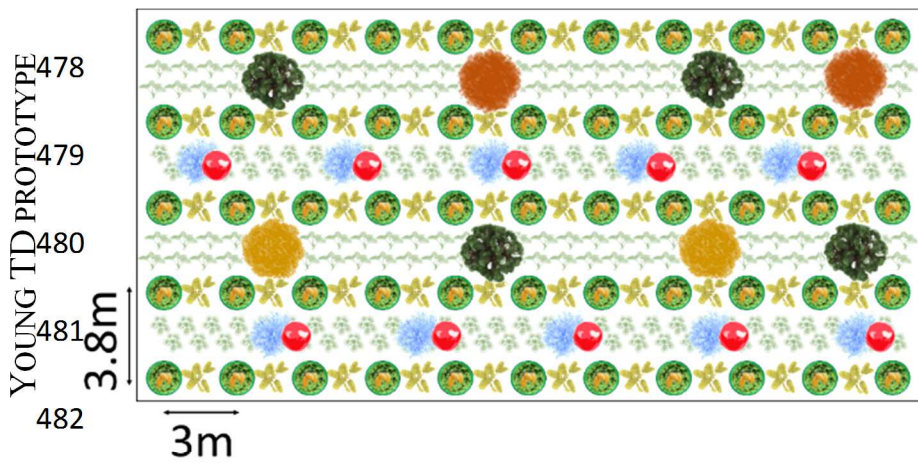
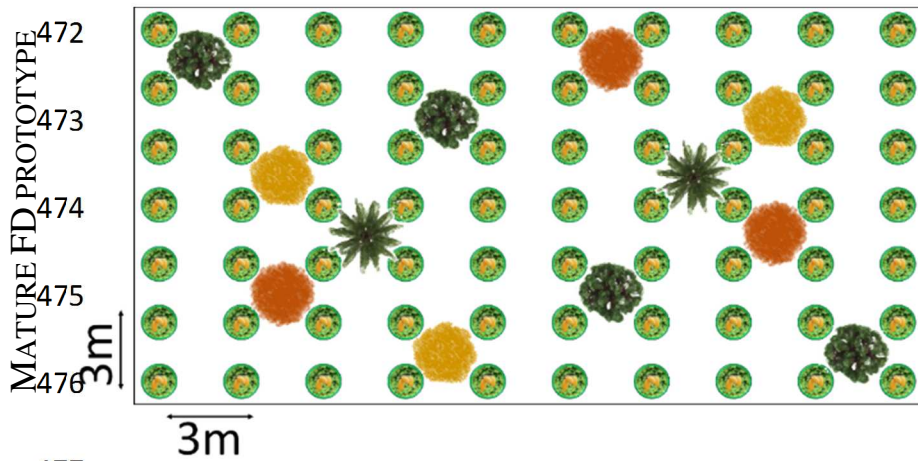
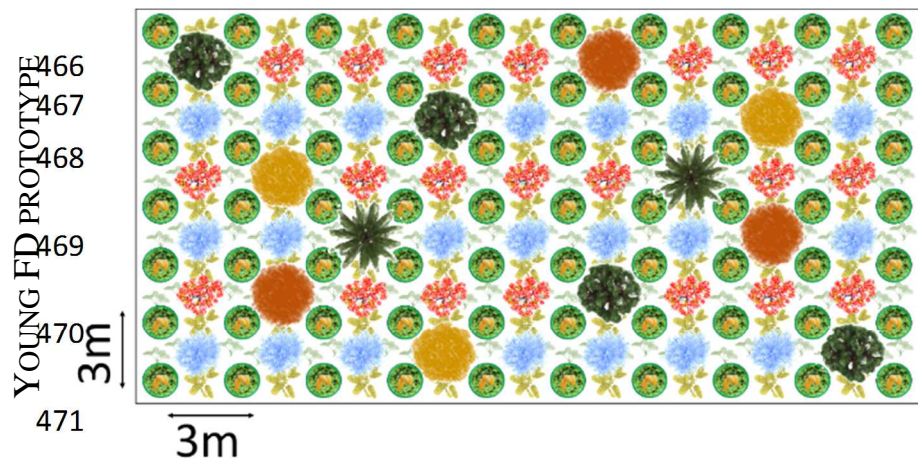


Figure 3. Schematic representation of the FSC and TSC prototypes on 1/16th of a hectare, in their young (the first 7 years) and mature (> 7 years) phases.



