Participative design of the spatial and temporal development of improved cocoa agroforestry systems for yield and biodiversity

Martin Notaro, Olivier Deheuvels, Christian Gary

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

Martin Notaro[1,3,*], Olivier Deheuvels[1,2,3], Christian Gary[3]

[1]CIRAD, UMR ABSys, F-34398, Montpellier, France

[2]CEDAF, Santo Domingo, Dominican Republic

[3]ABSys, Univ Montpellier, CIHEAM-IAMM, CIRAD, INRAE, Institut Agro, Montpellier, France

*corresponding author

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

1. Introduction

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

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

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

Agricultural innovations may originate from farmers themselves (Catalogna *et al.*, 2018), from public or private extension services, from technical institutes or from research (Reau and Doré, 2008). In some cases, the adoption of these innovations may be difficult. The “top-down” approach still often used by technical consulting organizations has shown weaknesses (Faure *et al.*, 2009). Technical recommendations are either not applied, because they are too expensive or time-consuming to set up (Valdivia *et al.*, 2012), or take time to be accepted by farmers. A different approach involving farmers themselves emerged in the 1990s, as demonstrated by Salembier *et al.* (2018) in their work on the genealogy of design reasoning in agronomy. Participatory design methods deal with the sometimes contradictory objectives of different stakeholders, for example in response to ecological issues in contexts of environmental degradation or conflicting natural resources management (Abrami *et al.*, 2012; Meylan *et al.*, 2013; Speelman *et al.*, 2014; Ravier *et al.*, 2015). Within the framework of the design of cropping and farming systems, the prototyping proposed by Vereijken (1997) initiated the co-design movements of the past 20 years. Nowadays, the design process can aim either at constructing novel cropping or farming systems (*de novo* design) or improving existing systems (*step-by-step* design) by involving farmers in the co-design process (Meynard *et al.*, 2012; Navarrete *et al.*, 2018). Prototypes are assessed experimentally, allowing improvements to be made in a new design cycle if required (Rapidel *et al.*, 2009; Le Bellec *et al.*, 2011; Husson *et al.*, 2015). To facilitate communication among stakeholders, several types of artifacts have been employed: conceptual models (Lamanda *et al*., 2012; Meylan *et al*., 2013), pebble distribution methods (Sheil *et al.*, 2004), serious games (Martin *et al*., 2011), mapping games (d'Aquino *et al.*, 2003; Speelman *et al.*, 2014), and companion modeling (Borodina *et al*., 2018). To estimate the expected level of success of prototypes, *ex ante* evaluation methods have been developed, based, for example, either on simulation models such as APSIM (Keating *et al.*, 2003) and BANAD (Blazy *et al.*, 2010) or multiple criteria assessment tools such as MASC (Sadok *et al.*, 2009; Ravier *et al.*, 2015) and DEXiPM (Pelzer *et al.*, 2012). Their use in participatory workshops facilitates the selection of the most effective innovations before testing them in on-farm trials.

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

2. Material and Methods

2.1. Location

Two zones offering contrasted cocoa-based AFS were selected for the participatory design workshops : the province of Duarte in the north of the Dominican Republic, which is the main and historic cocoa production area with 55,606 ha representing 36.5% of the national cocoa-growing area, and the province of San Cristobal in the south, which is a more extensive cocoa-growing zone with 2,548 ha representing 1.7% of the national cocoa-growing area (Deheuvels, 2015) (Figure 1). In the province of Duarte, the average density and the diversity of associated species are lower than in the San Cristobal area (Notaro *et al.*, 2020). The Duarte zone is more focused on the cultivation of cocoa, with a higher planting density of cocoa trees, the majority of which are produced in nurseries. Physico-chemical properties of the soils in the two areas do not differ significantly (data not shown).

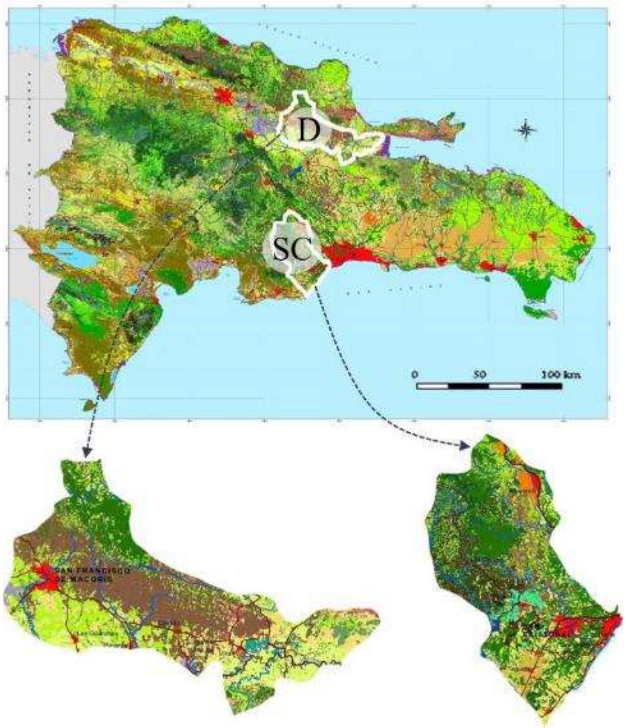

Figure 1. Map of the Dominican Republic showing the location of the two selected provinces, Duarte (D) and San Cristobal (SC) and where cocoa AFS are located (in brown). This map has been adapted from a land use cover map from the Ministry of Environment (Ministerio de Medio Ambiente y Recursos Naturales,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

2.2. Choice of participants

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

In each of the two zones, two different co-design groups were formed: the first was composed of Dominican cocoa farmers and the second of technicians and academics of the cocoa sector. This separation made the farmers feel more comfortable exchanging their views among peers. Mixing all participants from the beginning of the process would certainly have limited the voice of the participants with empirical knowledge, compared to those with academic knowledge (Faure *et al.*, 2009). The participatory process did not apparently favor any of the professions represented in these workshops, nor guide the decisions made by the participants.

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

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

2.3. The different stages of the participatory design process

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

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

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

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

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 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) *Ex ante* 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

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

2.4. Objectives of the co-design process

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

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

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

Increasing the income from AFS while maintaining at least the same level of plant biodiversity is equivalent to strengthening the agro-ecological character of cocoa farming in agroforestry (Altieri *et al.*, 2015). The co-design process aimed to identify the optimal combination of crop species to obtain satisfactory overall yields in the long term. The main technical levers discussed were: (i) the species and varieties to be planted in the AFS, (ii) the planting densities and (iii) spatial arrangement of each. The criteria for selecting the species were provided by the participants or presented by experts when knowledge input was required. This was the case, for example, for the tolerance of cocoa varieties to diseases that are still absent from the island such as *Moniliophtora roreri* and *Crinipellis perniciosa,* but which could one day be there.

