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I. INTRODUCTION

The first deliverable of WP4 (deliverable 4.1) provided an assessment of the existing knowledge regarding the use of shrub/tree species in the agricultural systems of Mali, Senegal and Burkina Faso, as well as the identification of crop-shrub interactions that are appropriate to the local contexts. The D4.1 was also instrumental to identify knowledge gaps that can be explored by the project, particularly in the design of innovative experiments and systems to be tested by researchers and farmers during the course of the project. This deliverable (D4.2) builds on the previous deliverable and reports on the promising crop, shrub, livestock integrated (CSL) systems to be tested across the project countries.

The results from the participatory rural appraisal (PRA) developed by WP2 also contributed to contextualize the assessment of the existing literature, providing useful insights regarding the social and cultural background and the use of local resources, which can inform better choices when designing appropriate CSL systems. Furthermore, the expertise and experience of the national teams was a decisive factor for the design of the on-farm and on-station experiments to be tested and implemented by the project.

The on-farm and on station trials were designed based on the species list produced in Task 4.1. As it was done with selection of species, community members were extensively consulted and participated in the design process. All the farmer field trials were set up based on the farmers' own wishes to try certain species or treatments. The on-station trials were designed based on the extensive discussions with the community members. Initial meetings with the community were held in community halls and diverse range of stakeholders were invited. Further more specific meetings were held in village squares. Equal representation of male, female and youth participation were always ensured. However, it is clear that the chief of the village is always male and has a great authority on decision making. SustainSahel is not designed to influence the change the social and cultural norms in these communities but we take great care to address to gender and intersectionality issues. Nevertheless, our discussions were lively and female members of the community were not shy expressing themselves. Some of these meetings are recorded in videos and available upon request.

Decisions on the species and treatments were often taken collectively during these meetings and then further refined based on the scientific principles by the researchers

In the three countries, a variety of on-station and on-farm trials will investigate the impact of numerous tree and bush species on soil properties, crop yields among other impacts on a more systemic approach where the field and landscape levels will be taken into account.

In Mali, *Leucaena leucocephala*, *Faidherbia albida*, *Guiera Senegalensis*, *Piliostigma reticulatum* and *Gliricidia sepium* were selected as the trees and shrubs to be tested in on-farm and on-station trials. In Senegal, the species considered for the trials were *Faidherbia albida*, *Guiera senegalensis*, *Combretum glutinosum*, *Acacia radiana* and *Piliostigma reticulatum*. In Burkina Faso, a strong focus on observational studies will include a wide diversity of species, in a landscape dominated by *Vitellaria paradoxa*, *Parkia biglobosa*, among others. The bushes *Guiera Senegalensis* and *Piliostigma reticulatum* will also be the targeted of in-depth studies, while an on-station trial in Gampéla will look at a variety of promising tree and bush species and monitor their growth rates, biomass levels, among other parameters. An overview list of the project's studies and trials is summarized in table I.

Table 1. Summary list of trials in the three countries.

Country	Site	Type of trial	Species used	Crops	Institutions
Mali	Koulikoro	On-station	<i>Faidherbia albida</i> , <i>Leucaena leucocephala</i>	Sorghum, cowpea	IPR
		On-station and on-farm	<i>Piliostigma reticulatum</i> , <i>Guiera senegalensis</i> , <i>Gliricidia sepium</i>	Sorghum	
	Sikasso	On-station and on-farm	<i>Leucaena leucocephala</i>	Cotton, maize	IER
Senegal	Niakhar	On-farm	<i>Guiera senegalensis</i>	Millet	ISRA INERA/UNB
		On-farm	<i>Faidherbia albida</i>	Millet	
	Ouarkhokh	On-farm	<i>Combretum glutinosum</i>	Groundnut	
		On-farm	<i>Guiera senegalensis</i>	Groundnut	
		On-station	<i>Acacia radiana</i>	Groundnut	
	Tambacounda	On-farm	<i>Piliostigma reticulatum</i>	Cotton	
Burkina Faso	Yilou	Observational	Various	Various	INERA/UNB
	Saria	On-farm/observational	<i>Piliostigma reticulatum</i> , <i>Guiera senegalensis</i>	Sorghum	
	Gampéla	On-station	Various	-	
All countries	All sites	Observational	Various	Various	All partners

1.1 Methodology for participatory research process

The participatory process in each site was designed in several stages where different actors were involved.