Common crops for both prototypes

-  Cocoa
-  Taro
-  Banana
-  Avocado
-  Sweet orange
-  Bitter orange
-  Gliricide

Crops for the FD prototype

-  Coconut
-  Roucou

Crops for the TD prototype




-  Pepper
-  Passion fruit
-  Ginger and/or turmeric

Figure 4. Schematic representation of the FD and TD prototypes on 1/16th of a hectare, in their young (the first 7 years) and mature (> 7 years) phases.

484 Table 5. Summary of the selected plant species and varieties, with their initial (0 to 7 years) and final (at least 7 years) planting density, yields and sales prices
 485 (min/medium/max) used in the ex ante economic evaluation of prototypes (see Figures 5 and 6).

Common name	Scientific name	Proto-type	Initial density (ha ⁻¹)	Final density (ha ⁻¹)	Varieties	Yield [min/medium/max]	Yield unit	Sales price [min/medium/max]	Sales price unit
Cocoa	<i>Theobroma cacao</i>	FSC	640	640	Clones ICS-39, UF-221, ML-4, ML-103 in equal quantities	1.6/3.2/4.8	kg tree ⁻¹	0.5/0.66/0.8	US\$.kg ⁻¹
		TSC	864	864	Clones ICS-95, UF-676, GS-36, ML-22 in equal quantities	1.35/2.7/4.05			
		FD	1120	1120	Clones ICS-1, ICS-39, RZ-12, RZ-44, RZ-83, RZ-100, IML-44, IML-53, ML-66, ML-103 in equal quantities	1.85/3.7/5.55			
		TD	832	832	Clones ICS-39, UF-296, ICS-95, IML-119, IML-53, ML-22, ML-105 in equal quantities	1.85/3.7/5.55			
Avocado	<i>Persea americana</i>	FSC	80	80	Local avocado, grafted with "Benny" and "Pola" variety grafts once a height of 3 m reached in plot	100/200/300	fruit tree ⁻¹	0.09/0.18/0.28	US\$.fruit ⁻¹
		TSC	48	48	Local avocado, grafted with "Benny" and "Pola" variety grafts once a height of 3 m reached in plot	100/200/300			
		FD	64	64	Local	200/400/600			
		TD	64	64	"Has" and "Popenol"	50/300/500			
Banana	<i>Musa spp.</i>	FSC	640	From 0 to a few	"Pluma fina y media mata" and "macho por hembra"	100/160/220	fruit bunch ⁻¹	0.06/0.08/0.12	US\$.fruit ⁻¹
		TSC	864	192	"Pluma fina y media mata" and "Macho por hembra" depending on pedoclimatic conditions	30/45/75			
		FD	1120	From 0 to a few	Local	30/45/60			
		TD	832	160	"Macho por hembra"	30/35/40			

Common name	Scientific name	Proto-type	Initial density (/ha)	Final density (/ha)	Varieties	Yield [min/medium/max]	Yield unit	Sales price [min/medium/max]	Sales price Unit
Taro	<i>Colocasia esculenta</i>	FSC	Up to 6400	From 0 to a few	White or yellow Taro	0.6/1.2/2.4	pound plant ⁻¹	0.26/0.34/0.42	US\$.pound ⁻¹
		TSC	Up to 3200	A few	Taro white or yellow depending on the type of soil	0.9/1.8/3.6			
		FD	4224	From 0 to a few	White Taro	1/2/4			
		TD	Up to 3200	0	White or purple	1/2/4			
Bitter orange	<i>Citrus aurantium</i>	FSC	64	64	Local bitter orange	200/500/800	fruit	0.02/0.04/0.06	US\$.fruit ⁻¹
		FD	48	48	Local	100/250/750			
		TD	32	32	Local	100/500/1000			
Sweet orange	<i>Citrus sinensis</i>	FD	48	48	Local	100/250/750	fruit	0.036/0.052/0.092	US\$.fruit ⁻¹
		TD	32	32	Local	100/500/1000			
Gliricide	<i>Gliricidia sepium</i>	FD	336	0	Local	-	-	-	-
		TD	160	160	Local	-	-	-	-
Ginger and/or turmeric	<i>Zingiber officinale</i> and/or <i>Curcuma longa</i>	TSC	Up to 3200	Up to 1600	Creole Ginger for Quality or American Ginger for productivity	0.5/1/2	pound	0.3/0.4/0.5	US\$.pound ⁻¹
		TD	Up to 3200	0 to 1600	American Ginger and local turmeric	0.7/1.3/2.2			
Mandarin	<i>Citrus reticulata</i>	FSC	64	64	The local half and the other half grafted onto bitter orange rootstocks	320/720/1120	fruit	0.025/0.05/0.075	US\$.fruit ⁻¹
Soursop	<i>Annona muricata</i>	FSC	32	32	Local soursop grafted once a height of 2 m reached with grafts of elite Soursop of Puerto Planta	30/60/90	fruit	0.16/0.28/0.4	US\$.fruit ⁻¹
Sapodilla	<i>Pouteria sapote</i>	FSC	32	32	Productive sapodilla grafted on local sapodilla rootstock	100/250/400	fruit	0.08/0.14/0.2	US\$.fruit ⁻¹