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

2.6. Selection of cocoa varieties and associated species

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

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

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

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

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

where

i = criterion considered

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

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

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

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

2.7. Choice of planting densities and spatial arrangement of species

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

To introduce the game and to ensure the participants understood the purpose of the workshop, we started with a schematic representation of existing AFS (Notaro *et al.*, 2020) characterized by the disorganized arrangement of cocoa trees and associated plants. Once this representation was validated by the participants, the discussion turned to the advantages and disadvantages of the spatial arrangement of species in existing AFS, which it was important to clarify in order to move on to the next stage of design.

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

2.8. Economic projections for the co-designed prototypes

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

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

(i) the yields of each cocoa variety included in the prototypes, obtained from experimental stations in the Dominican Republic for local varieties and other countries for international varieties (Turnbull and Hadley, 2017),

(ii) the farm gate sales prices for the past 10 years provided by the Ministry of Agriculture (Ministerio de Agricultura, 2017).

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

(i) the yields of each species (sp.) in the prototypes, estimated by the participants themselves,

(ii) the farm gate sales prices for each associated species (sp.) provided by the Ministry of Agriculture (Ministerio de Agricultura, 2017).

The three indicators described above were calculated as follows:

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

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

$$(\text{Eq. } 4) \qquad R_{total} = R_{cocoa} + R_{other}$$

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

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

The evaluation of the costs of labor, tools and plant material were estimated jointly by all the participants who took part in the co-design process. This step required the participants to establish a consensual management plan, that included the different practices to be used (soil preparation, setting up the planting system, planting, pruning, weeding, harvesting, etc.) and the associated workloads and costs. The estimated time requirements and cost of inputs (labor and tools) to carry out the different management practices in the prototypes (including their cultivated biodiversity) is not described in detail, as we focus here on the “structural” design of the prototypes.

3. Results

3.1. Specification of the desired agroecological functions in the AFS

Before being ready to make technical choices for the prototypes during the co-design process, a first phase of characterization of the current and envisaged future agroforestry systems was necessary. This step led the participants to define desired biophysical states such as plant structure, soil properties, shade level, climate under the canopy, etc. Then these states could be translated into agroecological functions, i.e. their role in improving the ecological functioning of the agroforestry system. Finally, these functions were transcribed into species selection criteria that could be multidimensional (mainly agronomic, biophysical, physiological, commercial, economic), ultimately enabling the selection of cocoa tree varieties and associated plant species.

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

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 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 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
		Regular shade over the cocoa trees in the intermediate stratum	*Keep cocoa trees cool*	
		Able to fix nitrogen in soil (Legumes) and **lose annual leaves (Caducifoliates)** 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**	Productivity Market access High selling price
		Hurricane resistant	*To protect the integrity of cocoa trees*	Hurricane resistant
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**	

Table 2 (Continued)

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**	**Prevent weeds growing**	
		Low and **productive (food)**	Avoid competition with cocoa trees for soil resources + **provision of products for sale or self-consumption**	
	Weeds	*Act as a barrier perpendicular to the slope*	*Limit erosion*	Productivity (cocoa and other products)
		In steeply sloping plots, let some weed species cover the soil (i.e. *Mimosa pudica, Arachis pintoi, Commelina nudiflora*)	**Limit erosion** and maintain good soil moisture	
	Soil	The first 5 cm are **rich in decomposing organic matter** (*black soil*) 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 *Musaceae* and *Ananas comosus* or attract them by letting some fruits rot, such as citrus fruits)	Pollinate flowers and **increase yields**	

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

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

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

3.3. Choice of cocoa varieties

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

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

Table 3. Results of the Sheil's method (number of points out of a total of 50 points per group) applied to the selection criteria of cocoa varieties by the two groups in the two zones (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).

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

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

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

3.4. Choice of associated plant species

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

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

Table 4. Results of Sheil's method (number of points out of a total of 50 per group) applied to the importance weight Pi given to each selection criterion of the species associated with cocoa trees in the two groups of the two zones (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).

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

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

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

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

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

Concerning the associated plant species, the differences were not as marked as for cocoa tree density. The FD group proposed 192 trees ha^{-1} and the TD group 288 trees ha^{-1}, the other two groups in the San Cristobal region proposed intermediate densities. None of the groups wished to mix cocoa trees with other tree species in the same row; the latter were therefore located in the inter-row. According to the participants, this ensures a certain continuity in the technical management by row, and makes it possible not to reduce the space allocated for cocoa trees and thus not to reduce cocoa production. In the young phase (phase A) of the prototypes, from planting to approximately 7 years of age, sometimes high densities of tubers (taro, ginger, turmeric), musaceae (dessert banana or plantain) or service trees (Gliricide and Annatto) were proposed (Table 5). In their mature phase (phase B), the prototypes exhibited a species richness of plants associated with cocoa trees of four (FD group), six (FSC group) and seven species (TSC and TD groups). Avocado (*Persea americana*) and citrus were introduced in all four prototypes. The farmers' prototypes (FSC and FD) were dominated by fruit trees (Table 5), the FSC prototype being distinguished by the presence of soursop and sapodilla (*Annona muricata* and *Pouteria sapote*) and the FD prototype by the presence of coconut trees (*Cocos nucifera*). In contrast, the two groups of technicians promoted forest trees: the TSC prototype was distinguished by the presence of three forest species (*Catalpa longissima*, *Gmelina arborea* and *Swietenia mahagoni*) whereas the TD prototype was distinguished by a significant association of Gliricides (*Gliricidia sepium*), arranged in parallel rows to the cocoa trees and serving as stakes for pepper plants (*Piper nigrum*).

