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Abstract

In the cotton-production zone of Burkina Faso, poor soil fertility and limited access to appropriate fertilizers call for alternative approaches to sustain productivity, such as the introduction of more legumes into the agroecosystem. Legumes have nearly disappeared from local cropping systems under the pressure of the cotton monocropping model. To develop new legume-based cropping systems using a bottom-up approach, this study was based on local farmers' agroecological innovations. In a first step, called on-farm innovation tracking, five innovative legume-based cropping systems were identified and characterized on farms located in the study area through interviews with "innovative farmers" who had designed and implemented these cropping systems: (i) Sorghum and legume (cowpea, soybean or peanut) intercropping in rotation with maize or cotton; (ii) Soybean as a cash crop in rotation with maize or cotton; (iii) Red cowpea intra-annual succession with a biomass crop; (iv) Mucuna in rotation with maize; and (v) Pigeon pea in rotation with maize. In a second step, these five "innovative cropping systems" (ICSs) were implemented in "participatory prototyping trials" (PPTs) in two communities located in the study area were they were evaluated during field days by local farmers ("field-day farmers") having no previous experience with ICSs. By comparing evaluations made by innovative farmers with those of field-day farmers, it was shown that (i) locally implemented ICSs adapted to local drivers of change are of great interest to other farmers, and (ii) the study's two-step participatory approach is an original and relevant way to co-design and introduce innovations.

1. Introduction

Soil depletion and reduced productivity are increasing issues faced by farmers in Sub-Saharan Africa (Giller et al., 2011; Ripoche et al., 2015) where chemical fertilizers and biomass return to the soil are insufficient to compensate for nutrient exports (Grillot et al., 2018; Van Vugt et al., 2018). In specialized production areas like the cotton *(Gossypium hirsutum)* production zone of West Africa (Giller, 2001; Ripoche et al., 2015), where land pressure is high (Jahel et al., 2015) and crop diversity is low (mainly maize-cotton rotation, Coulibaly et al., 2012), soil fertility maintenance is a huge challenge.

Poor soil fertility and limited access to fertilizers call for alternative approaches to farming, particularly, incorporating more legumes into the agroecosystem. Legumes provide important ecological services (Crews and Peoples, 2004), such as improved soil fertility through nitrogen fixation (Kermah et al., 2018; Giller, 2001), and reduced pest and disease pressure when intercropped or rotated with a non-legume (Gaba et al., 2015). These services result in improved soil health and increased crop productivity (Franke et al., 2018). Furthermore, grain legumes are a good source of protein and essential amino acids, thereby contributing to food and nutrition security (de Jager et al., 2019; Kerr et al., 2007). Legumes can also improve the short-term profitability of the cropping system as the grain often has a high selling price (Muoni et al., 2019).

Many projects have tried to incorporate legumes into cropping systems by improving local species management (Ronner et al., 2017; Falconnier et al., 2017), introducing new species, or transferring technologies such as rhizobium inoculation (Wolde-meskel et al., 2018; Rurangwa et al., 2018). However, technological change is difficult for poor farmers who are more risk-averse (Nederlof and Dangbégnon, 2007), especially those living where governments and value-chain stakeholders fail to create an environment favorable to change (Davies et al., 2017). In Burkina Faso's cotton-production zone, the cotton value chain places economic pressure on farmers to monocrop (Bazie et al., 2020), thereby limiting legume integration and innovative cropping systems (Audouin et al., 2018). In such sociotechnical systems (Geels and Schot, 2007; Meynard et al., 2017), it is difficult for scientists to scale-out otherwise appropriate innovations, especially agroecological innovations.

Previous studies have attempted to address these challenges by designing innovative solutions with farmers (Vall et al., 2016). Instead of being considered adopters of technology, farmers in this participatory approach are joint drivers of agricultural innovation within the context of their environment (Salembier et al., 2018; Schut et al., 2018). They actively participate in the innovation system (Dolinska and d'Aquino, 2016) by sharing their knowledge with local stakeholders, researchers, and extension agents, to co-design innovative practices or cropping systems (Meynard et al., 2012, Verret et al., 2020). Farmers who help develop these innovative solutions may be the catalysts of change necessary to drive wide-spread adoption within the community, as was shown by Pant and Hambly Odame, 2009 using the theory of positive deviance.

One promising participatory approach has been the use of innovation platforms (Dabire et al., 2017; Davies et al., 2017). Innovation platforms aim to stimulate the problem-solving capacity of farmers and other stakeholders. During platform meetings, actors identify and discuss ways to alleviate constraints that prevent innovation adoption. Past studies show this approach is more successful than simply transferring innovations designed by public or private research and development (R&D) to farming communities (Davies et al., 2017). However, innovation platforms can be costly and time-consuming and are rarely sustainable in the absence of a resource-rich local development project (Dabire et al., 2017). When development projects end, the constraints they helped minimize often creep back into the system, compromising the integrity of innovative systems.

To avoid this issue, and ensure innovations are sustained, this study sought out farmer innovations already in place (Salembier et al., 2016; Verret et al., 2020). It was hypothesized that if local farmers' innovations have enabled them to address their constraints and capitalize on opportunities (Waters-Bayer and Bayer, 2009), then these innovations can likely overcome other local farmers' constraints.

The study objectives were to (i) characterize innovative agroecological legume-based cropping systems designed by local farmers and (ii) assess the potential interest other area farmers had in these innovative systems.

To do this, an original two-step approach was implemented. It started by tracking on-farm innovations to identify and describe innovative cropping systems (ICSs) being implemented by local farmers (Salembier et al., 2016; Blanchard et al., 2017). The aim was to understand the link between innovative farmers' production practices, and the rationale behind them, to determine the criteria farmers used to evaluate their production. Then, participatory prototyping trials (PPTs) containing ICSs were set up in two communities, and local farmers were invited to view and discuss the benefits and constraints of the different systems in a collective participatory evaluation process. The researchers then worked to determine whether, and to what extent, farmers would be interested in ICSs. These two-complementary steps have been combined into a new approach to enhance a co-design process of innovative legume-based cropping systems

2. Materials and Methods

2.1 Context: Studying innovations in the cotton-production area of Burkina Faso

The study area of Tuy Province (Figure 1) is characterized by a Sudano-Sahelian climate, with a unimodal rainy season lasting from June to October. Average rainfall ranges between 850 and 950 mm per year, with strong inter-annual variability in the amount, duration, and distribution. With ongoing climate change, the rainy season is often starting later, with rains being less frequent and more intense (Ibrahim et al., 2014), thereby, exacerbating erosion and soil depletion. Rains are also becoming erratic and unreliable (Ibrahim et al., 2014), making it difficult for farmers to decide when to sow (Vall et al., 2008).

The vast majority of farmers in Tuy Province are smallholders. Farming systems are primarily producing cotton (Coulibaly et al., 2012). In 2018, out of 299 farms randomly selected in Tuy Province, cotton was grown on 40% of the cropped area, maize (*Zea mays*) on 30%, sorghum (*Sorghum bicolor*) on 14%, and legumes (peanut (*Arachis hypogaea*), soybean (*Glycine max*), cowpea (*Vigna unguiculata)*, Bambara bean (*Vigna subterranean*)) made up 8% of the cropped area (D. Gautier, CIRAD, unpublished data). Peanut and cowpea are the main legumes cropped, but in very limited areas and quantities compared with other regions of Burkina Faso (Dabat et al., 2012).

The cotton-production zone relies on annual rotations of two to three crops, animal traction, fertilizers, and herbicides (Bazie et al., 2020). The main access to fertilizer is through the *Société Burkinabè des Fibres Textiles* (SOFITEX). This company contracts farmers to produce cotton, then purchases cotton directly, and in exchange, provides seed and fertilizer in the form of campaign credit and technical support to improve production (Guenot and Huchet-Bourdon, 2014). The credit is reimbursed with cotton production.

Unlike pesticides, chemical fertilizers are not easily obtained apart from SOFITEX with priority on cotton production (Porgo et al., 2018). Consequently, farmers who do not crop cotton, find it difficult to obtain mineral fertilizers. Furthermore, to obtain credit, farmers need to be part of a shared liability group (Gray et al., 2018), and such groups are reluctant to include poor and risky farmers.

Maize cropping has also increased in the region thanks to its good response to fertilizers, increased home consumption, and a market for its grain. Maize follows the same monocrop intensification pattern as cotton (Guenot and Huchet-Bourdon, 2014), further marginalizing legume crops.

In the communities surveyed, livestock farming is mostly practiced by sedentary Fulani herders. Grazing is the rule on non-irrigated land, which makes up the majority of land in the region. After the cotton and cereals have been harvested, cattle and small ruminants are released and graze crop residues and/or crops left in the field throughout the dry season. The animals graze freely until the beginning of the rainy season when farmers start plowing. Farmers do not have enough animals to add manure to all of their fields despite the increasing number of cattle they own (Vall et al., 2017; Zoma-Traoré et al., 2020).

2.2 On-farm innovation tracking

On-farm innovation tracking was conducted using a methodology adapted from Salembier et al., 2016, which includes (i) characterization of the common practices in the study area, (ii) identification of farmers who implement innovative cropping systems (ICSs) significantly different from common practices, and (iii) characterization of ICSs and identification of the farmers' rationale (evaluation criteria) for implementing ICSs. In the current study, farmers' evaluation criteria were discussed and analyzed in greater detail than previous studies using on-farm innovation tracking (Salembier et al., 2016; Blanchard et al., 2017).