Common name	Scientific name	Proto-type	Initial density (/ha)	Final density (/ha)	Varieties	Yield [min/medium/max]	Yield unit	Sales price [min/medium/max]	Sales price Unit
Gmelina	<i>Gmelina arborea</i>	TSC	48	48	Local	48	tree	60/90/120	US\$.tree ⁻¹
Mahogany	<i>Swietenia mahagoni</i>	TSC	48	48	African mahogany	48	tree	80/120/180	US\$.tree ⁻¹
Catalpa	<i>Catalpa longissima</i>	TSC	32	32	Local	32	tree	100/140/200	US\$.tree ⁻¹
Lemon	<i>Citrus latifolia</i>	TSC	64	64	Local	100/300/600	fruit	0.04/0.05/0.08	US\$.fruit ⁻¹
Coconut	<i>Cocos nucifera</i>	FD	32	32	Local	150/200/300	fruit	0.185/0.227/0.301	US\$.fruit ⁻¹
Roucou	<i>Bixa orellana</i>	FD	336	0	Local	2/4/6	pound	2.7/2.91/3	US\$.pound ⁻¹
Pepper	<i>Piper nigrum</i>	TD	160	0	Balankotta and/or Guayarina and/or Singapur	0.6/1/1.6	kg	6.22/6.94/7.64	US\$.kg ⁻¹
Passion fruit	<i>Passiflora edulis</i>	TD	0	160	Oval yellow Passion fruit	75/150/300	fruit	0.037/0.051/0.069	US\$.fruit ⁻¹

488 Some original practices were proposed in San Cristobal (FSC and TSC prototypes):

489 - Citrus other than *Citrus aurantium* grafted in the nursery on rootstocks of *Citrus aurantium* which is

490 the most resistant species of the Citrus genus to Huanglongbing disease according to participants;

491 - Benny and Pola improved varieties of avocado trees grafted on the endemic ("Criollo") avocado

492 seedlings once they reach 3 m height in order to avoid overcrowding of the strata where the

493 branches of the cocoa trees are located;

494 - the particularly productive *Annona muricata* from the province of Puerto Plata grafted on local

495 plants of this species for the FSC prototype once they have reached a height of 2 m.

496 In Duarte, only *Citrus sinensis* will be grafted onto *Citrus aurantium* plants in the nursery before being

497 planted.

498 **3.6. Ex ante evaluation of the economic performance of the four co-designed prototypes**

499 Our method of evaluating the total revenue R_{total} (Eq. 4) of prototypes produced highly contrasting

500 results between the three R_{total} projections (Figure 5). At the minimum projection, R_{total} was between

501 US\$ 4,000 and US\$ 6,000 ha⁻¹ yr⁻¹ among the four prototypes, which is higher than current average

502 values, i.e. US\$ 2,500 ha⁻¹ yr⁻¹ and corresponds to the highest range of current values (Notaro *et al.*,

503 2020). On the other hand, the maximum estimates of between US\$ 9,000 and US\$ 10,000 ha⁻¹ yr⁻¹,

504 were a little higher than the maximum current value. On average over the 20-year period, the share

505 of cocoa revenue (R_{cocoa}) in the R_{total} varied between the four prototypes, ranging from 15% for

506 prototype FSC to 31% for prototype FD, with 18% and 26% for prototypes TSC and TD respectively.

507 R_{cocoa} values estimated for the prototypes were higher than those observed in current AFS. This

508 relates to the significant difference in cocoa productivity on farm and on station. The R_{cocoa} that

509 would be obtained in each prototype from current productivity in the two zones would be between

510 US\$ 748 and US\$ 1,744 ha⁻¹ yr⁻¹, whereas it would be between US\$ 2,600 and US\$ 5,544 ha⁻¹ yr⁻¹ if

511 the prototype cocoa trees were as productive as those on the experimental station (Figure 5).