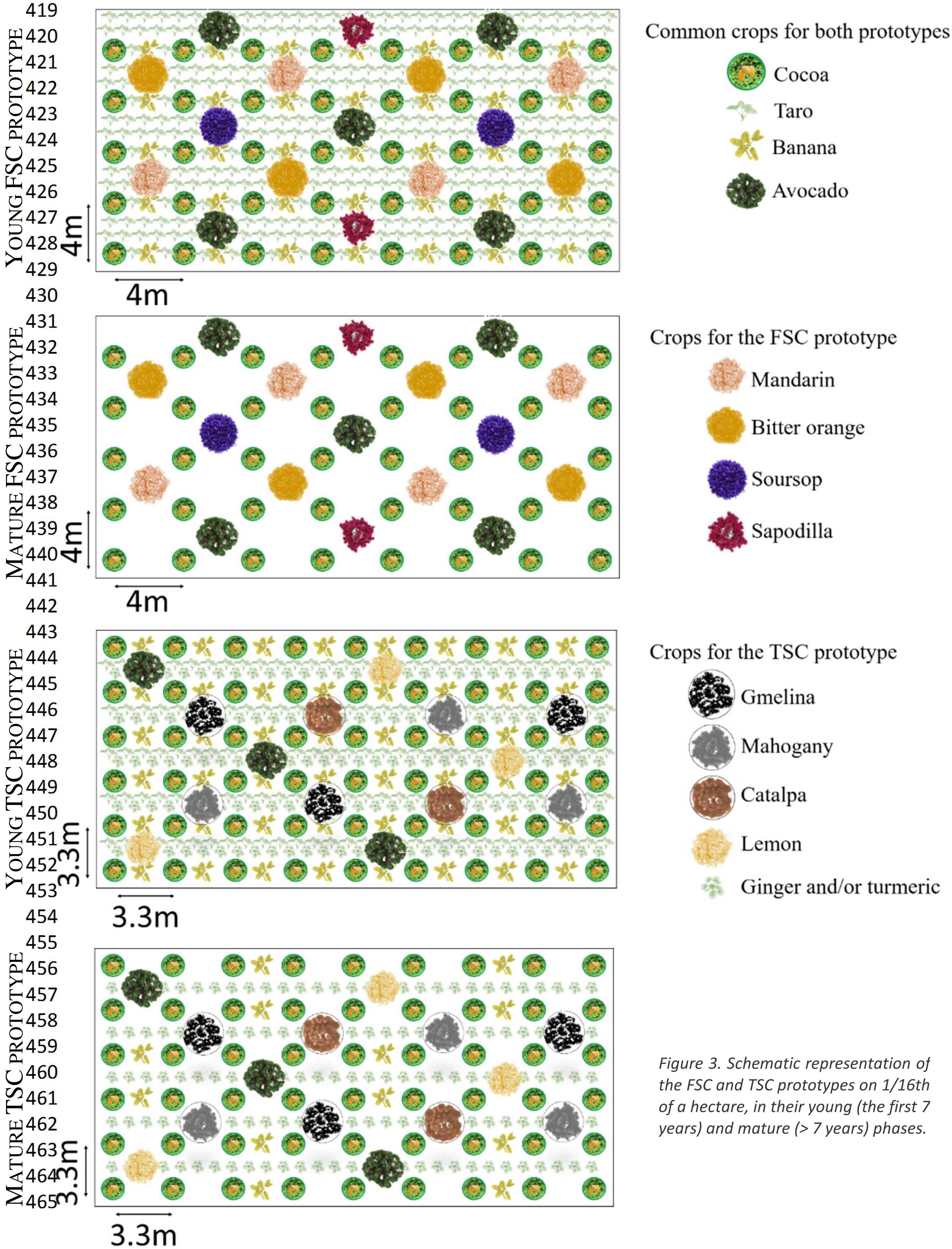

Figure 3. Schematic representation of the FSC and TSC prototypes on 1/16th of a hectare, in their young (the first 7 years) and mature (> 7 years) phases.