First stage was the appointment of the site facilitators by WP2. These site facilitators were in close contact with WP4, 5 and 6. Site facilitators were selected by the farmer organizations.

In the second stage, WP4 representatives and site facilitators asked the government representatives in each site to organize a stakeholder meeting. In the project countries, it is mandatory approach the government representatives first before approaching the other stakeholders and farmers. These meetings included farmers, traditional leaders, and local representatives of farmers' associations, as well as other value chain actors, mayors, regional government representatives etc. SustainSahel project was introduced to the larger community. Already during these meetings, many constraints to adoption of CSL systems, as well as species selection were discussed. The participants suggested villages where the SustainSahel activities can potentially be implemented. The project's initial expectations of carrying out a radically co-designed and co-created approach in this phase, where all community members could participate in an equal way, collided with the local bureaucracy, hierarchical structures and local traditional values. These aspects had to be considered and accepted as constraints to the previously designed methodology, according to the chosen ethical approach of the project of non-imposing interventions. Still, it was possible to directly approach some of the community members that are usually not included in this type of meetings and ask their perspectives and opinions, which allowed to integrate messages from traditionally excluded groups from decision making processes in the local realities, especially women and younger farmers. These approaches were sometimes done in informal contacts in the villages, both by the visiting teams of WP4, WP2, WP6 and WP3, but also by the local site managers.

The third stage involved contacting the village chiefs in these suggested villages and visiting them collectively. Again, here the project collaborated in a non-imposing way by accepting the consuetudinary customs on how to involve the local community in a multi-stakeholder dialogue, which must reflect the direct influence of the village chiefs on who is participating, upon the request of the project. Each village was visited several times by international and national teams including members of different WPs. In each

instance, large group of villagers (women, youth and other groups) were present and we ensured that their opinions were heard. There were targeted questions to women and youth, seeking to understand their particular concerns and their particular perspectives on potential solutions, something that was not always easy due to the fact that these community members are not used to speak out in front of their communities, due to the hierarchal structures typical of the local realities. These discussions were facilitated by the site facilitators and national research teams, who promoted equal participation of all participants. The dialogue was informal and the team avoided to be seen as a donor or government officials. We put emphasis on collective decision making to solve the problems in the community. The initial discussions included topics outside of agriculture. Youth migration, education opportunities, labor availability were some of the topics that were discussed. Spending time discussing the participants' priorities other than exclusively focusing on the topics related directly with the project was seen as an important step in building a relationship with the local community.

Consequently, SustainSahel's objectives were communicated to the community, relating these objectives with the bigger picture, where the community's concerns are also considered. Unlike meetings and activities from other work packages, such as WP2, WP3 and WP6, these meetings focused on the scope of WP4 dealt with a more systemic approach and tried not to over burden the community with more structured interviews. WP2 and 3 (also WP6 in collaboration with WP2) were already collecting data in parallel. The main purpose was to discuss with the farmers what types of agricultural challenges they were facing; how they try to solve these issues; what do they think about integration of shrubs and trees in their cropping systems and where we could have trials and demonstration plots.

Fourth stage was about finalizing the selection of species and type and location of the trials and the demonstration fields. To achieve this, international and national teams visited the same villages again and had extensive discussions on the species selection and the trial design with the villages. People involved in this process were the field owners, sometimes chief, site facilitators and other interested villagers. The process took part in the main village square and also directly in the fields suggested by the farmers. Farmers introduced their fields, their crop rotation and shrub and tree species and where/how SustainSahel activities can be established.

The whole introduction, discussion and selection process took around nine months. One of the lessons learned from these first steps of co-designing locally adapted agroforestry systems is that it must be seen as a continuous process, in which the trust built between the project and the community is built over time. This continuity over the years, where many events are planned, such as dissemination events and IP meetings, will contribute to build this mutual trust and understanding, which we expect will naturally translate in a stronger participation from all community members, especially those that are usually excluded from the first steps of such processes, such as women and the youth.