Innovation tracking in the current study was conducted in the seven communes of Tuy Province (Figure 1), which is within the cotton-production zone. In each commune, local agricultural extension agents were asked to identify farmers who grew more legumes than most area farmers. They identified 70 farmers, and the research team interviewed the farmers about their legume cropping systems. Cropping systems selected for consideration in further studies were (i) atypical, i.e., different from legume production in the area (cowpea, soybean, or peanut grown alone on small areas for household consumption (Andrieu et al., 2015; Dugué et al., 2014)) (ii) implemented or improved regularly for several years, and (iii) following agroecological principles (for instance cropping systems with increased used of pesticide or chemical fertilizer compared to common practices were not considered).

From the 70 farmers interviewed, 22 were chosen as "innovative farmers" and underwent a further, in-depth interview with the research team about their innovative practices. The in-depth interviews focused on (i) ICS management: the farmer was asked to describe his practices from land selection to selling or consumption; (ii) the rationale behind the ICS: the farmer was asked the reasons why he chose his practices; and (iii) ICS evolution over time: the farmer was asked about the origin of his ICS and its evolution during the last years. Various innovative systems, identified from these interviews, were combined into five promising types of ICS (ICS1 to ICS5 in Table 1), which were demonstrated in participatory prototyping trials (PPTs). Innovative farmers were also asked about their overall farming system, including what other crops they produced and on what area, and how many cattle they have.

The reasons given by innovative farmers for their farming choices were used to describe the innovative farmers' evaluation criteria (Tables 2a-2e). For the analysis, a criterion that was considered a constraint or an obstacle to adopting the ICS was classified as "weakness" and a criterion that was considered an opportunity or a motivation to adopting the ICS was classified as "strength" (Table 2 color key). To rate the importance of each criterion for each type of ICS, the number of in-depth interviews in which the criterion was mentioned was counted (summarized in Table 2 color key as ”fewer than” or “more than” 50% of the interviews). A criterion considered a weakness by some and strength by others, was rated as “no consensus” (Table 2 color key). Literature on the origins and evolution of the ICSs’ was used, along with farmers’ interview responses during innovation tracking, to better understand each type of ICSs’ novelty and potential benefits.

2.3 Participatory workshops and Participatory prototyping trials (PPTS) in two communities

Two communities within two different communes of Tuy Province were selected for further participatory activities: Boni (in the Hounde commune, 115 km by road from the main city in the region, Bobo Dioulasso) and Founzan (in the Founzan commune, 145 km by road from Bobo Dioulasso) (Figure 1). These communities were selected primarily because literature detailing their farming systems was available, and connections with community leaders and farmers were established (Coulibaly et al., 2011). Both communities are part of the same agroecosystem in the cotton-production zone. However, Boni is located close to the cotton processing plant, so cotton is very important for farmers, while Founzan is close to a dam, so the farmers produce a wider range of products, including fish and irrigated vegetables.

In each community, a contact person was tasked with inviting between 20 and 30 farmers representing a wide range of local farming systems and demographics (low and high resource endowed farmers; cotton farmers, herders and farmers-herders; young and old; male and female) to participatory workshops (Reau et al., 2012) (Table 3). The workshops were used to present the results of on-farm innovation tracking with farmer participants, open up a discussion on the ICSs, introduce the participatory approach of the study, and encourage farmer involvement. One participatory workshop was conducted per community in May just before the 2017 growing season. Farmer participants were then invited to attend field days at the participatory prototyping trial (PPT) in their community.

One PPT was set up in each community. The PPTs were set up to generate discussion among farmers by enabling them to see and compare the different cropping systems, including ICSs, within the trial plots. The two trial sites were selected based on ease of access by farmers attending PPT field days, and both held the same field location (belonging to a local farmer) over the two growing seasons (2017 and 2018). The layout of the PPTs was the same for both locations and organized to display a diversity of cropping systems like the matrix in Husson et al., 2016. The layout was not designed for statistical analysis of crop performance, so treatment replications were not included.

Sixteen 400 m^2 plots were set up in each PPT (Table 4). Plots contained either one of the five ICSs, or a sole crop (peanut, cowpea, soybean, sorghum, maize, or cotton), with some plots split into two parts (Table 4). The research team designed and managed the ICSs based on information collected during on-farm innovation tracking, comments made by farmers during participatory workshops, and appropriate agronomic practices. Fertilizers were applied to crops at rates typical for the region (150 kg/ha of NPK 14-23-14 and 50 kg/ha of urea 46% on cotton and maize). Plowing and sowing were done five days later in Founzan than in Boni because cattle grazing was controlled later in Founzan.

The first cropping season of the study (2017) is referred to as PPT1, and the second one (2018), as PPT2. In PPT1, six of the 16 plots were sole maize set up on parameter plots to verify soil homogeneity. In PPT1, farmers could easily compare the intercropped species in the ICS plots, with the same species cropped alone on adjacent plots during field days. All the plots had the same previous crop. After year one, the research team provided (for free) legume seeds for farmers to try whatever ICS they wanted on their farm. There was also an evaluation workshop in each community between the two seasons, where the research team presented yields from PPT1 to field-day farmers and held discussions on what improvements could be made for PPT2 in 2018.

Changes to PPT2 included: (i) new arrangements for intercropping systems to allow ridging by animal traction; (ii) addition of an earlier variety of pigeon pea; (iii) another ICS (sorghum – red cowpea intercrop) at the request of field-day farmers; and (iv) another check (cotton after maize which is the common rotation in the area) (Table 4). PPT2 was organized to enable field-day farmers to see the carry-over effect of unfertilized legumes (Mucuna, pigeon pea, 2 successive cowpea), unfertilized sorghum, and fertilized cotton and maize from PPT1 on the cropping systems in PPT2, and make comparisons.

The research team used field days as a multi-step participatory approach to obtaining farmers' evaluations of ICSs. Farmers who attended their community's participatory workshop were invited to visit and comment on the cropping systems demonstrated in PPTs. Some of these farmers had shared what they learned at the participatory workshop with friends and family, leading more farmers to attended the first field day. After the first field day, only farmers who had participated in either a participatory workshop or the first field day were included in the study. Innovative farmers interviewed during the tracking phase did not belong to either of the two communities (except for one farmer from Founzan), so they were not invited to avoid disturbing the local dynamic between farmers from the same community.

Three field days were organized in each community: two for PPT1 (one after germination and one just before the main harvest), and one for PPT2 (just before the main harvest) (Table 3). The first field days (Figure 2) (labeled Field-day Intro. in Table 3) occurred at PPT1 in August when plants were young and were used as a presentation of the trial. Each plot was described, and farmers asked questions, but did not evaluate the various cropping systems. Just before harvest, during field evaluation days (labeled Field-day Eval. in Table 3) at PPT1 and PPT2, the farmers were divided into groups of five to 10 to facilitate discussion, and to give each farmer time to speak. There were three groups per community, making a total of six groups per PPT. Women had their own group to allow them to speak freely, while men were randomly mixed into the two other groups.

Field evaluation days started with an introduction explaining the purpose of the visit. Then, each ICS was examined plot by plot, starting with ICSs growing common local crops, assuming those would be easiest for farmers to evaluate. The activity leader asked the field-day farmers what they liked or disliked about the ICS they were looking at, and how they would improve it. Questions were purposely open-ended to avoid influencing responses, and farmers were incited to react to others' comments.

As the activity leader could not speak any local languages, the research technician translated from French to Dioula—the most widely spoken language in the area—and vice versa. He also assisted the activity leader in answering farmers' questions, giving a voice to every participant (including women and youth), reopening the discussion, or asking for clarification when needed; but always avoided giving his own opinion or evaluation. Farmer discussions were recorded with a voice recorder, and an assistant mastering Dioula was in charge of taking the minutes of farmers' exchanges—especially small spontaneous debates occurring between farmers aside.

The day after the visits, the activity recording and the minutes were discussed among the activity leader, technician, and assistant, and compiled. This material was used to describe the field-day farmers' evaluation criteria of the ICSs (Tables 2a-2e). The same method was used to analyze and rate the importance of the field-day farmers' criteria as was used for the innovative farmers' criteria (Table 2 color key): a criterion that was considered a constraint or an obstacle to adopting the ICS was classified as "weakness", and a criterion that was considered an opportunity or a motivation to adopt the ICS was classified as "strength". To rate the importance of each criterion, the number of groups that mentioned the criterion during discussions was counted (summarized in Table 2 color key as "fewer than" or "more than" 50% of the groups). A criterion considered a weakness by some farmers and strength by others was rated as "no consensus" (Table 2 color key). Evaluations between innovative and field-day farmers for each type of ICS were then compared. Contextual information given by farmers (i.g. climate, prices, value chain) was crosschecked with available literature (reports, diagnosis, scientific paper, etc.).

2.4 Surveys to characterize field day farmers

During the second year of the study (2018), 64 of the 74 farmers who had participated in at least one activity in 2017 were surveyed. Data from this survey were used to analyze the diversity among field-day farmers in regard to their farming systems and endowment. Two important characteristics of the farming systems (Vall et al., 2017) were used to compare field-day farmers, innovative farmers, and 299 randomly selected farmers of the Tuy Province, who were surveyed the same year for another project ("RELAX - Agropolis Fondation," n.d., unpublished data): (i) cropped area in 2017, and (ii) number of cattle owned by the household.