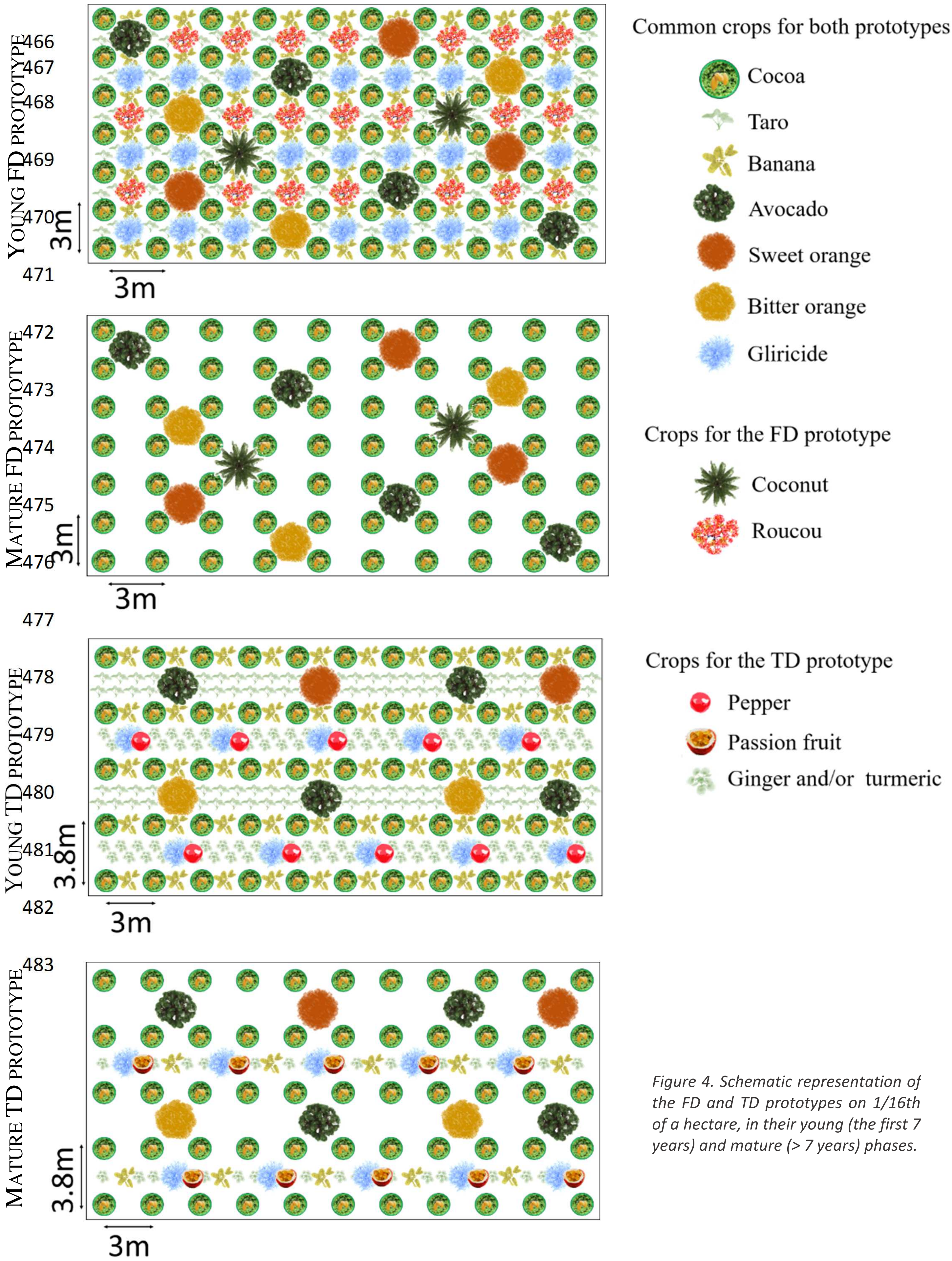

Figure 4. Schematic representation of the FD and TD prototypes on 1/16th of a hectare, in their young (the first 7 years) and mature (> 7 years) phases.

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 (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	*Theobroma cacao*	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$.kg^{-1}
		TSC	864	864	Clones ICS-95, UF-676, GS-36, ML-22 in equal quantities	1.35/2.7/4.05			
		FD	1120	1120	Clones ICS-1, ICS-39, RZ-12, RZ-44, RZ-83, RZ-100, IML-44, IML-53, ML-66, ML-103 in equal quantities	1.85/3.7/5.55			
		TD	832	832	Clones ICS-39, UF-296, ICS-95, IML-119, IML-53, ML-22, ML-105 in equal quantities	1.85/3.7/5.55			
Avocado	*Persea americana*	FSC	80	80	Local avocado, grafted with “Benny” and “Pola” variety grafts once a height of 3 m reached in plot	100/200/300	fruit tree^{-1}	0.09/0.18/0.28	US$.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	*Musa spp.*	FSC	640	From 0 to a few	“Pluma fina y media mata” and “macho por hembra”	100/160/220	bunch	2.4/3.2/4	US$.bunch^{-1}
		TSC	864	192	"Pluma fina y media mata" and "Macho por hembra" depending on pedoclimatic conditions	30/45/75	fruit bunch^{-1}	0.06/0.08/0.12	US$.fruit^{-1}
		FD	1120	From 0 to a few	Local	30/45/60			
		TD	832	160	“Macho por hembra”	30/35/40			

 Table 5 (Continued)

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	*Colocasia esculenta*	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	*Citrus aurantium*	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	*Citrus sinensis*	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	*Gliricidia sepium*	FD	336	0	Local	-	-	-	-
		TD	160	160	Local				
Ginger and/or turmeric	*Zingiber officinale* and/or *Curcuma longa*	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	*Citrus reticulata*	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	*Annona muricata*	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	*Pouteria sapote*	FSC	32	32	Productive sapodilla grafted on local sapodilla rootstock	100/250/400	fruit	0.08/0.14/0.2	US$.$fruit^{-1}$

487 *Table 5 (Continued)*

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	*Gmelina arborea*	TSC	48	48	Local	48	tree	60/90/120	US$.tree^{-1}
Mahogany	*Swietenia mahagoni*	TSC	48	48	African mahogany	48	tree	80/120/180	US$.tree^{-1}
Catalpa	*Catalpa longissima*	TSC	32	32	Local	32	tree	100/140/200	US$.tree^{-1}
Lemon	*Citrus latifolia*	TSC	64	64	Local	100/300/600	fruit	0.04/0.05/0.08	US$.fruit^{-1}
Coconut	*Cocos nucifera*	FD	32	32	Local	150/200/300	fruit	0.185/0.227/0.301	US$.fruit^{-1}
Roucou	*Bixa orellana*	FD	336	0	Local	2/4/6	pound	2.7/2.91/3	US$.pound^{-1}
Pepper	*Piper nigrum*	TD	160	0	Balankotta and/or Guayarina and/or Singapur	0.6/1/1.6	kg	6.22/6.94/7.64	US$.kg^{-1}
Passion fruit	*Passiflora edulis*	TD	0	160	Oval yellow Passion fruit	75/150/300	fruit	0.037/0.051/0.069	US$.fruit^{-1}

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

- Citrus other than *Citrus aurantium* grafted in the nursery on rootstocks of *Citrus aurantium* which is the most resistant species of the Citrus genus to Huanglongbing disease according to participants;

- Benny and Pola improved varieties of avocado trees grafted on the endemic ("Criollo") avocado seedlings once they reach 3 m height in order to avoid overcrowding of the strata where the branches of the cocoa trees are located;

- the particularly productive *Annona muricata* from the province of Puerto Plata grafted on local plants of this species for the FSC prototype once they have reached a height of 2 m.

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

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

Our method of evaluating the total revenue R_{total} (Eq. 4) of prototypes produced highly contrasting results between the three R_{total} projections (Figure 5). At the minimum projection, R_{total} was between US$ 4,000 and US$ 6,000 ha^{-1} yr^{-1} among the four prototypes, which is higher than current average values, i.e. US$ 2,500 ha^{-1} yr^{-1} and corresponds to the highest range of current values (Notaro *et al.*, 2020). On the other hand, the maximum estimates of between US$ 9,000 and US$ 10,000 ha^{-1} yr^{-1}, were a little higher than the maximum current value. On average over the 20-year period, the share of cocoa revenue (R_{cocoa}) in the R_{total} varied between the four prototypes, ranging from 15% for prototype FSC to 31% for prototype FD, with 18% and 26% for prototypes TSC and TD respectively.

R_{cocoa} values estimated for the prototypes were higher than those observed in current AFS. This relates to the significant difference in cocoa productivity on farm and on station. The R_{cocoa} that would be obtained in each prototype from current productivity in the two zones would be between 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 the prototype cocoa trees were as productive as those on the experimental station (Figure 5).