512 Globally, R_{total} increased up to a threshold reached in the eleventh year after the establishment of the
513 FSC and FD prototypes, because after this period all the associated crops have reached their
514 production potential, according to participants. The first year was a blank year and, except for the
515 TSC prototype, there was generally a small reduction in economic performance between the third
516 and fifth year. This is explained by a decrease in the density of staple crops in order to gradually leave
517 space for the development of cocoa and other trees (Figures 3 and 4, Table 5). Significant variations
518 in the estimated R_{total} were observed in the TSC and TD prototypes: (i) in the case of prototype TSC,
519 the three peaks in R_{total} corresponded to the sale of *Gmelina arborea*, *Swietenia mahagoni* and
520 *Catalpa longissima* timber trees in this chronological order as they have decreasing growth rates, (ii)
521 in prototype TD, the variations in R_{total} are explained by the presence of *Passiflora edulis* which is a
522 multiannual that has to be replanted every five years.

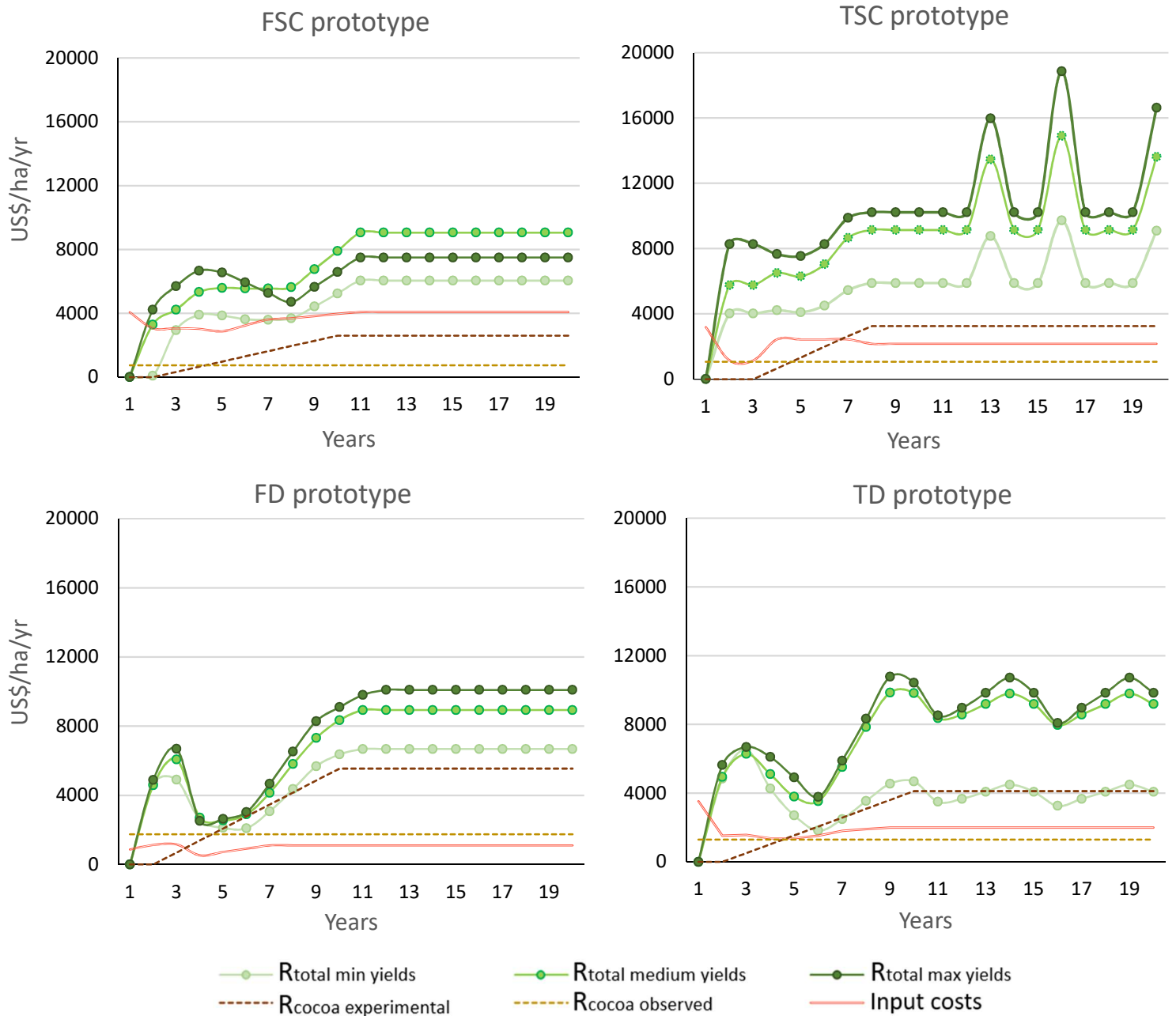


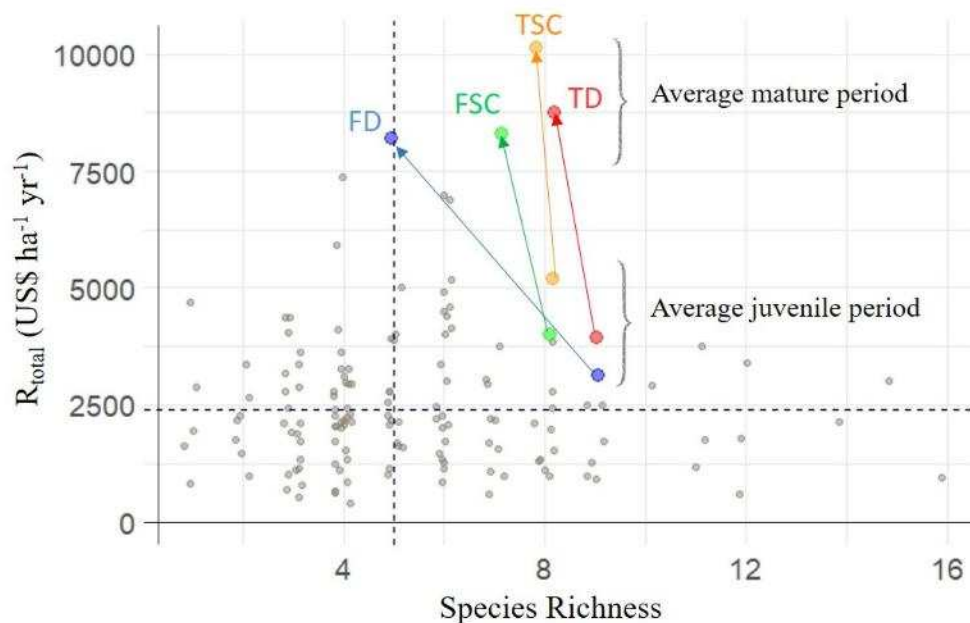
Figure 5. Economic projections (R_{total} in green) of the four co-designed prototypes over a period of 20 years, based (i) for each associated crop on minimum, medium and maximum yields provided by the participants, which was multiplied according to the maximum, average and minimum prices, respectively, provided by the Ministry of Agriculture and (ii) for cocoa, on yields provided by experimental stations (25%, 50%, 75% of the value respectively for minimum yields, medium yields and maximum yields) and purchase prices provided by the Ministry of Agriculture. The dark brown dotted line shows the **annual revenue** produced by the prototype cocoa trees if they produced at the same level as the cocoa trees on experimental stations ($R_{cocoa\ experimental}$), while the light brown