3. Results

3.1 ICSs characterized through the on-farm innovation tracking and innovative farmers' evaluations

During on-farm innovation tracking (brief interviews with 70 farmers identified as producing legumes, and in-depth interviews with 22 of those farmers identified as innovative), the evolution of local farm innovations was discussed, and five types of innovative cropping systems with legumes were identified and characterized (Table 1): (i) ICS1 Sorghum and legume (red or white cowpea, soybean, or peanut) intercropping in rotation with maize or cotton, for seven farmers; (ii) ICS2 sole soybean as cash crop in rotation with cotton or maize, for five farmers; (iii) ICS3 red cowpea in intra-annual succession with biomass crop, for five farmers; (iv) ICS4 Mucuna in rotation with maize, by four herders; and (v) ICS5 pigeon pea in rotation with maize, by one farmer. ICS belonging to the same type rely on the same agronomic rationale, even if they do not combine exactly the same management practices.

During in-depth interviews with the 22 innovative farmers, the researchers identified criteria the farmers used when developing and evaluating their innovative systems (Tables 2a-2e, Criteria column). The evaluation criteria include: (i) Production/Yield - evaluation of crop performance and yield; (ii) Soil fertility – evaluation of the legumes' effect on soil productivity and Striga (*Striga hemonthica*); (iii) Flexibility/Risk management – evaluation of the ICS's adaptability and resilience to unexpected circumstances without reducing productivity; (iv) Post-production strategy – evaluation of strengths and weaknesses associated with the use of the harvested products; and (v) Labor management – evaluation of workload and labor.

The following paragraphs present the evolution and characteristics of each of the five ICSs and the main results of the innovative farmers' evaluation of these systems (Tables 2a-2e, column 2) using the five evaluation criteria mentioned above. It should be noted that these farmers' evaluations are based on their understanding and implementation of the systems within their particular context.

ICS1 (Table 2a) is a mixed-cropping system of sorghum with a legume (cowpea, peanut, or soybean), dibbled on the same line, and rotated with cotton or maize. According to some farmers interviewed during on-farm tracking, a mixed system of sorghum and cowpea, in which the seeds of each were mixed for sowing, used to be a common practice. This system has all but disappeared with the introduction of mechanical weeding and ridging with animal traction, which makes this traditional system difficult to manage. In ICS1, instead of mixing seeds and planting everything together, innovative farmers sow the two crops between each other on the same ridge at different times. Sorghum is generally sown first, with the legume sown between the newly emerged sorghum. Innovative farmers said that this organization of sowing made weeding (using animal traction based on the legume cycle) easier (Table 2a, column 1, row 5), although sowing involved more time and effort compared to the traditional system. Nevertheless, even with this weeding being easier than the traditional system, sowing, and harvesting were still considered a weakness of this ICS compared to sole crops (Table 2a, column 1, row 5). The main strength of the system, as indicated by more than 50% of farmers, was having a gap between the harvests, one of which coinciding with the lean season (Table 2a, column 1, row 4): If the legume is cowpea or peanut, the farmer will be able to harvest it just before ridging. Furthermore, the two harvests translated into increased grain productivity per hectare compared to either sole crop (i.e. Land Equivalent Ratio >1) (Table 2a, column 1, row 1).

ICS2 (Table 2b) is a rotation of sole soybean with sole maize or cotton, all three being cash crops on a large area (at least 1ha). According to interview responses from the 70 farmers, sole soybean is mostly grown as a staple crop on very small plots (between 0.1 and 0.25 ha) by women for processing into products (condiments made from fermented pulses called “soumbala”) consumed by the household. Soybean in ICS2 is much more input-intensive, uses larger areas, and is intended for the emerging market linked to the development of a soybean oil-processing unit in Ouagadougou. According to innovative farmers, the main strength of the system is the sale of grain to private buyers (Table 2b, column 1, row 4), which more than offsets the labor costs associated with harvesting large areas quickly (to avoid pods opening in the field) at a time that coincides with the lean season. (Table 2b, column 1, rows 3 and 5). Farmers also highlighted that growing soybean helps improve soil fertility, and reduces populations of Striga-a plant parasite of cereals (Table 2b, column 1, row 2).

ICS3 (Table 2c) is sole red cowpea followed the same season by a crop that can be valued for its biomass. During interviews, farmers said that red cowpea is often the first crop sown because the pods can be harvested during the rainy season, as they are less sensitive to fungi than other cowpea varieties. It was also explained that some farmers used to follow red cowpea with sesame (*Sesamum indicum)*—a crop quite resistant to drought, but with no significant biomass value. However, with climate change, farmers complain that the rainy season is getting shorter, and it is increasingly difficult to harvest the second crop. Innovative farmers reduced this risk by sowing a second crop that can be valued for its biomass, such as white cowpea or maize (stalks) for fodder, or hibiscus (leaves) for soup. Being able to manage risk in this way was seen as a strength by more than 50% of innovative farmers (Table 2c, column 1, row 3). Perhaps a more important strength of ICS3 is that it allows for two harvests, providing greater household (and livestock) food security (Table 2c, column 1, rows 1 and 4). However, two harvests mean extra labor. Fortunately, this extra work does not overlap with the labor requirements of cash crops such as cotton or maize on other fields (many innovative farmers are also producing cash crops), so it was not considered a weakness (Table 2c, column 1, row 5). The carry-over effect of the legume on soil fertility and biomass crop performance was also highly valued by farmers (Table 2c, column 1, row 2).

ICS4 (Table 2d) is sole Mucuna for fodder production followed by maize, and is farmed by Fulani herders. Previous projects aimed to expand Mucuna cultivation within the study area to feed cattle (Coulibaly et al., 2012b). Some of the 70 interviewed farmers were part of that project and explained that they did not have the necessary equipment to make or store bales of fodder from Mucuna biomass. They considered the need to feed their family before the need to feed their cattle, and as they could not use Mucuna beans for human consumption, they did not grow Mucuna. Only a few herders with access to balling equipment and covered storage facilities adopted Mucuna. These farmers did not mention labor-management issues, unlike the other innovative farmers who considered the need for equipment and facilities as a weakness (“no consensus” Table 2d, column 1, row 5). Innovative Mucuna farmers used the crop to feed ruminants kept near the house: mainly dairy cows or sick cattle during the dry season, a practice appreciated by more than 50% of the farmers (Table 2d, column 1, rows 1, 3, and 4). They also appreciated the fact that Mucuna is a good crop to grow before maize for its positive carry-over effect on soil fertility (Table 2d, column 1, row 2). For these farmers, the hardest part is producing seed (Table 2d, column 1, row 3).

ICS5 (Table 2e) sole pigeon pea grown on a small area followed by maize. According to several farmers interviewed, pigeon pea has been promoted in the past by extension agents and NGOs for fodder production. However, farmers involved in such projects said it has not been adopted because the cattle did not eat the plant biomass, and seed was difficult to produce due to the length of the crop cycle. Pigeon pea was the only ICS whose production was not considered a strength by innovative farmers (Table 2e, column 1, row 1). The one innovative farmer who crops pigeon pea sows it on poor soils in a very small area. The seeds are difficult to find in Burkina Faso, so the farmer bought them in Ivory Coast. The farmer’s main incentive was diversifying the household’s diet (Table 2e, column 1, row 4), even though grain yield is quite low (Table 2e, column 1, row 1). He also mentioned the crop’s resistance to drought (Table 2e, column 1, row 3), and role in managing weeds and improving soil fertility (Table 2e column 1 row 2) as strengths of the system. The main difficulty expressed by the farmer was the risk of cattle damaging the pigeon pea before it flowers when free grazing starts (Table 2e, column 1, row 3).

3.2 Participatory Prototyping Trials and Field Days.

When compiling the evaluation results from field-day farmers (Tables 2a-2e, columns 2 and 3), it was determined that they used the same five general criteria (refer to paragraph 2 in Section 3.1) to evaluate the ICSs as innovative farmers. Contrary to the evaluation by innovative farmers, field-days farmers rated the productivity of ICS1 a weakness in PPT1, explaining that the total crop density was too high, especially in Boni where farmers are less familiar with intercropping practices. Farmers argued that there would be competition for light and soil nutrients, meaning there was a risk of individual sorghum and legume plants underperforming (Table 2a, column 2, row 1). However, many farmers strongly highlighted how the intercropped sorghum looked much better (more biomass and greener) than sole sorghum, suggesting the legume enhanced soil fertility (Table 2a, column 2, row 2). A few farmers suggested alternating crops between the rows instead of within the rows, even though it implies a lower density of sorghum. Therefore, in PPT2, sorghum-legume intercropping systems using either inter-row or within-line sowing were placed side by side, but the field-day farmers did not agree on which layout they preferred (Table 2a, column 3, row 1). According to fewer than 50% of the field-day-farmer groups, the soil should not be too fertile to prevent sorghum from overtaking the legume (Table 2a, column 2, row 3), but should be sufficiently fertile to make the sorghum strong enough to resist competition from the legume; especially if the legume was sown first (Table 2a, column 2, row 3). Both innovative farmers and field-day farmers agreed that intercropping makes it possible to separate the harvest periods and enhance household food security (Table 2a, row 4). Even though fewer than 50% of innovative farmers complained about labor (Table 2a, column 1, row 5), it was the main worry of most field-day farmers during PPT1 (Table 2a, column 2, row 5), especially the possibility of not being able to ridge with animal traction. In response to this concern, PPT2 was organized in a way that enabled ridging using animal traction. This reorganization resulted in some farmers assessing the ICS more positively in PPT2 (Table 2a, column 3, rows 1 and 3).