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

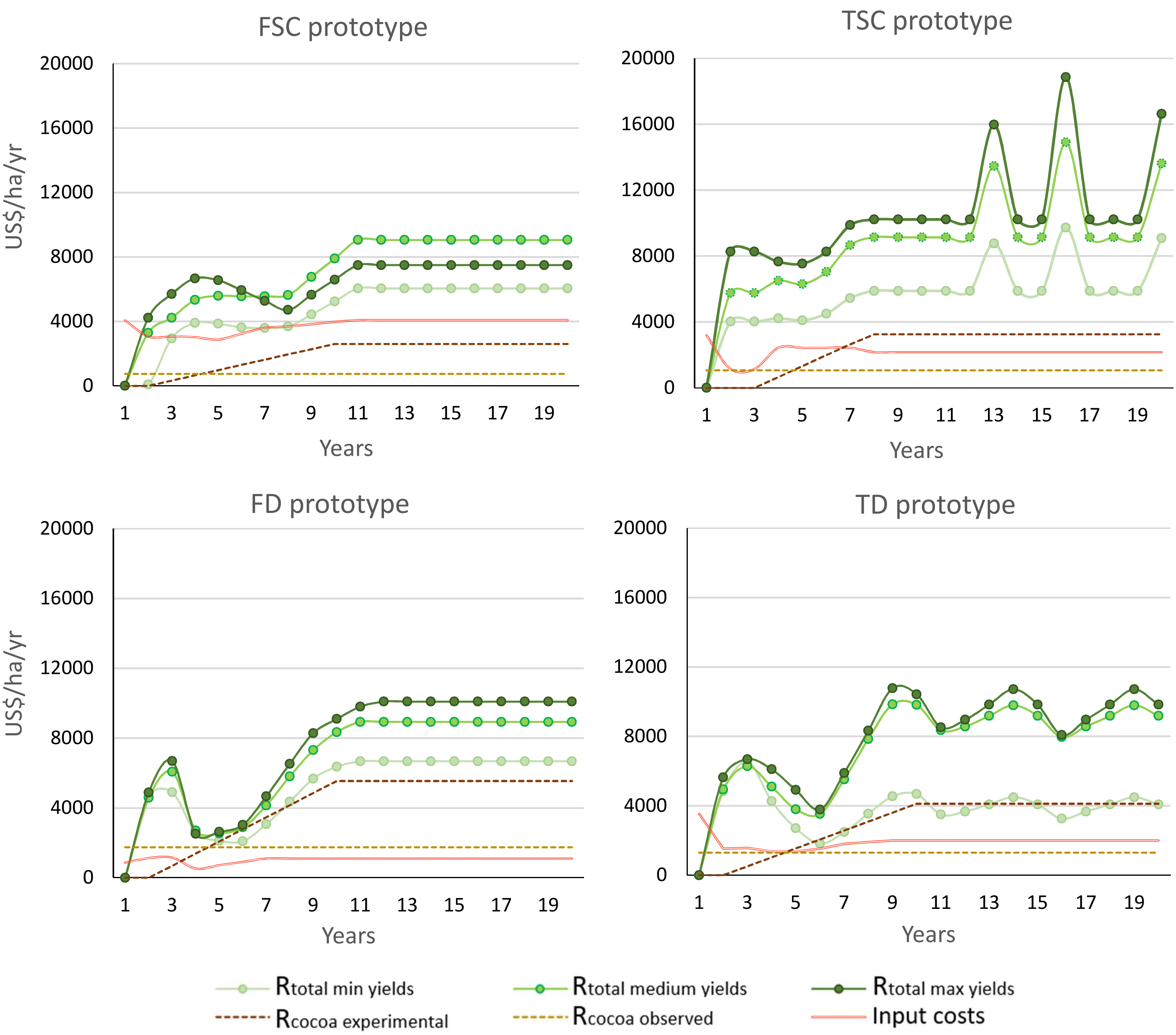

Figure 5. Economic projections (R_{total} in green) of the four co-designed prototypes over a period of 20 years, based (i) for each associated crop on minimum, medium and maximum yields provided by the participants, which was multiplied according to the maximum, average and minimum prices, respectively, 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.

When the medium economic predictions were applied to the 20-year period, the mean annual revenue was around US$ 7,000 ha^{-1} yr^{-1} for the FD, FSC and TD prototypes and about US$ 8,670 ha^{-1}

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

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

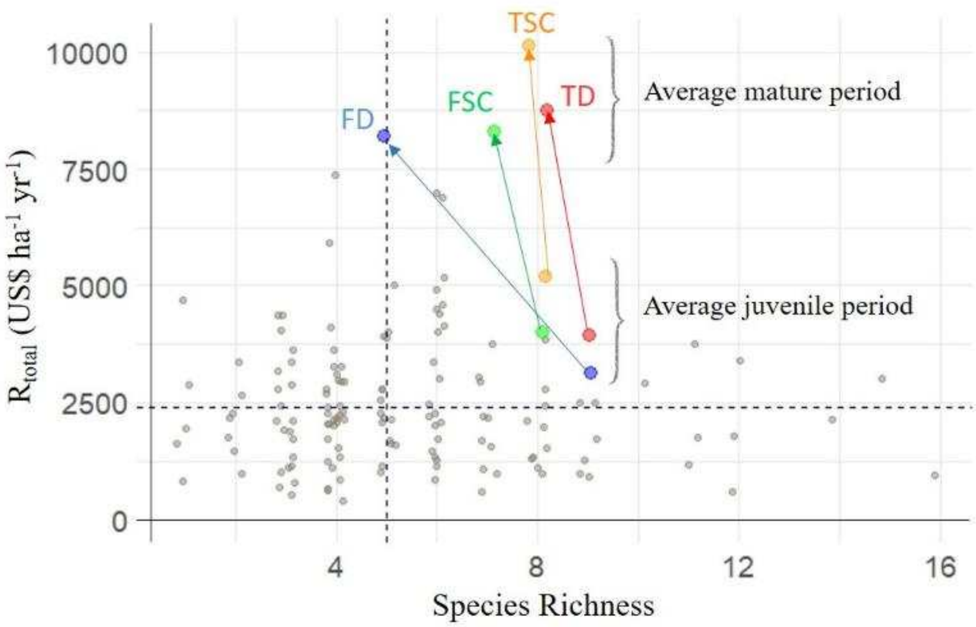

Figure 6. Replacement of the species richness and R_{total} potentially provided by the four prototypes in relation to the situations currently observed represented by the grey dots. The vertical and horizontal dotted lines indicate the average species richness and R_{total}, respectively 5 and US$ 2,400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

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

4. Discussion

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

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

The participatory prototyping tested in our study therefore strived to innovate in a systemic way, i.e. by taking into account all the components of AFS, and not just a few selected services which was the case in some previous design work, for example in Meylan *et al.* (2013). We focused on multi-species systems, which are extremely complex systems due to the diversity of the species that form them, both in space and over time. The interactions between the species considered in this co-design work are more diverse than in temperate agroforestry systems, where the diversity and spatial organization of cultivated species is generally simpler in orchards (Simon *et al.*, 2017) and field croplands (Debaeke *et al.*, 2009).