dotted line shows the **annual revenue** produced by the prototype cocoa trees if they had the same productivity as those currently observed in **on an average farm** ($R_{cocoa\ observed}$). The red line represents the estimated costs of labor and materials (plants and tools). FSC = farmers' group from San Cristobal province, TSC = technicians' group from San Cristobal province, FD = farmers' group from Duarte province, TD = technicians' group from Duarte province.

523 When the medium economic predictions were applied to the 20-year period, the mean annual

524 revenue was around US\$ 7,000 ha⁻¹ yr⁻¹ for the FD, FSC and TD prototypes and about US\$ 8,670 ha⁻¹

525 yr⁻¹ for the TSC prototype. Farmers' prototypes produced the lowest average R_{total} , even if they were
 526 not too far from the TD prototype's R_{total} . In contrast, the TSC prototype produced a better average
 527 R_{total} since timber is a high added-value product. The estimated cost of inputs (plant prices, labor and
 528 tools) was between US\$ 1,500 and US\$ 4,000 ha⁻¹ yr⁻¹, far below the R_{total} , except for the lowest R_{total}
 529 in the immature phase of the prototypes. Even if external labor was needed to carry out all the
 530 farming practices, all four prototypes would generate a total earnings (TE) higher than or equal to
 531 US\$ 5,943 ha⁻¹ yr⁻¹, the initial target of the co-design process, with the exception of the FSC prototype
 532 which would generate a TE of US\$ 4,976 ha⁻¹ yr⁻¹.

533 Whether in their juvenile or mature phase, the R_{total} for each prototype was higher than the average
 534 R_{total} currently observed in the Dominican Republic (Figure 6). In the mature phase, the R_{total} was even
 535 higher than the best R_{total} observed in the field, especially for the TSC prototype. The four prototypes
 536 are promising, whether they are in the juvenile or mature phase, because they are at above-average
 537 levels in terms of both revenue and species richness.