Concerning ICS2 (Table 2b), while innovative farmers intensified their soybean production to harvest enough grain to access the value chain, field-day farmers were not very confident about the market (Table 2b, column 2, row 5), but appreciated soybean for household consumption (Table 2b, column 3, row 5). A few groups appreciated the fact that sole soybean requires much less labor than intercropped soybean, especially because selective herbicides can be used (Table 2b, columns 2 and 3, row 5). Field-day farmers agreed with innovative farmers that, soybean is good for soil fertility and Striga management (Table 2b, row 2). Field-day farmers also talked about the fact that soybean needs to be harvested quickly (Table 2b, columns 2 and 3, row 3), but did not refer to this as a major obstacle, unlike the innovative farmers (Table 2b, column 1, row 5). For this ICS, the evaluations in the two communities were similar.

Concerning ICS3 (Table 2c), according the field-day farmers, the possibility of harvesting two crops in one field, including one that helps during the lean season, is the main strength of the intra-annual succession system (Table 2c, column 2, row 1). The choice of a second crop whose biomass can be exploited reduces the risk of losing the second crop if the rainy season ends early, and is another main strength of the ICS (Table 2c, columns 2 and 3, row 1). In PPT2, the field-day farmers did not emphasize this strength, as they were aware of the difficulty of sowing the first crop sufficiently early to be able to sow a second one, especially due to free grazing (Table 2c, column 3, row 3). The farmers in Founzan stressed this difficulty more than farmers in Boni, saying that this ICS could not succeed because of this problem. Unlike the innovative farmers (Table 2c, column1, row 3), the field-day farmers did not emphasize the benefits of red cowpea improving soil fertility for the second crop (Table 2c, column 2, row 2), and sometimes saw it as a difficulty for weed management (Table 2c, column 3, row 2). The field-day farmers also had more comments to make about the extra work required to grow two crops successively (Table 2c, columns 2 and 3, row 5).

Concerning ICS4 (Table 2d), both innovative and field-day farmers viewed Mucuna as an easy way to obtain large quantities of quality fodder while improving soil fertility (Table 2d, rows 1, 2, 3, and 4). The main difficulty is producing seed (Table 2d, row 3), especially in the opinion of the field-day farmers in Founzan, where some had tried the crop but stopped after losing the seeds. There was a notable knowledge gap between farmers in Founzan and Boni, where most had never seen the crop before. This resulted in greater variation in responses from field-day farmers, whereas innovative farmers' evaluations of this system were relatively consistent. The field-day farmers regretted that the grains are not fit for human consumption (Table 2d, column 2, row 4). In Founzan, however, one farmer said that the grain could be used to feed fowl, which triggered a positive reaction from the others (Table 2d, column 3, row 4). A concern expressed by some of the field-day farmers was the difficulty involved in properly drying, transporting, and storing it without the necessary equipment (Table 2d, columns 2 and 3, row 5).

Concerning ICS5 (Table 2e), none of the field-day farmers were familiar with pigeon pea, so they based their evaluation on what they could see, and on the agronomist's answers to their questions. As with innovative farmers, they also appreciated the fact that pigeon pea grows well on poor soils (Table 2e, row 3), and improves soil fertility (Table 2e, row 2), especially after seeing the carry-over effect on PPT2 by comparing the same maize cultivar after pigeon pea, Mucuna, cowpea, cotton, or another maize. The main difficulty is the length of the crop cycle resulting in low grain yields (Table 2e, column 2, row 1). Furthermore, farmers noted that even though there are benefits to it being drought resistant, the fact that its leaves stay green after the rains stop makes it at risk of being grazed before the grains reach maturity (Table 2e, row 3). Consequently, we introduced a cultivar with a shorter growth cycle in PPT2, which was assessed more positively (Table 2e, column 3, row 1).

3.3 Characteristics of Farmers and their participation and contribution

Herders are more represented among innovative farmers than among field-day farmers or the 299 farmers from the "RELAX - Agropolis Fondation," (n.d.) study (Figure 4). This can be explained by the fact that several legume-based innovations enable farmers to produce fodder, especially Mucuna or, to a lesser extent, intra-annual succession. In terms of farm area, only one innovative farmer among 22 had less than three hectares of cropped area, which is a much lower proportion than other farmer groups (Figure 3). Field-day farmers tend to crop larger areas than the 299 farmers sample (Figure 3). However, there is no obvious difference concerning the number of cattle owned by the household (Figure 4).

During the participatory workshops (Table 3), farmers provided feedback and ideas that helped the researcher decide the final design of ICSs. During the evaluation workshop (Table 3), farmers were particularly interested in ICS crop yields, which were shared by the researcher. Comments made by farmers about the ICSs were consistent with their comments during evaluation field days, no new information was obtained from these evaluation workshops.

Farmer attendance rate throughout the study was between 60% and 130% in Boni, and between 70% and 163% in Founzan (Table 3). The 130% attendance rate in Boni and 163% rate in Founzan occurred during the first field day (Field-day Intro.) as some farmers came without having been invited. Women were a minority in all activities representing only 12% (nine) of the 73 total participants, and did not speak much during the workshops. The women were particularly interested in the multipurpose characteristics of pigeon pea, which can be used as fodder for cattle and small ruminants, as well as for household consumption.

4. Discussion

4.1 Introducing innovative legume-based cropping systems

In the Tuy Province where legume farming is minimal (Coulibaly et al., 2012), on-farm innovation tracking was used to identify farmers growing atypical legume-based cropping systems. With the help of extension agents, the researchers identified 22 such innovative farmers out of 70 legume-producing farmers. This approach to identifying innovation differs from traditional approaches where researches rely heavily on farm typology information (Alvarez et al., 2018; Tittonell et al., 2020), and focus their attention on, and focus their attention on dominant systems (Bainville, 2017). In such classical approaches, potentially transformative innovations among atypical systems are often overlooked, and therefore, rarely studied (Doré et al., 1997). The current study focused on the innovations developed by innovative farmers to reveal and/or confirm solutions to local drivers of change. Pant and Hambly Odame (2009) also worked with innovative farmers, whom they identified as “positive deviants”. The literature describes positive deviants as individuals within a community whose atypical behaviors or actions address complex local challenges that their peers, with similar available resources, also face. In our study, innovative farmers may have larger farms and livestock than most farmers in the area, but they belong to the same sociotechnical system as field day farmers. Positive deviants are usually seen as performing particularly well (Bradley et al., 2009), hence the term “positive”. In this paper, the innovations studied met innovative farmers’ criteria while respecting agroecological principles, so the innovations themselves may be considered as “positive”. In this positive aspect, positive deviants and farmer’s innovations are what may inspire peers and catalyze change in the community. In the current study the PPTs, played the role of revealing innovations to initiate adoption by other farmers.

Although the five types of ICSs in this study were considered atypical for the area, components of each ICS are comparable with cropping systems existing in other regions of Africa. For example, sorghum intercropped with cowpea (Dabat et al., 2012) is common in the north of Burkina Faso (Zongo et al., 2016) and Mali (Falconnier et al., 2017). The climate being dryer there, it is easier to grow cowpea using less pesticide (Dabat et al., 2012). Soybean is grown as a cash crop in several West African countries (Odendo et al., 2011) with good technical knowledge. The system with cowpea in intra-annual succession is less common in the literature. Cowpea is usually cultivated as a sole crop, or intercropped with a cereal (Dabat et al., 2012). Cowpea has the advantage of a short cycle (60 to 70 days) but is quite sensitive to pest and disease (Bado et al., 2006). Only a hardy variety such as red cowpea can be used as an early sown crop that can be harvested when it is still raining. Pigeon pea is common in neighboring countries (Jalloh et al., 2012)—sometimes in intercropped systems, where the grains are part of the traditional diet (Kerr et al., 2007; Ene-Obong and Obizoba 1995). Mucuna is farmed primarily in East Africa where the leaves are used as fodder, and the grains are sometimes consumed by people after special treatment to eliminate their toxicity (Muoni et al., 2019b).

Although the ICSs introduced here are not completely innovative for Africa, the innovative farmers made specific adjustments, for instance in the selection of crop variety and its management, to adapt their ICSs to constraints and opportunities in their particular environmental and sociotechnical system. Some of the ICSs are more atypical than others. Pigeon pea (ICS5), for example, was found on only one farm, whereas the four other ICSs were found on four to seven farms in the study area.

4.2 Innovative farmers' evaluations of ICSs and links to local drivers of change

Analyzing and crossing innovative farmers' evaluation criteria with the local drivers of change described in the literature, suggest that the innovative cropping systems have been implemented and adapted in responseto the main drivers of change in the area. For example, farmers were interested in sorghum-legume intercropping (ICS1) to increase their productivity per hectare, which addresses the challenge of increasing land pressure in the cotton-production zone (Jahel et al., 2015). Soybean as a cash crop (ICS2) is grown by innovative farmers in response to the emergence of the soybean market, whose value chain is currently taking shape (Guilloux et al., 2018). In intra-annual successions (ICS3), the choice of a second crop that can be valued before its cycle is completed is a strategy to adapt to the shortening of the cropping season, and the uncertain rainfall pattern caused by climate change (Gérardeaux et al., 2015; Vall et al., 2008). Mucuna as a fodder crop (ICS4) is expanding with the intensification of livestock farming. Fodder crops are produced for dairy cows, traction bullocks, and sometimes for cattle fattening, and these activities are being developed by both Fulani herders and farmers (Vall et al., 2017; Zoma-Traoré et al., 2020). Finally, pigeon pea (ICS5), whose leaves begin to fall quite early in the cycle and form litter, may help for both restoring soil fertility and managing weeds (Hepperly et al., 1992). This decreases the need for a fallow to counteract soil fertility depletion in the context of increasing land pressure (Jahel et al., 2015). Innovative farmers are aware of soil fertility depletion, and they see the use of legumes as a way to improve productivity in the short term (carry-over effect, Striga management, etc.).