2. CROP-SHRUB-LIVESTOCK SYSTEMS PER SITE

2.1 Mali

The literature review (D4.1) showed that Mali had the lowest level of references found among the three countries (48, against 108 in Burkina Faso and 128 in Senegal). Furthermore, the country also had a lower number of species studied (24, against 44 in Burkina Faso and 56 in Senegal), potentially indicating a higher relative proportion of existing knowledge gaps for the Malian context. There is also a relatively higher concentration of studies in a single species, *Gliricidia sepium*, compared to Senegal and Burkina Faso, where the available references include a more balanced distribution in terms of number of species.

Altogether, the information concerning the impact of shrubs/trees on crop yields and soil parameters in the Malian context is scarce, and while some studies provided yields of associated crops to shrubs/trees

in Mali, these have not been compared with control (without shrubs/trees). Thus, there are significant knowledge gaps of the local systems, providing room for experiments and approaches that will increase the knowledge on the effects of selected species on soil, yields and livestock under the local conditions.

The project team has built on these insights and designed experiments using trees and bushes that are considered promising regarding their potential for soil fertility enhancement, livestock feed and yield improvement. The team has considered *Leucaena leucocephala*, *Faidherbia albida*, *Guiera Senegalensis*, *Piliostigma reticulatum* and *Gliricidia sepium* as the trees and shrubs to be included in the experimental designs, and crops such as maize and cotton (Sikasso region) and sorghum (Koulikoro region), selected in a participatory way with farmers.

The consultative process with farmers confirmed that *Guiera Senegalensis* and *Piliostigma reticulatum* are key species in the development of locally adapted CSL practices due to the fact that they are locally abundant and provide a reliable source of biomass to be used as an organic resource. A group of farmers from the site of Koulikoro was consulted in the development of the treatments in tables 3 and 4, in order to make sure that the trials are considering realistic scenarios for the local reality when it comes to the chosen treatments.

The also native *Faidherbia albida* tree was also approved by the consulted farmers for the trials in the research station, because according to local indigenous knowledge it is a “fertilizer tree” and all farmers stated that crops grown under these trees yield better. However, the PRA exercise and interviews with farmers in the project sites showed that farmers did not know what was the ideal density of the tree to be used in potential agroforestry designs in their fields. The idea for the design seen in figure 1 comes from this knowledge gap, present in both indigenous knowledge systems and scientific literature.

Even though the contacted farmers are well aware of the many advantages of native shrubs and trees, they have also repeatedly requested to researchers and farmers’ organizations responsables to be offered the chance to experiment with non-native trees that can have a beneficial impact on soil and crops. In the light of these requests, the species *Gliricidia sepium* and *Leucaena leucocephala* were included in the on-farm and on-station experiments as can be seen in tables 3 to 6. The reason for the choice of these two species is that despite its value being recognized in scientific literature, as stated above, there are considerable knowledge gaps, particularly in the studied context.

2.1.1 Koulikoro

With an average annual rainfall of around 700 mm, the site of Koulikoro is the drier of the two sites in Mali, in the heart of the Sahelian zone. Sorghum and cowpeas are two of the most common crops, with livestock being very important for the livelihoods of local farmers.

The chosen species for the on-station and on-farm trials in the site were *Faidherbia albida*, *Leucaena leucocephala*, *Guiera Senegalensis*, *Piliostigma reticulatum* and *Faidherbia albida*. *Faidherbia* is native to the area, was chosen due to its adaptability to the local conditions, for its adequacy as source of fodder, and for its unique characteristic of reverse phenology, shedding its leaves in the beginning of the rainy season (contrary to most of other local tree species) and thus reducing competition for light with crops. Furthermore, despite the great potential of this tree in the design of appropriate agroforestry systems adapted to the local context, the species was only targeted by one of the 24 analyzed references for Mali, highlighting the lack of scientific evidence and knowledge about the species and its potential. The non-native tree *Leucaena leucocephala* was also chosen for the experiments in the site, due to its promising role in improving soil fertility and providing fodder for livestock under the local conditions. Despite being included in three of the 24 analyzed references, there are serious knowledge gaps in how this species performs in terms of crop yields and soil fertility indicators. The local shrubs of *Guiera Senegalensis* and *Piliostigma reticulatum* were selected for the experiments on the site of Koulikoro based on their relative abundance in the area, potentially providing an important source of mulch for soil cover and increase of soil organic matter.