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

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

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

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

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

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

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

4.3. Consistent agronomic impact for sustainable environmental conditions

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

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

4.4. Technical and economic feasibility of the prototypes

Maintaining species richness with between five and nine species (including cocoa) in the prototypes will provide high yields and should therefore improve the economic conditions of farming households. The diversity of production crops and therefore of potential revenue reduces the risks of economic losses in the event of economic shocks (e.g. sudden drop in sales prices) or agronomic hazards (e.g. yield losses due to strong disease or pest pressure) (Cardozo *et al.*, 2015; Mbow *et al.*, 2014).

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

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

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

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

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

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

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

Inviting professionals from sectors other than cocoa, for example technicians, engineers and salespeople from other sectors (fruit, vegetables, spices, wood, etc.) would ensure the emergence of more substantial innovations for these co-productions. The knowledge of these experts would have increased the confidence of farmers and consequently the probability of acceptance of the innovations, with a better evaluation of the market opportunities for cocoa co-products and perhaps opening the way to the signing of trade agreements for niche markets (Meynard *et al.*, 2017; Berthet *et al.*, 2018).

5. Conclusion

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

Acknowledgements

We thank all the participants and institutions that have been involved in the co-design process: the Dominican Foundation of Organic Farmers (FUNDOPO), the National Confederation of Dominican Cocoa Farmers (CONACADO), The Foundation for Social Assistance, Recovery and Organic Management of Cocoa Plantations (FUPAROCA) and Rizek Cacao S.A.S, the Ministry of Agriculture, the Dominican Institute for Agricultural and Forestry Research (IDIAF). We thank Raymond Reau (INRAE) for his valuable methodological support. We also thank the Cacao Forest project, a partnership combining stakeholders from the agri-food industry, NGO and research, especially chocolate manufacturers and craftsmen who funded this research (Valrhona, Bjorg Bonneterre & Cie, Weiss, Révillon and the Relais Desserts). Finally, we thank our colleagues Patrick Jagoret and Stéphane Saj (CIRAD) for their proofreading of the article and their constructive remarks.

References

Abrami, G., Ferrand, N., Morardet, S., Murgue, C., Popova, A., De Fooij, H., Farolfi, S., Du toit, D., Aquae-Gaudi, W., 2012. Wat-A-Game, a toolkit for building role-playing games about integrated water management. In: Seppelt R, V.A.A.L.s.B.D. (Ed.), International Congress on Environmental Modelling and Software (iEMSs). IEMSS, Leipzig, Allemagne, pp. 1912-1919.

Altieri, M.A., Nicholls, C.I., Henao, A., Lana, M.A., 2015. Agroecology and the design of climate change-resilient farming systems. Agronomy for Sustainable Development 35, 869-890.

Andreotti, F., Mao, Z., Jagoret, P., Speelman, E.N., Gary, C., Saj, S., 2018. Exploring management strategies to enhance the provision of ecosystem services in complex smallholder agroforestry systems. Ecol. Indicators 94, 257-265.

Andreotti, F., Speelman, E.N., Van den Meersche, K., Allinne, C., 2020. Combining participatory games and backcasting to support collective scenario evaluation: an action research approach for sustainable agroforestry landscape management. Sustainability Science 15, 1383-1399.

Andrieu, N., Howland, F., Acosta-Alba, I., Le Coq, J.-F., Osorio-Garcia, A.M., Martinez-Baron, D., Gamba-Trimiño, C., Loboguerrero, A.M., Chia, E., 2019. Co-designing Climate-Smart Farming Systems With Local Stakeholders: A Methodological Framework for Achieving Large-Scale Change. Frontiers in Sustainable Food Systems 3, 37.

Beer, J., 1987. Advantages, disadvantages and desirable characteristics of shade trees for coffee, cacao and tea. Agrofor. Syst. 5, 3-13.

Berthet, E.T., Hickey, G.M., Klerkx, L., 2018. Opening design and innovation processes in agriculture: Insights from design and management sciences and future directions. Agricultural Systems 165, 111-115.

Blazy, J.-M., Tixier, P., Thomas, A., Ozier-Lafontaine, H., Salmon, F., Wery, J., 2010. BANAD: A farm model for ex ante assessment of agro-ecological innovations and its application to banana farms in Guadeloupe. Agricultural Systems 103, 221-232.

Brickhill, D., 2015. Ecosystem services and the environment. In-depth report 11 produced for the European Commission, DG Environment. Available at: http://ec.europa.eu/science-environment-policy.

Catalogna, M., Dubois, M., Navarrete, M., 2018. Diversity of experimentation by farmers engaged in agroecology. Agronomy for Sustainable Development 38.

Cerda, R., Allinne, C., Gary, C., Tixier, P., Harvey, C.A., Krolczyk, L., Mathiot, C., Clément, E., Aubertot, J.-N., Avelino, J., 2017. Effects of shade, altitude and management on multiple ecosystem services in coffee agroecosystems. Eur. J. Agron. 82, 308-319.

Clough, Y., Barkmann, J., Juhrbandt, J., Kessler, M., Wanger, T.C., Anshary, A., Buchori, D., Cicuzza, D., Darras, K., Putra, D.D., Erasmi, S., Pitopang, R., Schmidt, C., Schulze, C.H., Seidel, D., Steffan-Dewenter, I., Stenchly, K., Vidal, S., Weist, M., Wielgoss, A.C., Tscharntke, T., 2011. Combining high biodiversity with high yields in tropical agroforests. Proc Natl Acad Sci U S A 108, 8311-8316.

d'Aquino, P., Bah, A., 2012. A bottom-up participatory modelling process for a multi-level agreement on environmental uncertainty management in West Africa. Journal of Environmental Planning and Management - J ENVIRON PLAN MANAG 56, 1-15.

d'Aquino, P., Le Page, C., Bousquet, F., Bah, A., 2003. Using Self-Designed Role-Playing Games and a Multi-Agent System to Empower a Local Decision-Making Process for Land Use Management: the SelfCormas Experiment in Senegal. Journal of Artificial Societies and Social Simulation 6.