4.3 Comparison between evaluations made by innovative farmers and field-day farmers

Both innovative and field-day farmers mentioned the same general criteria (Criteria Column in Tables 2a-2e) when discussing how they evaluated an innovative system. Furthermore, the evaluations themselves revealed many similarities between both categories of farmers, supporting the study's hypothesis that many farmers in the study area have the same concerns or challenges: farmers, regardless of their innovative potential, make farming decisions using similar agronomic rationale, and are more likely to adopt innovations from other farmers who operate within the same sociotechnical system. However, to verify this hypothesis, it would be interesting to monitor field-day farmers' adoption of the ICSs.

The criteria that mattered most to both innovative and field-day farmers were concerned with short-term benefits, supporting evidence that farmers do not use the same indicators and criteria as agronomists (Toffolini et al., 2016). Agronomists highlight the quantitative performance of the systems, including yield, gross margin, and labor productivity (Sadok et al., 2008), while farmers are also sensitive to more qualitative, operational, or organizational aspects (Ronner et al., 2019). For instance, regarding harvest timing, short-cycle legumes harvested in August provide household food while waiting for the cereal harvest, even though yields of short-cycle legumes are often low. The distribution of the workload and system flexibility also mattered to farmers, as illustrated by the fact that the main challenge with soybean is that harvest cannot wait and happens at the same time as the maize harvest (Table 2b).

Resilience and flexibility are also important criteria for both innovative and field-day farmers, sometimes even more important than productivity, because they enable farmers to better adapt to drivers of change and risks (Milestad et al., 2012). For example, several field-day farmers emphasized that their interest in pigeon pea is its ability to grow on poor soils and its resistance to drought, despite its low productivity in actual conditions. Field-day farmers also appreciated the multi-purpose characteristics of the second crop in the red cowpea intra-annual succession (ICS3). Resilience and flexibility are rarely among the set of sustainability indicators established by researchers (Sadok et al., 2008), who focus more on the medium and long-term impacts of cropping systems (e.g. soil fertility, greenhouse gas emissions, water pollution).

The three sustainability dimensions that usually structure cropping system evaluation (Smith et al., 2017) appeared several times among the farmers' criteria: (i) "economic sustainability" appeared in the form of agricultural income and market access; (ii) "human wellbeing" was mentioned in connection with food security and workload; and (iii) "environmental sustainability" was taken into account through soil fertility. However, the farmers did not mention long-term criteria such as biodiversity, carbon sequestration, erosion, or soil biological activity and quality, which are frequently used by agronomists. They also did not mention social aspects like gender equity or information access.

There were also differences between the evaluations made by innovative and field-day farmers that revealed the concerns and possible obstacles to the adoption of the ICSs. Some of these obstacles depend on the producer and represent perceptions, beliefs, or knowledge gaps (Leclère et al., 2018). For example, farmers who do not grow intercrops tend to overestimate the risks of competition between species and lack knowledge of practices that avoid such competition. Other obstacles are more dependent on the sociotechnical system (Meynard et al., 2017). For instance, free grazing can hamper ICSs that require early sowing (e.g. in the intra-annual succession system – ICS3), or late harvesting (e.g., in the pigeon pea system – ICS5).

4.4 Use of ICSs and PPTs to introduce innovation

The ICSs designed by innovative farmers in the study area in response to local drivers of change will probably require fewer organizational changes when implemented by other local farmers, compared to breakthrough innovations designed by researchers at experimental stations (Geels and Schot, 2007; Duru et al., 2015). For instance, conservation agriculture (Scopel et al., 2013; Corbeels et al., 2014) may be efficient in improving both short- and long-term soil fertility, but often requires strong changes linked to the sociotechnical system (e.g. landscape management, supply chain) (Dabire et al., 2017). In the current study, the field-day farmers identified very few obstacles to the implementation of the ICSs. This is consistent with the fact than the ICSs are already implemented within the local sociotechnical system. Moreover, even though the field-day farmers did not have the opportunity to test the ICSs on their farms, they were able to imagine the ICSs in their context.

The PPTs enabled visual and hands-on comparisons of the ICSs at evaluation field-days, timed just before harvest, when differences in crop productivity are most evident. Moreover, focusing on local innovative systems, and demonstrating them under local conditions in terms of soil, climate, and land-use management, made it easier to trigger conversations between farmers by enabling them to use and gain situated knowledge (Navarrete et al., 2018). For instance, the PPT in Founzan was sown later than in Boni because cattle were left out to graze longer in Founzan. Therefore, the ICS was decontextualized in its relation to the farming system of the innovative farmers, but partially re-contextualized it in its relation to the community. While researchers consistently gained information from farmers during field days, evaluation workshops provided no new criteria or evaluations, suggesting the actual visualization of ICSs in the field was crucial to the initiation of fruitful discussions among farmers.

Due to the characteristics of PPTs, ICSs could not be evaluated taking into account all the farmers' local conditions and criteria (Amudavi et al., 2009). This may have resulted in evaluation biases (Ashby, 1987). For instance, the ICS with soybean as a cash crop (ICS2) could not be properly assessed by field-day farmers in a PPT plot, as one of its main issues is the difficulty in harvesting rapidly large areas. Similarly, it was not possible to demonstrate the storage issue associated with the Mucuna system (ICS4), or the food security benefit of the pigeon pea system (ICS5). Future studies utilizing the PPT approach should consider ways to illustrate system characteristics that are not revealed through small-trial plots.

PPTs made it possible to involve farmers without implementing themselves a system they are unfamiliar with, thus saving them from taking associated risks. A variety of approaches can be used to study the relevance of innovations, including participatory workshops, modeling tools (Dogliotti et al., 2014; Berthet et al., 2016), field days on producers' fields, or experimental plots, such as with Farmer Field Schools (Phillips et al., 2014; Duveskog et al., 2011). The advantages of the last two are that the farmers can observe what actually happens in the field (Amudavi et al., 2009). The practices to be evaluated are concrete. Prototype trials, which are generally used for agronomic evaluation and demonstration for farmers (Meynard et al., 2012; Husson et al., 2016; Compagnone et al., 2018), were successfully used here for participatory evaluation, and to trigger a process of innovation by the field-day farmers.

4.5 Farmers' knowledge and co-learning

The farmers' evaluations were dependent on their knowledge and experiences (Van Asten et al., 2009). For example, intercropped systems and Mucuna were more appreciated in Founzan, where farmers have a better knowledge of intercropping than in Boni. Moreover, all field-day farmers assessed pigeon pea in the same way, as none of them were familiar with this crop. Farmers' evaluations of the ICSs evolved from one season to the next, supporting the idea that, as knowledge of, a system increases, opinions and evaluations of the system change. From one field day to the next, evaluation comments came faster in the discussion, and opinions were firmer, revealing a learning process on legumes and on the legume-based ICSs.

Collaboration between researchers and farmers enabled co-learning (Falconnier et al., 2017). In the PPTs, researchers learned about the systems resulting from the innovation tracking, even though scientific evaluation was not a prior objective of these trials. Researchers also learned about ICSs' strengths and weaknesses for different farmers, and about the range of evaluation criteria farmers have apart from yields (Ronner et al., 2019). Simultaneously, the field-day farmers began to understand the management and performance of the ICSs through observation and discussions. This interwoven learning, combining farmers' empirical knowledge with researchers' scientific knowledge, is a source of new agronomic knowledge (Girard and Navarrete, 2005). This "actionable knowledge, that can be mobilized for the implementation of cropping systems" (Leclère et al., 2018), helped the researchers define ICS management on the PPTs, and improve the ICSs between year 1 and year 2. These improvements, based not only on agronomic principles, but also on farmers' knowledge and evaluations, constitute a first step in a co-design process (Meynard et al., 2012; Ronner et al., 2019; Reckling et al., 2020).

Thanks to collective dynamics, the study's approach also supported co-learning among farmers**,** despite their different farming systems and previous experiences with legumes. Informal knowledge exchanges among farmers occurred during field-days, and also at the margins of PPTs, before and after field-days, with no researcher present to record the discussion.

4.6 Initiation of a co-design process with a wide range of farmers

This study aimed to develop cropping systems with, and for, any farmer, without distinction of income, in an inclusive innovation process (Heeks et al., 2014; Swaans et al., 2014). The purpose was not to establish an ex-ante typology (Tittonell et al., 2009), or design different technical options to fit the biophysical and socio-economic niches (Ojiem et al., 2006; Pigford et al., 2018). Instead, this study emphasized bringing together farmers with diverse farming experiences, including livestock farmers, to foster diverse conversations, and obtain their evaluations with no prior information on which ICS they would appreciate most, as it is difficult to predict farmers' preferences from their household characteristics (Ronner et al., 2017). To better involve a diversity of farmers, the study used an inclusive method of evaluation, where the evaluation criteria came from the farmers themselves and were mostly qualitative. Although the study does represent a wide range of farmers, marginalized people, such as women, were underrepresented. This may be due to the biases of the community contact people tasked with identifying farmer volunteers for the study, as they likely identified farmers within their circles.