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In both on-station trials, the set-ups are planned to become long-term trials, providing a valuable contribution for the long-term effects on the selected tree species on crop yields and soil fertility indicators.

2.1.1.1 Effects of *Faidherbia albida* and *Leucaena leucocephala* tree density on crop yield and soil fertility indicators (on-station trial in Katibougou)

Two different trials will be implemented in the research station of Katibougou – set up and managed by the “Institut Polytechnique Rurale” (IPR).

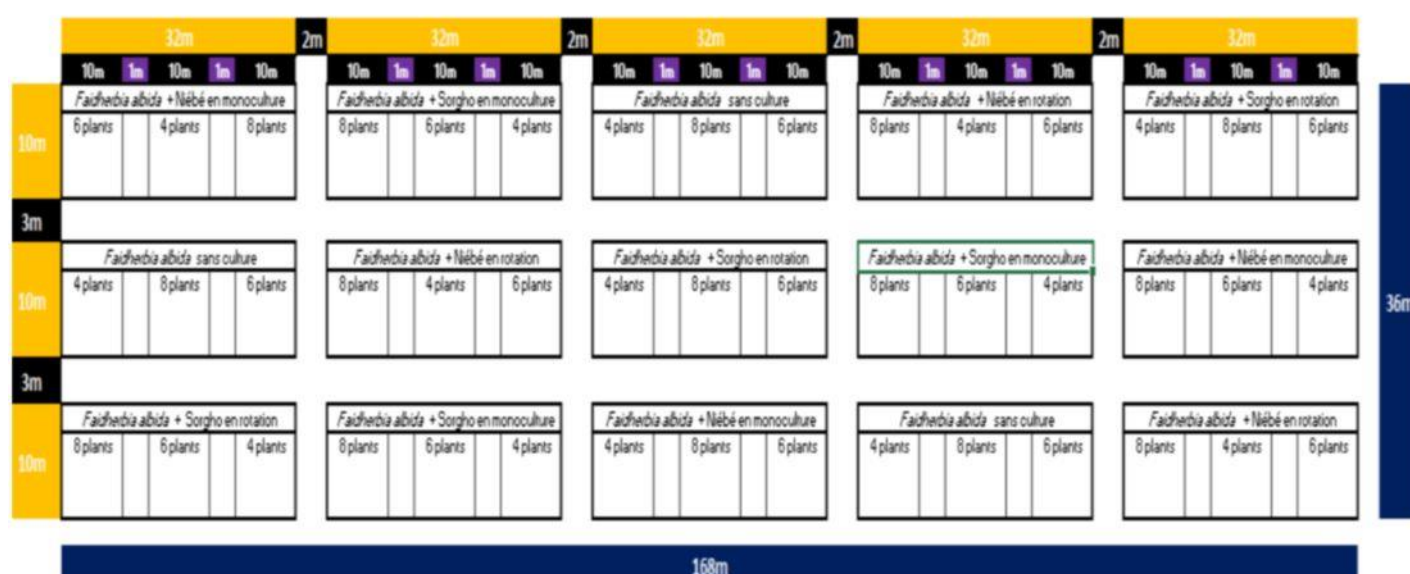
One trial will focus on *Faidherbia albida* and the other one on *Leucaena leucocephala*. In both trials, the trees will be intercalated with sorghum and cowpea, in rotation or in monoculture. The trials will be implemented in a split-plot design with two main factors: 1) Tree density and 2) cropping system, with 2.1) rotation between sorghum and cowpea, or 2.2) monoculture of the same crops or 2.3) no crops (trees only). The treatments can be summarized as in table 2.

Table 2. Studied factors and treatments in the experimental design of the Katibougou on-station trial.

STUDIED FACTORS		TREATMENTS		
FACTOR 1	Tree density	1) 8m X 8m (400 plants/ha)	2) 8m X 4m (600 plants/ha)	3) 8m X 2m (800 plants/ha)
FACTOR 2	Cropping system	1) Rotation between sorghum and cowpea	2) Monoculture of sorghum or cowpea	3) No crops (trees only)

Two sets of experimental plots are implemented, one for *Faidherbia albida* and another one for *Leucaena leucocephala*, in a split-plot design that includes the two above mentioned factors and three repetitions for each plot. The same trial design will be used for the two experimental set-ups, one per species. The example for *Faidherbia albida* is demonstrated in the figure 1.