Debaeke, P., Munier-Jolain, N., Bertrand, M., Guichard, L., Nolot, J.-M., Faloya, V., Saulas, P., 2009. Iterative design and evaluation of rule-based cropping systems: methodology and case studies. A review. Agronomy for Sustainable Development 29, 73-86.

Deheuvels, O., 2015. Rapport d'expertise. Caractérisation des systèmes de culture du cacaoyer de République Dominicaine dans les provinces de Duarte, Hato Mayor et El Seibo.

Deheuvels, O., Avelino, J., Somarriba, E., Malezieux, E., 2012. Vegetation structure and productivity in cocoa-based agroforestry systems in Talamanca, Costa Rica. Agric., Ecosyst. Environ. 149, 181-188.

Dogliotti, S., García, M.C., Peluffo, S., Dieste, J.P., Pedemonte, A.J., Bacigalupe, G.F., Scarlato, M., Alliaume, F., Alvarez, J., Chiappe, M., Rossing, W.A.H., 2014. Co-innovation of family farm systems: A systems approach to sustainable agriculture. Agricultural Systems 126, 76-86.

FAOSTAT, 2019. Statistics Database of the Food and Agriculture Organization of the United Nations. Rome, Italy. Retrieved June, 2019 from http://www.fao.org/faostat/en/.

Faure, G., Gasselin, P., Triomphe, B., Temple, L., Hocdé, H., 2009. Innover avec les acteurs du monde rural : la recherche-action en partenariat. Agricultures tropicales en poche.

Gidoin, C., Avelino, J., Deheuvels, O., Cilas, C., Bieng, M.A.N., 2014a. Shade Tree Spatial Structure and Pod Production Explain Frosty Pod Rot Intensity in Cacao Agroforests, Costa Rica. Phytopathology 104, 275-281.

Gidoin, C., Babin, R., Bagny Beilhe, L., Cilas, C., ten Hoopen, G.M., Bieng, M.A.N., 2014b. Tree Spatial Structure, Host Composition and Resource Availability Influence Mirid Density or Black Pod Prevalence in Cacao Agroforests in Cameroon. PLoS One 9, e109405.

Graves, A.R., Burgess, P.J., Liagre, F., Terreaux, J.P., Borrel, T., Dupraz, C., Palma, J., Herzog, F., 2011. Farm-SAFE: the process of developing a plot- and farm-scale model of arable, forestry, and silvoarable economics. Agrofor. Syst. 81, 93-108.

Hazard, L., Steyaert, P., Martin, G., Couix, N., Navas, M.-L., Duru, M., Lauvie, A., Labatut, J., 2017. Mutual learning between researchers and farmers during implementation of scientific principles for sustainable development: the case of biodiversity-based agriculture. Sustainability Science Online, 14 p.

Husson, O., Tran Quoc, H., Boulakia, S., Chabanne, A., Tivet, F., Bouzinac, S., Lienhard, P., Michellon, R., Chabierski, S., Boyer, J., Enjalric, F., Rakotondramanana, Moussa, N., Jullien, F., Balarabe, O., Rattanatray, B., Castella, J.-C., Charpentier, H., Séguy, L., 2015. Co-designing innovative cropping systems that match biophysical and socio-economic diversity: The DATE approach to Conservation Agriculture in Madagascar, Lao PDR and Cambodia. Renewable Agriculture and Food Systems 31, 452-470.

Jagoret, P., Kwesseu, J., Messie, C., Michel-Dounias, I., Malézieux, E., 2014. Farmers' assessment of the use value of agrobiodiversity in complex cocoa agroforestry systems in central Cameroon. Agrofor. Syst. 88, 983-1000.

Jagoret, P., Ngnogue, H., Malézieux, E., Isabelle, M., 2018a. Trajectories of cocoa agroforests and their drivers over time: Lessons from the Cameroonian experience. Eur. J. Agron. 101.

Jagoret, P., Snoeck, D., Bouambi, E., Ngnogue, H.T., Nyassé, S., Saj, S., 2018b. Rehabilitation practices that shape cocoa agroforestry systems in Central Cameroon: key management strategies for long-term exploitation. Agrofor. Syst. 92, 1185-1199.

Keating, B.A., Carberry, P.S., Hammer, G.L., Probert, M.E., Robertson, M.J., Holzworth, D., Huth, N.I., Hargreaves, J.N.G., Meinke, H., Hochman, Z., McLean, G., Verburg, K., Snow, V., Dimes, J.P., Silburn, M., Wang, E., Brown, S., Bristow, K.L., Asseng, S., Chapman, S., McCown, R.L., Freebairn, D.M., Smith, C.J., 2003. An overview of APSIM, a model designed for farming systems simulation. European Journal of Agronomy 18, 267-288.

Lamanda, N., Roux, S., Delmotte, S., Merot, A., Rapidel, B., Adam, M., Wery, J., 2012. A protocol for the conceptualisation of an agro-ecosystem to guide data acquisition and analysis and expert knowledge integration. European Journal of Agronomy 38, 104-116.

Le Bellec, F., Rajaud, A., Ozier-Lafontaine, H., Bockstaller, C., Malezieux, E., 2011. Evidence for farmers' active involvement in co-designing citrus cropping systems using an improved participatory method. Agronomy for Sustainable Development 32, 703-714.

Malézieux, E., 2011. Designing cropping systems from nature. Agronomy for Sustainable Development 32, 15-29.

Malézieux, E., Crozat, Y., Dupraz, C., Laurans, M., Makowski, D., Ozier-Lafontaine, H., Rapidel, B., Tourdonnet, S., Valantin-Morison, M., 2009. Mixing plant species in cropping systems: concepts, tools and models. A review. Agronomy for Sustainable Development 29, 43-62.

Meylan, L., Merot, A., Gary, C., Rapidel, B., 2013. Combining a typology and a conceptual model of cropping system to explore the diversity of relationships between ecosystem services: The case of erosion control in coffee-based agroforestry systems in Costa Rica. Agric. Syst. 118, 52-64.

Meynard, J.-M., Dedieu, B., Bos, A.P., 2012. Re-design and co-design of farming systems. An overview of methods and practices. In: Darnhofer, I., Gibbon, D., Dedieu, B. (Eds.), Farming Systems Research into the 21st Century: The New Dynamic. Springer Netherlands, Dordrecht, pp. 405-429.

Meynard, J.-M., Jeuffroy, M.-H., Le Bail, M., Lefèvre, A., Magrini, M.-B., Michon, C., 2017. Designing coupled innovations for the sustainability transition of agrifood systems. Agricultural Systems 157, 330-339.