The methodology used in this study could be used by development operators to trigger change in a region. This study builds on tools already used for development, such as participatory workshops, trials, and field-days. For instance, the PPTs constitute an interesting "basket of options" from which farmers can select an ICS that they can adapt to their context (Ronner et al., 2017). Also, using farmers' evaluations to improve PPTs enables a participatory dynamic that resembles the Farmer Field Schools approach for the dissemination of new practices (Phillips et al., 2014; Duveskog et al., 2011). This type of participatory approach is considered time-consuming but has shown effective for farmer capacity building and empowerment (Friis-Hansen and Duveskog, 2012). However, if field-days and participatory trials are common tools to enhance the dissemination of "good practices" (Phillips et al., 2014; Amudavi et al., 2009), or to support the co-design process (Ronner et al., 2017), building PPTs from farmers' own innovations is original. This new approach helped farmers adverse to the risks associated with new practices to validate ICSs, likely because the innovations were designed by local farmers, responding to similar drivers of change.

Just as environmental conditions and sociotechnical system are inherently dynamic, so too is innovation. Farming innovation continuously evolves as farmers address new drivers of change (Salembier et al., 2018). Therefore, it is important to continuously track innovations and extend the panel of innovations in comparative trials to satisfy the farmers' curiosity. From a development perspective, it would be interesting to create a feedback loop between continuous innovation tracking and prototyping trials, to account for new opportunities or constraints, and to monitor closely the dynamics of the territory.

5. Conclusion

By combining on-farm innovation tracking and farmers' evaluations in participatory prototyping trials, a new method was tested that accounts for farmers' expectations and constraints in an inclusive innovation process, while simultaneously fostering co-learning. This study reveals the reasons why, and to what extent, farmers in the region may be interested in integrating legumes into their cropping systems. ICSs that were identified through this process can respond to local drivers of change and meet many of the farmers' interests. By identifying and characterizing local innovations and understanding the rationale behind their development, researchers can help drive an innovation process with local farmers. Therefore, this approach could be an efficient starting point for a co-design process. To go further in an inclusive movement and with the aim of co-designing legume-based cropping systems, farmers who began to familiarize themselves with ICSs through field-days should test them on their farms and adapt them to their conditions. This additional step will trigger another cycle of knowledge co-building that should reinforce farmers' empowerment, and facilitate the inclusion of legumes in the local range of cropping systems.

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Tables and figures

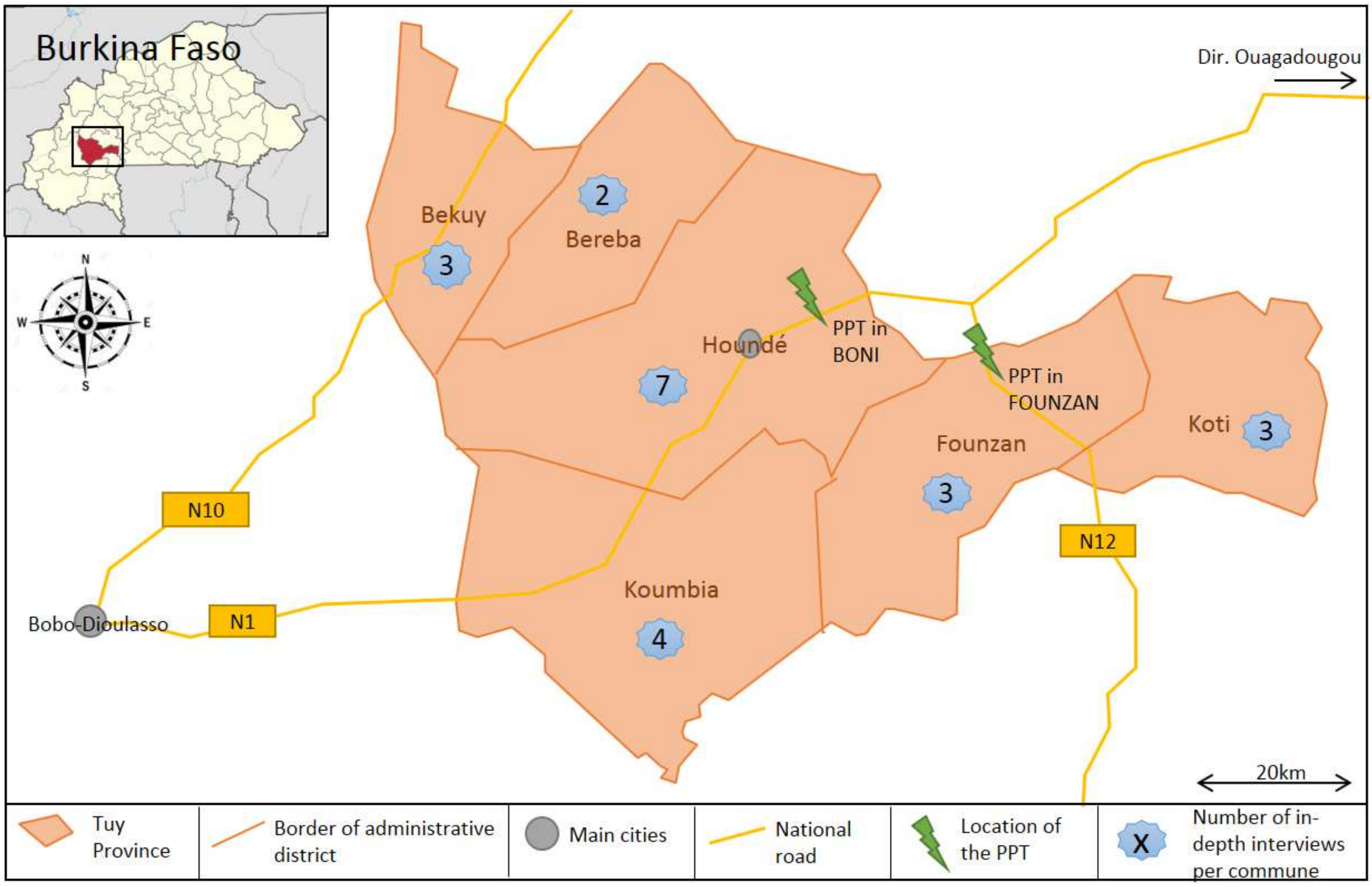

Figure 1: Tuy Province in Burkina Faso, with the location of the two participatory prototyping trials (PPT), and the number of in-depth interviews conducted per commune during on-farm innovation tracking.

Figure 2: First field day of the participatory prototyping trials in Boni, July 2017

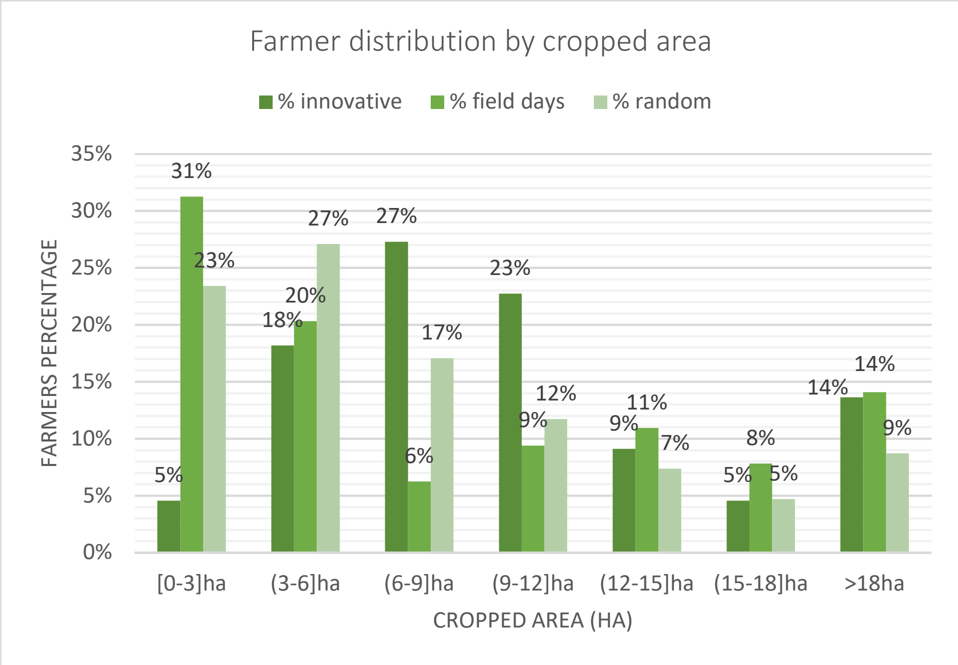

Figure 3: Distribution in percentage of 22 innovative farmers ("% innovative"), 64 field-day farmers ("% field days") and 299 randomly selected in the Tuy Province ("% random") by the cropped area (ha) in their farm in 2017.