Figure 1. Randomized split-plot design of the on-station trial in the research station of Katibougou.



2.1.1.2. Effects of *Guiera Senegalensis*, *Piliostigma reticulatum* and *Gliricidia sepium* as mulch on sorghum yields and soil fertility indicators in Koulikoro/Katibougou (on-farm and on-station trials in Koulikoro)

The on-station and on-farm trials will study the effect of biomass transfer from the locally abundant shrubs *Guiera Senegalensis*, *Piliostigma reticulatum* and the non-native tree *Gliricidia sepium*.

The study will include an on-station trial in the research station of Katibougou, with treatments including different combinations of the biomass of the *Piliostigma reticulatum*, *Guiera senegalensis* and *Gliricidia sepium*, and organic and mineral fertilizers – in a total of 13 treatments. The studied treatments are summarized in table 3, below.

Table 3. Studied treatments in the experimental design of the Katibougou on-station trial with *Piliostigma reticulatum*, *Guiera senegalensis* and *Gliricidia sepium*.

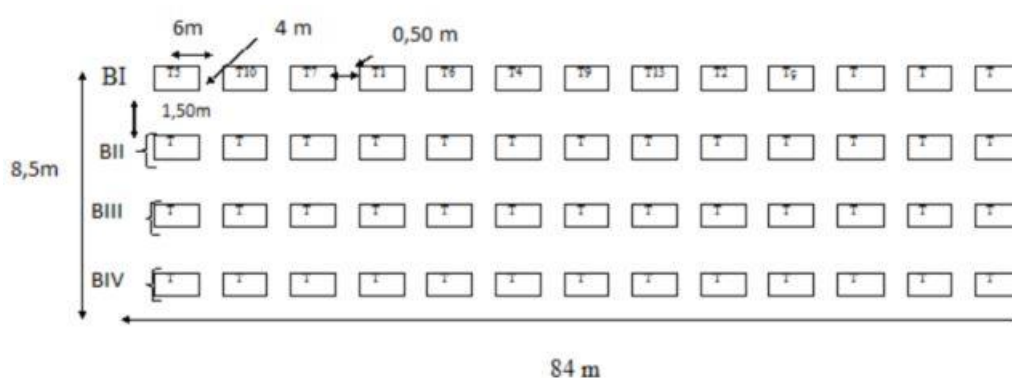
TREATMENTS						
1) <i>Piliostigma</i> (2.5 ton/ha)	2) <i>Guiera</i> (2.5 ton/ha)	3) <i>Gliricidia</i> (2.5 ton/ha)	4) <i>Piliostigma</i> (1.25 ton/ha) + <i>Guiera</i> (1.25 ton/ha)	5) <i>Piliostigma</i> (1.25 ton/ha) + <i>Gliricidia</i> (1.25 ton/ha)	6) <i>Guiera</i> (1.25 ton/ha) + <i>Gliricidia</i> (1.25 ton/ha)	7) <i>Piliostigma</i> (0.83 ton/ha) + <i>Guiera</i> (0.83 ton/ha) + <i>Gliricidia</i> (0.83 ton/ha)
8) <i>Piliostigma</i> (2.5 ton/ha) + MF (50% of RD)	9) <i>Guiera</i> (2.5 ton/ha) + MF (50% of RD)	10) <i>Gliricidia</i> (2.5 ton/ha) + MF (50% of RD)	11) <i>Piliostigma</i> (0.83 ton/ha) + <i>Guiera</i> (0.83 ton/ha) + <i>Gliricidia</i> (0.83 ton/ha) + MF (50% of RD)	12) MF (100 % of RD)	13) No fertilisation (control)	

*MF – Mineral fertilization; RD – Recommended dose

The study will evaluate the impact of the above mentioned treatments on sorghum yields and growth rates, as well as the biochemical composition of the different combinations and the mineralization rates of the biomass of the three plants.

The experimental plots are implemented in a split-plot design to include the above mentioned treatments and four repetitions for each treatment, as demonstrated in the figure 2.

Figure 2. Randomized split-plot design of the on-farm trials of Katibougou.



The study also includes on-farm trials with 5 farmers with a simplified version of the on-station treatments (8 instead of 13). Each farmer will be considered as a repetition and will be located in the villages of Mafeya, Feya and Tanabougou. The studied treatments in the on-farm trials are summarized in table 4, below.