538
 539 Figure 6. Replacement of the species richness and R_{total} potentially provided by the four prototypes in relation to
 540 the situations currently observed represented by the grey dots. The vertical and horizontal dotted lines indicate
 541 the average species richness and R_{total} , respectively 5 and US\$ 2,400 ha⁻¹ yr⁻¹, observed in Dominican AFS
 542 (adapted from Notaro et al., 2020). FSC = farmers' group prototype from San Cristobal province, TSC =

543 *technicians' group prototype from San Cristobal province, FD = farmers' group prototype from Duarte province,*
544 *TD = technicians' group prototype from Duarte province.*

545

546

547 **4. Discussion**

548 **4.1. An original and simple participative method for the design of complex cropping systems**

549 The design method described here is original in that it combines tools used independently in other
550 studies and that were easily appropriated by the participants and gave everyone the opportunity to
551 explain their choices. First, similar to Lamanda *et al.* (2012), we conceptually modelled the expected
552 functioning of AFS based on the participants' descriptions of the underlying ecological functions
553 and/or processes with the aim of improving their agro-economic performance. Second, criteria for
554 the selection of cultivars and species were ranked using the pebble counting method (step 1), a
555 method originally used to characterize the importance of the environmental components of
556 Indonesian rural communities (Sheil *et al.*, 2004). This prioritization method has been adapted in
557 other research to understand the choice of species according to their use in complex cocoa and
558 coffee agroforestry systems (Jagoret *et al.*, 2014; Rigal *et al.*, 2018). Third, the spatial arrangement of
559 species in AFS (step 2) was defined using a schematization artifact similar to the ones used, for
560 example, in "ComMod" Companion Modelling (d'Aquino and Bah, 2012; Redpath *et al.*, 2018) or in
561 the forecasting and backcasting game to support scenario evolution (Andreotti *et al.*, 2020). The
562 difference with these approaches is that the AFS schematization artifact is only used to decide on the
563 spatial distribution of the technical choices decided upstream, and not to model complete scenarios
564 of evolution. Finally, the *ex ante* evaluation of the performance of prototypes (step 3) was carried
565 out to check if the technical choices matched the objectives set (Sadok *et al.*, 2008).

566 The participatory prototyping tested in our study therefore strived to innovate in a systemic way, i.e.
567 by taking into account all the components of AFS, and not just a few selected services which was the
568 case in some previous design work, for example in Meylan *et al.* (2013). We focused on multi-species

569 systems, which are extremely complex systems due to the diversity of the species that form them,
570 both in space and over time. The interactions between the species considered in this co-design work
571 are more diverse than in temperate agroforestry systems, where the diversity and spatial
572 organization of cultivated species is generally simpler in orchards (Simon *et al.*, 2017) and field
573 croplands (Debaeke *et al.*, 2009).

574 Co-designed prototypes take agroecological objectives into account, i.e. desired states that fulfil
575 certain functions such as the need to include trees to provide homogeneous shade and allow an
576 optimal amount of light to pass through for cocoa trees. However, these functional traits can be
577 provided by a large range of tree species. Consensus was reached when deciding which of these
578 potential species would be included in the prototypes and which would be left out. However, some
579 participants would have preferred to include trees which were left out in the prototypes, and the
580 adoption of prototypes by these farmers could be weakened. An approach that is more focused on
581 the needs expressed by farmers and not on a pre-determined objective would probably have
582 resulted in more straightforward and potentially better adopted innovations (Dogliotti *et al.*, 2014;
583 Hazard *et al.*, 2017).

584 **4.2. Innovations influenced by the territory and the socio-professional stakeholder category**

585 The innovations implemented can be analyzed from two main perspectives: (i) the temporal
586 sequence of combinations of species and their respective densities, and (ii) the spatial arrangement
587 of these species. All four groups innovated in the spatial arrangement of plant species, unexpectedly
588 choosing similar patterns: cocoa trees in rows and other perennial species in the inter-row evenly
589 distributed over space, whereas the arrangements observed in existing AFS are rather random, and
590 rarely aggregated as in the cocoa AFS seen in Costa Rica (Salazar-Díaz and Tixier, 2019).

591 With respect to the time sequence of species combinations, more significant differences emerged
592 between the farmer and technician groups. The species chosen in the farmers' prototypes and their
593 chronosequence were similar to existing ones, but technical innovations were incorporated.

594 Examples include the choice of certain avocado varieties and grafting from specific plant material in
595 nurseries or plots. The species selected in the technicians' prototypes were more original: (i) in San
596 Cristobal, three forest species for timber exploitation were staggered over time, allowing for
597 replanting and maintenance of a continuous forest cover, and (ii) in Duarte, liana type species
598 (pepper and passion fruit) staked on nitrogen-fixing trees (*Gliricidia*) in lines between the rows of
599 cocoa trees. The development of the species over time was therefore taken into account in the
600 prototypes produced by technicians. This distinguished them from the prototypes chosen by farmers'
601 groups, which remained the same from the fourth year onwards.