Ministerio de Agricultura, 2017. Datos de transparencia. http://agricultura.gob.do/transparencia/index.php/estadisticas/estadisticas-agropecuarias/category/981-precios-del-productor.

Ministerio de Medio Ambiente y Recursos Naturales, 2014. Estudio de uso y cobertura del suelo, 2012. Informe metodológico y resultados. Santo Domingo, Republica Dominicana, Dirección de Información Ambiental y de Recursos Naturales, MARENA. 56 p.

Navarrete, M., Brives, H., Catalogna, M., Gouttenoire, L., Heinisch, C., Lamine, C., OLLION, E., Simon, S., 2018. Farmers' involvement in collective experimental designs in a French region, Rhône-Alpes. How do they contribute to farmers' learning and facilitate the agroecological transition? , 13th European IFSA Symposium (IFSA 2018), La Canée (Crete), Greece.

Niether, W., Schneidewind, U., Armengot, L., Adamtey, N., Schneider, M., Gerold, G., 2017. Spatial-temporal soil moisture dynamics under different cocoa production systems. CATENA 158, 340-349.

Nijmeijer, A., Lauri, P.-E., Harmand, J.-M., Freschet, G.T., Essobo Nieboukaho, J.-D., Fogang, P.K., Enock, S., Saj, S., 2019. Long-term dynamics of cocoa agroforestry systems established on lands previously occupied by savannah or forests. Agric., Ecosyst. Environ. 275, 100-111.

Notaro, M., Gary, C., Deheuvels, O., 2020. Plant diversity and density in cocoa-based agroforestry systems: how farmers’ income is affected in the Dominican Republic. Agroforestry Systems.

ONE, 2016. Boletin de estadisticas oficiales de pobreza monetaria. Oficina Nacional de Estadisticas, p. 20p.

Pelzer, E., Fortino, G., Bockstaller, C., Angevin, F., Lamine, C., Moonen, C., Vasileiadis, V., Guérin, D., Guichard, L., Reau, R., Messéan, A., 2012. Assessing innovative cropping systems with DEXiPM, a qualitative multi-criteria assessment tool derived from DEXi. Ecological Indicators 18, 171-182.

Rapidel, B., Ripoche, A., Allinne, C., Metay, A., Deheuvels, O., Lamanda, N., Blazy, J.-M., Valdés-Gómez, H., Gary, C., 2015. Analysis of ecosystem services trade-offs to design agroecosystems with perennial crops. Agron. Sustainable Dev. 35, 1373-1390.

Rapidel, B., Traoré, B.S., Sissoko, F., Lançon, J., Wery, J., 2009. Experiment-based prototyping to design and assess cotton management systems in West Africa. Agronomy for Sustainable Development 29, 545-556.

Ravier, C., Prost, L., Jeuffroy, M.-H., Wezel, A., Paravano, L., Reau, R., 2015. Multi-criteria and multi-stakeholder assessment of cropping systems for a result-oriented water quality preservation action programme. Land Use Policy 42, 131-140.

Reau, R., Doré, T., 2008. Systèmes de culture innovants et durables : quelles méthodes pour les mettre au point et les évaluer? Educagri Editions.

Redpath, S.M., Keane, A., Andren, H., Baynham-Herd, Z., Bunnefeld, N., Duthie, A.B., Frank, J., Garcia, C.A., Mansson, J., Nilsson, L., Pollard, C.R.J., Rakotonarivo, O.S., Salk, C.F., Travers, H., 2018. Games as Tools to Address Conservation Conflicts. Trends Ecol Evol 33, 415-426.

Rigal, C., Vaast, P., Xu, J., 2018. Using farmers' local knowledge of tree provision of ecosystem services to strengthen the emergence of coffee-agroforestry landscapes in southwest China. PloS One 13, e0204046.

Sadok, W., Angevin, F., Bergez, J.-É., Bockstaller, C., Colomb, B., Guichard, L., Reau, R., Doré, T., 2008. Ex ante assessment of the sustainability of alternative cropping systems: implications for using multi-criteria decision-aid methods. A review. Agronomy for Sustainable Development 28, 163-174.

Sadok, W., Angevin, F., Bergez, J.-E., Bockstaller, C., Colomb, B., Guichard, L., Reau, R., Messéan, A., Doré, T., 2009. MASC, a qualitative multi-attribute decision model for ex ante assessment of the sustainability of cropping systems. Agronomy for Sustainable Development 29, 447-461.

Salazar-Díaz, R., Tixier, P., 2019. Effect of plant diversity on income generated by agroforestry systems in Talamanca, Costa Rica. Agrofor. Syst. 93, 571-580.

Salembier, C., Segrestin, B., Berthet, E., Weil, B., Meynard, J.-M., 2018. Genealogy of design reasoning in agronomy: Lessons for supporting the design of agricultural systems. Agric. Syst. 164, 277-290.

Sanial, E., 2018. L'appropriation de l'arbre, un nouveau front pour la cacaoculture ivoirienne ? Contraintes techniques, environnementales et foncières. Cah. Agric. 27.

Schroth, G., Mota, M., 2014. Agroforestry: Complex Multistrata Agriculture. pp. 195-207.

Sheil, D., Rajindra, b., Puri, K., Langap, R., Nyarit, L., Jalan, L., Mutai, L., Solok, G., 2004. Exploring biological diversity, environment and local people's perspectives in forest landscapes Methods for a multidisciplinary landscape assessment. CIFOR, 106p.

Simon, S., Lesueur-Jannoyer, M., Plénet, D., Lauri, P.-É., Le Bellec, F., 2017. Methodology to design agroecological orchards: Learnings from on-station and on-farm experiences. European Journal of Agronomy 82, 320-330.

Speelman, E.N., García-Barrios, L.E., Groot, J.C.J., Tittonell, P., 2014. Gaming for smallholder participation in the design of more sustainable agricultural landscapes. Agric. Syst. 126, 62-75.

Turnbull, C.J., Hadley, P., 2017. International Cocoa Germplasm Database (ICGD). [Online Database]. CRA Ltd./ICE Futures Europe/University of Reading, UK. Available: http://www.icgd.reading.ac.uk (29th July, 2019).

Vereijken, 1997. A methodical way of prototyping integrated and ecological arable farming systems in interaction with pilot farms. European Journal of Agronomy 7, 235 - 250.

Voinov, A., Bousquet, F., 2010. Modelling with stakeholders. Environmental Modelling & Software 25, 1268-1281.