Table 4. Studied treatments in the on-farm trials with *Piliostigma reticulatum*, *Guiera senegalensis* and *Gliricidia sepium*.

TREATMENTS						
1) Piliostigma (5 ton/ha)	2) Guiera (5 ton/ha)	3) Gliricidia (5 ton/ha)	4) Piliostigma (5 ton/ha) + MF (50% of RD)	5) Guiera (5 ton/ha) + MF (50% of RD)	6) Gliricidia (5 ton/ha) + MF (50% of RD)	7) MF (100 % of RD)
8) No fertilization (control)						

2.1.2 Sikasso

With an average annual rainfall of 1100 mm, the Sikasso site is relatively humid for the Malian context, with cotton and maize as the main crops.

The chosen species for the on-station and on-farm trials in the site was *Leucaena leucocephala*, due to its promising role for local conditions, similar to the case of Koulikoro site (see above). Existing studies have not fully explored the potential of this species to improve soil fertility parameters and crop yields for the studied context, with important knowledge gaps remaining.

2.1.2.1 Effects of alley cropping with *Leucaena leucocephala* on maize and cotton crop yield, under different combinations of organic and mineral fertilization treatments (On-station trial in Sikasso area)

One trial will be implemented in the research station of Farako, set up and managed by l'Institut d'economie Rurale (IER).

Leucaena leucocephala trees will be intercalated with cotton and maize in a split-plot design with two main factors: 1) presence or absence of trees, and 2) 6 different fertilization treatments, mirroring the realistic options that are available to farmers in the local reality. The treatments can be summarized as in the table 5.

Table 5. Studied factors and treatments in the experimental design of the Farako on-station trial.

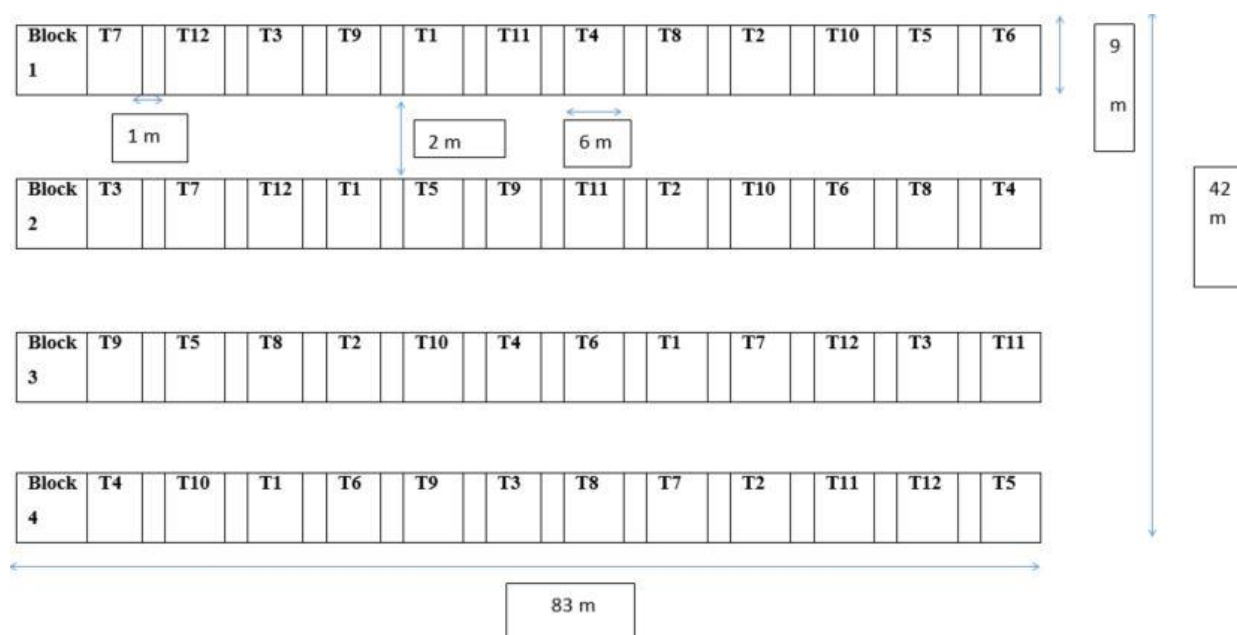
STUDIED FACTORS		TREATMENTS					
FACTOR 1	Agroforestry with <i>Leucaena leucocephala</i>	1) With	2) Without				
FACTOR 2	Fertilization treatments adapted to the local reality	1) No fertilisation (control)	2) Organic fertilisation (5 ton/ha)	3) Mineral fertilisation (recommended dose)	4) OF + 1/2 MF	5) 1/2MF + limestone	6) 1/2 MF + NPT