602 The four groups were innovative in their choice of cocoa hybrid varieties, in contrast to the mass
603 selection method which is currently the most widely used method conducted by farmers themselves.
604 However, there was a stronger emphasis on cocoa trees in the Duarte farmers' prototypes with
605 1,120 cocoa trees.ha⁻¹ compared to 640 cocoa trees.ha⁻¹ in San Cristobal. This difference may be due
606 to the agricultural context of the two regions. The province of Duarte is the historical production area
607 in the Dominican Republic, which has developed with substantial investments in the structuring of
608 the cocoa sector. Indeed, in comparison with the province of San Cristobal, there are well established
609 cooperatives in charge of fermentation, drying and sale of cocoa, which also provide technical advice.
610 It is clear that this has an impact on the technical choices of farmers in relation to the room left to
611 cocoa trees and associated species in their agroforestry systems.

612 In a final workshop not described and analyzed in the present article, the two groups from each
613 region met to present their prototypes. The innovations proposed by the technicians, which were
614 more disruptive to current AFS management than those proposed by the farmers, did not convince
615 the farmers. Risk aversion seems stronger among farmers, so they may not adopt the technicians'
616 prototypes or even test them, even though they were the subject of joint discussions between
617 farmers and technicians in the final workshop.

618 **4.3. Consistent agronomic impact for sustainable environmental conditions**

619 Even though agroecology has reached a certain maturity in terms of the main impacts of biodiversity
620 (Malézieux, 2011), precise knowledge on the underlying processes is still lacking. Malézieux *et al.*
621 (2009) and Clough *et al.* (2011) have shown that highly diversified AFS do not prevent good cocoa
622 yields. Furthermore, the more diversified the cropping system is, the greater its resilience to major
623 climatic events such as hurricanes (Altieri *et al.*, 2015), which occur in the Dominican Republic.
624 Brickhill (2015) and Notaro *et al.* (2020) have shown that the highest yields are achieved with an
625 intermediate level of biodiversity. This is what is obtained in the prototypes with mixtures of five to
626 nine species depending on the age of the prototypes, making it possible to maximize the amounts
627 produced in order to attract buyers and also to negotiate prices. In addition, agronomic innovations
628 should make it possible to intensify the agroecological functioning of the AFS. For example, both
629 farmers and technicians stated that trees which are taller than cocoa trees maintain a high moisture
630 content in the upper soil horizon where cocoa trees root, as shown by Niether *et al.* (2017), and then
631 selected trees with this feature.

632 One might have expected the continuity of cocoa trees within a row would sometimes be interrupted
633 by the presence of a different type of tree, but none of the four groups expressed the possibility of
634 having a spatial arrangement of species following this pattern. The regular spatial arrangement
635 chosen for both cocoa and shade trees is not necessarily optimal in all respects, for example it could
636 have negative effects on the prevalence of pests, as demonstrated for moniliasis in Costa Rica and
637 mirids in Cameroon (Gidoïn *et al.*, 2014a; Gidoïn *et al.*, 2014b). However, in the workshops, particular
638 care was taken to select species favorable for the development of cocoa trees. The preservation of a
639 species richness equivalent to that of the current AFS and the continued avoidance of synthetic
640 products should ensure the environmental sustainability of the prototypes.

641 **4.4. Technical and economic feasibility of the prototypes**

642 Maintaining species richness with between five and nine species (including cocoa) in the prototypes
643 will provide high yields and should therefore improve the economic conditions of farming

644 households. The diversity of production crops and therefore of potential revenue reduces the risks of
645 economic losses in the event of economic shocks (e.g. sudden drop in sales prices) or agronomic
646 hazards (e.g. yield losses due to strong disease or pest pressure) (Cardozo *et al.*, 2015; Mbow *et al.*,
647 2014).

648 In addition, the spatial arrangement of the species has been designed to facilitate work in the plots.
649 Indeed, rows of cocoa trees are spatially separated from rows of other species. Among these other
650 species, we even distinguish rows by their family of use such as timber rows (TSC) or citrus rows (FSC)
651 and sometimes even by species such as pepper and passion fruit (TD). These technical choices for the
652 spatial organization of the system should facilitate the organization of labor in the plot.