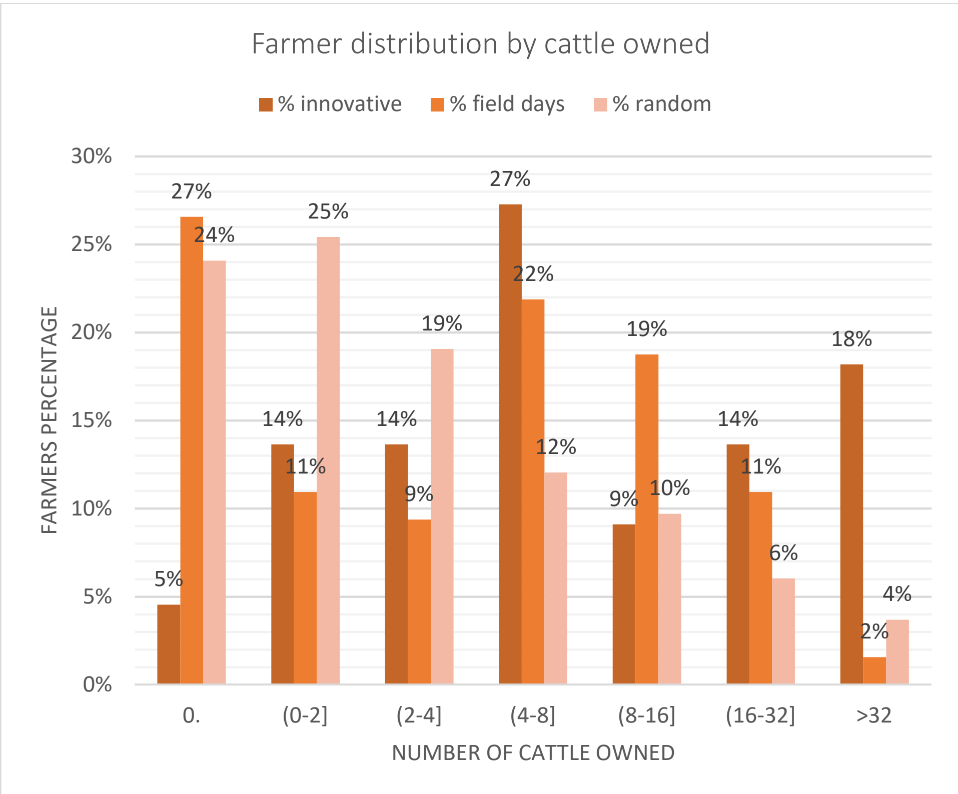

Figure 4 : Distribution in percentage of 22 innovative farmers ("% innovative"), 64 field-day farmers ("% field days") and 299 randomly selected in the Tuy Province ("% random") by the number of cattle owned by the household (logarithmic scale).

Table 1: Characterization of the 5 types of Innovative Cropping Systems (ICS) identified during on-farm innovation tracking.

ICS		**Number of interviewed farmers**	**Crops (layout and rotation)**	**Field size**	**Crop management**				**Production and use**	**Source of seeds**
					Sowing	**Fertilization**	**Weeding**	**Harvesting**		
1	**Sorghum legume Intercropping in rotation with maize or cotton**	7	Sorghum intercropped with cowpea, peanut, or soybean dibbled on the same line	Small areas (<1 ha)	Sorghum and legume sown separately	None	Sorghum ridging with animal traction	Legume harvested first, allowing sorghum harvest by cutting the whole plant	Sorghum and legume (cowpea, sometimes peanut) for household consumption	Kept from the previous year or purchased on the market
2	**Soybean in rotation with maize or cotton**	5	Sole soybean in rotation with maize or cotton, all on large areas	1 to 4 ha	Among the first crops sown in the farm	NPK sometimes on soybean; NPK and urea always on maize	By selective herbicide application and/or animal traction.	Harvesting must be done quickly to avoid losses by pods opening; performed with external labor	For sale (emerging market for soybeans) as cash crops	Certified seeds bought
3	**Red cowpea- in intra-annual succession with biomass crop**	5	Sole red cowpea followed by a crop whose biomass can be used (cowpea, maize, hibiscus, etc.)	Small areas (<1 ha)	Early seeding of the first crop (end of May)	None	Mostly by hand except between the 2 crops (plowing)	First crop at maturity, during the rainy season. Second crop at the end of the rains	Cowpea and hibiscus leaves used for soup, and maize stalks for fodder	Kept from the previous year, or purchased on the market
4	**Mucuna in rotation with maize**	4 **herders**	Sole Mucuna alone in rotation with Maize	Small areas (<1 ha)	After the other crops have been sown	No chemical fertilizer (only manure)	Only at the beginning for Mucuna; by animal traction for maize	Fodder harvested when the weather is dry, but before seeds are ripe	For fodder production, stored as bales	Mucuna kept from the previous year; maize bought
5	**Pigeon pea in rotation with maize**	1	Pigeon pea alone in rotation with maize	Very small areas (<0.25ha)	After the other crops have been sown	None on pigeon pea; NPK on maize	Only at the beginning for pigeon pea; by animal traction for maize	Harvesting of the pigeon pea seeds during the dry season (needs to be protected from grazing livestock)	For the production of peas (seeds and household consumption)	Pigeon pea kept from the previous year; maize bought

Tables 2a,b,c,d,e: Summary tables of the ICS evaluations by innovative farmers made during in-depth interviews (column 1 "Innovative tracking") and by field days farmers during field day 2 on PPT1 (column 2 " PPT1 evaluation") and field day 3 on PPT2 (column 3 "PPT2 evaluation"). Criteria are classified in 5 categories (organized in rows, from row 1 "production/yield" to row 5 "labor management").

***Color Key** for tables 2a, b, c, d, e.*

	weakness mentioned in more than 50% of the groups (field-day farmers) or interviews (innovative farmers)
	weakness mentioned in fewer than 50 % of the groups (field-day farmers) or interviews (innovative farmers)
	no consensus among the groups (field-day farmers) or interviews (innovative farmers)
	strength mentioned in fewer than 50 % of the groups (field-day farmers) or interviews (innovative farmers)
	strength mentioned in more than 50% of the groups (field-day farmers) or interviews (innovative farmers)

Table 2a: ICS 1 Sorghum legume intercropping in rotation with cotton or maize

Criteria	Farmer's **evaluation** and *quotes*		
	1. Innovative Farmers	**2. Field-day farmers on PPT 1**	**3. Field-day farmers on PPT 2**
1. Production/ yield	**Land equivalent Ration (LER)>1** *"I harvest more than with mono crops"*	**Risks of LER<1** *"You need to reduce sorghum density or it will have a negative effect on both crops, you'd better do interlines."*	**LER>1** *"you get the same amount of sorghum plus peanuts and the residues can be used for fodder"* *"With interlines there is less competition, so each crop produces more"*
2. Soil fertility	**Beneficial effect of legume on sorghum** *"sorghum produces more when intercropped"*	**Beneficial effect of legume on sorghum** *"intercropped sorghum looks stronger than sorghum grown alone"*	**Beneficial effect of legume on sorghum** *"cowpea fertilizes the soil, even better if you bury the biomass while ridging the sorghum"* *"soybean helps fighting against striga"*
3. Flexibility/ Risk management	**Better distribution of the risks (2 crops)** *"there is always at least one crop to harvest"*	**Limited flexibility in terms of soil type:** need to be grown on relatively poor soil to avoid the risk of competition. *"It cannot work on a good soil because both crops would develop well and there would be competition for light"*	**Limited flexibility in terms of soil type** *"It doesn't work on a too poor soil either: sorghum won't grow fast enough"* **-Small sowing window** *"It is important to sow the sorghum at the right time after cowpea"*
4.Post production strategy	**Improving household food security** *"The cowpea being harvested early, it helps to finish the hunger season or to feed the cotton harvesting labor"*	**Improving household food security** *"farmers who only have a small farm intercrop to get different products"*	**Improving household food security** *"'I can grow more different crops'"*
5.Labor management	**Labor intensive** *"As the soybean needs to be harvested quickly, it is difficult to grow it on large area"* *"Sowing and weeding may take more time than in sole crops, but it's easier than in the traditional sorghum-cowpea intercrop"*	**Labor intensive, especially for weeding:** *"after sowing, you can't use animal traction in the field"* *"you can't use selective herbicides"*	**Labor intensive, especially for weeding:** *"Manual weeding is more difficult in intercropped cropping systems, because you can destroy the weaker crop"*

Table 2b: ICS 2 Soybean in rotation with maize or cotton as cash crops

Criteria	Farmer's **evaluation** and *quotes*		
	1. Innovative Farmers	**2. Field-day farmers on PPT 1**	**3. Field-day farmers on PPT 2**
1. Production/ yield	**Intensive production** *"A company came and said that we should produce, they would buy the whole harvest"*	**Intensive production** *"Soybean is better alone than intercropped, you get a bigger yield"*	

2. Soil fertility	**Striga management** *« Sorghum will do well after soybean, because it's good against striga »*	**Good previous crop for cereal** « soybean is a better previous crop than cotton »	**Good previous crop for cereal and cotton** *"Better previous crop for cotton and maize than maize"* *"it helps fight striga"*
3. Flexibility/ Risk management	**High risk of losing grain at harvest time** *"the harvest has to be done quickly, or the pods open"*	**High risk of losing grain at harvest time** "you need to harvest quickly or you will lose"	**High risk of losing grain at harvest time** *"the problem is the harvest cannot wait"*
4. Post production strategy	**Market opportunity** *« I grow soybean to be ready when the market opens »*	**Unsure market opportunity** *"The market is not reliable"*	**For household food security** *"My wife makes soumbala or soya meat for the family and to sell"*
5. Labor management	**Need labor for harvest** *"I need to hire labor for the harvest as it has to be done quickly"*	**Allow the use of selective herbicides** *« it is better than in association because you can't use selective herbicides on sorghum »*	**Allow the use of selective herbicides** *« you can use selective herbicide for weeding »*