653 Our economic modeling over twenty years is simplistic since we only considered the turnover and
654 the global costs, which were calculated from the yields and the costs according to the farmers'
655 statements. The main limitation of our analysis is that it is static: it does not take into account the
656 discount rate, nor the variations of the climate, which have nevertheless an impact on the species
657 choices and on the yields achieved. Farmers generally have time preference for money and therefore
658 tend to plant species that produce quickly in order to generate income rapidly (Graves *et al.*, 2011),
659 and not to invest in plants whose economic benefits will occur over the long term and one-off. This is
660 particularly the case in the TD prototype where timber species were chosen. Scenarios of climate
661 change, such as increased temperatures or frequency of intense cyclones, or of appearance of
662 emerging pests and diseases could have been discussed in workshops with farmers and technicians
663 (Andrieu *et al.*, 2019), from experienced situations of such hazards.

664 Our choice to mimic the law of supply and demand by calculating revenue as the product of
665 minimum yield and maximum price, or maximum yield by minimum price, could also be discussed as
666 an individual farmer producing low yield cannot not necessarily expect a high selling price. But we
667 found it was a reasonable solution to compare prototypes and avoid an unrealistically huge range of
668 revenues by multiplying high yields by high prices and low yields by low prices.

669 **4.5. Agro-economic performance to be assessed *in situ***

670 According to our economic assessment, the medium R_{total} would be US\$ 1,500 ha⁻¹ yr⁻¹ above the
671 income enabling 75% of farmers and their families to escape from poverty. This would be equivalent
672 to multiplying by three the medium R_{total} currently generated by Dominican AFS farmers (Notaro *et*
673 *al.*, 2020). The low proportion of R_{cocoa} in the R_{total} contrasts sharply with what has been observed in
674 the current AFS, where this share is 63% (Notaro *et al.*, 2020). **There are several reasons that could**
675 **explain this large gap:**

676 (i) the choice of associated species with commercial production, with relatively high planting
677 densities, compared to current AFS, (ii) an overestimation of the purchase price to farmers of other
678 productions than cocoa, (iii) an overestimation of the quantities sold of other productions (here
679 100%) while we observe that many fruits are not harvested and rot in the plots, and (iv) an
680 underestimation of cocoa yields due to our low average conversion coefficient (50%) between on-
681 station and on-farm yields.

682 The uncertainty surrounding the expected agro-economic performance of each prototype reveals the
683 limit of *ex ante* evaluation and the need to test the prototypes *in situ*. For this reason, a few
684 volunteer farmers who took part in the design process have installed (or are in the process of
685 installing) the co-designed prototypes. In total, each prototype will have a surface area of 0.25 ha
686 and will be installed six times, half on bare land and half in aging AFS. The three replications of each
687 prototype (new AFS and AFS under renovation) will allow robust conclusions to be drawn on the
688 relevance of each of the four prototypes with respect to the stated economic objectives. Concerning
689 the transition from an aging AFS to the prototype, considerable work is required to prepare the plot
690 according to the planting scheme described in the technical guide prepared by Deheuvels and Notaro
691 (2019) but is not detailed here.

692 Inviting professionals from sectors other than cocoa, for example technicians, engineers and
693 salespeople from other sectors (fruit, vegetables, spices, wood, etc.) would ensure the emergence of

694 more substantial innovations for these co-productions. The knowledge of these experts would have
695 increased the confidence of farmers and consequently the probability of acceptance of the
696 innovations, with a better evaluation of the market opportunities for cocoa co-products and perhaps
697 opening the way to the signing of trade agreements for niche markets (Meynard *et al.*, 2017; Berthet
698 *et al.*, 2018).

699 **5. Conclusion**

700 The participatory design method conceived in this work, and tested with those working in the
701 Dominican cocoa sector, resulted in the development of four promising prototypes. Our hypothesis
702 that there is scope for improving yields without reducing biodiversity and associated **environmental**
703 services in AFS, and that it can be explored by mobilizing the expertise of farmers and technicians,
704 has been verified. This generic method based on consensus takes into account participants'
705 knowledge (experience and academic) and specific regional characteristics of the two regions but
706 lacks *de facto* adaptability to the specific constraints of each farmer. Agroecological innovations have
707 been updated, particularly concerning the choice of combinations of species over space and time,
708 with the aim of increasing yields of cocoa and companion crops and consequently total **revenue**
709 through good **combinations of** cocoa and other productions. At present, the "on farm" evaluation of
710 newly installed prototypes or renovation of old AFS is essential to confirm or invalidate the benefits
711 of the prototypes. The active involvement of farmers in the process of designing and setting up
712 prototypes in their fields makes us confident that these technical innovations, and their evolution
713 over the course of the project, will be adopted and adapted.

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