Table 2c: ICS 3 Red cowpea- in intra-annual succession with biomass crop

Criteria	Farmer's **evaluation** and *quotes*		
	1. Innovative Farmers	**2. Field-day farmers on PPT 1**	**3. Field-day farmers on PPT 2**
1. Production/ yield	**Two harvests per season** *"You can sow the second crop even more densely than the first one"* *"you'll harvest more from the second crop than from the first one"*	**Two harvests per season** *"If you can sow early enough, you can double the yield"*	**Two harvests per season** *"You may even get the grain for maize as second crop"*
2. Soil fertility	**Soil improvement by the first crop** *"the second crop looks better than the first one"* *"when you plow between the 2 crops, you burry the cowpea residues, it's like a fertilizer"*	**Fertilizer still needed for some fodder crops** *« It's good but we may need to fertilize the maize if it's the second crop »*	**Soil improvement by the first crop** "and plowing allows you to bury cowpea residues" "you need to plow between the two crops to avoid weeds"
3. Flexibility/ Risk management	**Low risk of losing the first harvest due to the rain** *"Unlike white cowpea, red cowpea can be harvested in the rainy season"*	**Location constraint due to free grazing** *"to be able to sow early you need a field where the cattle can't get in"*	**Limited flexibility for sowing** *"it won't work if you can't sow early, and you need rain early"*
	Multipurpose second crop *"If the rain stops early, you harvest the leaves"*	**Multipurpose second crop** *"It can work well if you sow early enough" "sesame is more resistant to water stress but with cowpea, you get the leaves"*	**Multipurpose second crop** *"You may even get two grain harvests if the rain lasts"*
4. Post production strategy	**Household food security (red cowpea)** *"red cowpea is for the family, there is no real market for it, but it helps in the lean period"*	**Household food security (red cowpea)** "As red cowpea is harvested early , it can be used to feed the laborers who harvest the cotton"	
	Good fodder value for the second crop *"I cut the maize green and give it to the cattle, they like it"*	**Good fodder value for the second crop** *"green fodder is better than brown"*	**Good fodder value for the second crop** *"you may get the grains, perhaps maize cobs to grill"*
5. Labor management	**Work management** "Sowing and harvesting do not happen at the same time as for cotton and maize so here is no competition for work" "Less pests on the second crop as it rains less"	**Work intensive** *"It's interesting if you have a small farm but you have to be strong"*	**Work intensive** *"I can't do it because I don't have enough time to plow between the two crops"*

	"I don't grow the second crop if I am short of laborers: Two crops need more work than one"		

Table 2d: ICS 4 Mucuna in rotation with maize, by herders

Criteria	Farmer's **evaluation** and *quotes*		
	1. Innovative Farmers	2. Field-day farmers on PPT 1	3. Field-day farmers on PPT 2
1. Production/ yield	**High yield** *"I get enough fodder from very small areas"*	**High yield** *"it has lot of leaves" "it grows fast"*	**High yield** "on a better soil, you can get more that what you've got here"
2. Soil fertility	**Positive effect on the following crop** *"Mucuna is a good previous crop "*	**Good previous effect** *"Mucuna covers the soil well" "it will feed the soil"*	**Good previous effect** *"It's a better previous crop for maize than soybean, peanut, cotton and maize"*
3. Flexibility/ Risk management	**Easy fodder production** *"you can sow it anywhere" "you don't always need to weed after planting" "I grow it on my poorest soil"* **Risks of losing the seeds** "I produce my own seeds on 1/5 of the Mucuna area" "you can't find the seeds on the market"	**Easy fodder production** « it's a crop that can grow even on a poor soil » **Risks of losing the seeds** "some of us tried it but we stopped because we couldn't find any seeds"	**Easy fodder production** "It has grown very well considering the soil is not fertile"
4. Post production strategy	**Good quality fodder** "It is very rich for cattle, they like it" "I give it to my cows to get milk"	**Good quality fodder** « It's a really good fodder crop » **Not fit for human consumption** "It's a pity that the grains are not eatable" "What else can you do with the grains?"	**Grains valuable for fowls feed** "It's interesting if it's possible to use the grain to feel fowl, how do you make that kind of feed?"
5. Labor management	**Difficult drying and storage management** *"The problem is drying the fodder properly"* *"It's easy. The hardest part is the drying and storage but I've got the equipment I need"*	**Difficult drying and storage management** *"It is a lot of work to harvest, make bales and transport them back to the house"*	**Difficult drying and storage management** *"How do you dry it if the rain lasts like it did this year?"*

Table 2e: ICS 5 Pigeon pea in rotation with maize

Criteria	Farmer's **evaluation** and *quotes*		
	1. Innovative Farmers	2. Field-day farmers on PPT 1	3. Field-day farmers on PPT 2
1. Production/ yield	**Low grain yields** "I just get some grains for the family and to re sow"	**Low grain yields** "the cycle is too long, it's going to be difficult to get the grains" **Multipurpose** « It's good if the leaves can be given to the animals » « it's good because it is multipurpose: you can also eat the beans »	**Good grain yields from short cycle variety** "the shorter variety is really good to get grains" **High fodder production on the fodder variety** "It is good for fodder production, especially if it re grows after cutting"
2. Soil fertility	**Good previous effect for cereals** "Pigeon pea helps control weeds, and the maize does better the following year"	**Good previous effect for cereals** "The litter made of the leaves seems to be good for the soil"	**Good previous effect for cereals** "It is a better previous crop for maize than soybean, peanut, cotton and maize"
3. Flexibility/ Risk management	**Can be cropped on poor soil** "I can plant it anywhere" **Drought resistant** "It stays green even after the rain stops"	**Drought resistant** « It's good if it is drought resistant »	**Drought resistant** "so you can get 2 harvests of fodder because it regrows after cutting and stays green for a while"

	Risks of losing production due to grazing “Last year I couldn’t harvest before the cow destroyed it.” “I started with some seeds I brought from Cote d’Ivoire. Since then, I produce my own seeds but I couldn’t get any seeds last year”	**Risks of losing production due to grazing** "The problem is how to protect it from cattle grazing in the dry season?” « So you need to grow it where it is easy to protect it from free grazing » “fencing is too expensive”	**Risks of losing production due to grazing** “the short variety is much better because you can harvest the grain before the cattle get intç the field”
4. Post production strategy	**Food diversification** « I don’t sell lit. People don’t know it” “I didn’t know it was good as fodder” “the grain is very sweet. My wife likes cooking it”		
5. Labor management	**Low work load** “I plant it last”. “I don’t always weed”		

Table 3: List of activities involving the field day farmers per communities; .Workshops are collective activities led in a municipal room, and Field days are collective activities led on the Participatory Prototyping Trials of 2017 (PPT 1) or 2018 (PPT2). The counted attendees are farmers participating to the activity.

Community	Activity name	Location	Date (DD/MM/YY)	Attendance rate (%)
Boni	Participatory workshop	Municipal room	11/05/17	92%
Boni	Field day Intro.	PPT1	04/08/17	130%
Boni	Field day Eval.	PPT1	21/09/17	67%
Boni	Evaluation workshop	Municipal room	18/04/18	60%
Boni	Field day Eval.	PPT2	03/10/18	100%
Founzan	Participatory workshop	Municipal room	10/05/17	76%
Founzan	Field day Intro.	PPT1	14/08/17	163%
Founzan	Field day Eval.	PPT1	27/09/17	71%
Founzan	Evaluation workshop	Municipal room	19/04/18	87%
Founzan	Field day Eval.	PPT2	02/10/18	70%

Table 4: List of the 16 treatments implemented in the participatory prototyping trials (PPT), ICS: Innovative cropping system (described in table 3); each box represents a 400m², some plots are divided into 2 parts (boxes divided with a dotted line)

Plot n°	Treatment PPT1	Treatment PPT2	ICS or check
1	Sole mucuna	Sole maize	ICS 4
2	Sole maize	Sole mucuna	ICS 4
3	Sole pigeon pea	Sole maize	ICS 5
4	Sole maize	Sole pigeon pea	ICS 5
5	Succession red cowpea- white cowpea	Sole maize	ICS 3
6	Succession red cowpea- maize	Succession red cowpea- maize	ICS 3
7	Sole maize	Succession red cowpea- white cowpea	ICS 3
8	Sole sorghum	cotton	check
	Sole soybean		ICS 2
9	Sorghum -soybean inter-hole intercropping	Sorghum -soybean inter-hole intercropping	ICS 1
		Sorghum -soybean inter-row intercropping	ICS 1
10	Cotton	Sole sorghum	check
		Sole soybean	ICS 2
11	Sole sorghum	Cotton	check
	Sole peanut		check
12	Sorghum- peanut inter-hole intercropping	Sorghum- peanut inter-hole intercropping	ICS 1
		Sorghum- peanut inter-row intercropping	ICS 1
13	Cotton	Sole sorghum	check
		Sole peanuts	check
14	Sole maize	Sorghum- red cowpea intercropping	ICS 1
15	Sole maize	Sole cotton	check
16	Sole maize	Sole maize	check