*OF – Organic fertilization; MF – Mineral fertilization; NPT – Natural Phosphate of Tilemsi

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Two sets of experimental plots have been implemented, one for cotton and another one for maize, in a split-plot design to include the two above mentioned factors and four repetitions for each plot, resulting in a total of 48 plots of 54 m² each, separated in 4 blocks, as demonstrated in the figure 3.

Figure 3. Randomized split-plot design of the on-station trial in the research station of Farako



The management of the trial and its final design are still being optimized in cross-country and cross-discipline discussions, and it can still change. The main parameters to be analyzed will be soil fertility and quality indicators such as soil physical (soil texture, pH, CEC, nutrients etc.) and biological properties (soil respiration, microbial biomass, enzymatic activity etc.), crop yields and *Leucaena* biomass.

2.1.2.2 Effects of alley cropping with *Leucaena leucocephala* on maize and cotton crop yield, under different combinations of organic and mineral fertilization treatments (On-farm trials in four villages in the Sikasso area)

A total of 12 farmers in the villages of Zoumana Diassa, Tourmatié, Nagnasoni and Kouroumasso (three farmers per village) will work with the project and implement simplified versions of the on-station trials with *Leucaena* in their fields. The farmers will also work with two crops (maize and cotton), two systems (with *Leucaena* and without) and three fertilization treatments, as in the table 6. The treatments took into consideration the reality of the farmers and were conceived in a participatory way.

Table 6. Studied factors and treatments in the experimental design in the on-farm trials

STUDIED FACTORS		TREATMENTS	
FACTOR I	Agroforestry with <i>Leucaena leucocephala</i>	1) With	2) Without

FACTOR 2	Fertilization treatments adapted to the local reality	1) Organic fertilisation (5 ton/ha)	2) Mineral fertilisation (recommended dose)	3) OF + 1/2 MF
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*OF – Organic fertilization; MF – Mineral fertilization

Similar parameters will be analyzed as described above, and farmers will receive training and follow-up on the activities by the students and researchers, thus creating a continuous and interactive flow of co-learning between all involved actors. Distributing the farmers within four different villages enables the project's activities to reach a wider audience and expand the outreach of the future activities developed by the project in the coming years, by establishing a trust relationship with the local communities.

2.2 Senegal

The literature review in Senegal had the highest number of references (n=128) as well as number of species considered in the studies (n=56). The species with the highest number of references were *Piliostigma reticulatum*, *Balanites aegyptiaca*, *Adansonia digitata* and *Combretum glutinosum*. Some studies have shown the positive effects of shrubs such as *Guiera senegalensis* and *Piliostigma reticulatum* on crop yields, but knowledge gaps regarding effects on soil fertility remain.

The project has chosen to work in three different sites in Senegal; Niakhar, Ouarkhokh and Tambacounda, representing three different levels of precipitation in the Sahelian zone, with Ouarkhokh being the most arid and Tambacounda the least. The species selected for the trials in Senegal were *Faidherbia albida*, *Guiera senegalensis*, *Combretum glutinosum*, *Acacia radiana* and *Piliostigma reticulatum*. These species are considered promising for the design of appropriate agroforestry systems but still represent with important knowledge gaps in the existing literature, which the project seeks to fill.

The PRA process and multiple interviews with farmers in the course of the first year of the project allowed to confirm the above-mentioned species as important for the local farmers, who are well aware of their value and benefits for the soil and use as forage. Women often referred the advantages of introducing more trees in the fields and to learn the best practices to manage them, in order to have a potential source of firewood through the improvement of traditional methods of coppicing/pruning, thus allowing them to avoid long excursions under difficult weather conditions in order to find firewood for their cooking activities. This helped inspire the trials described in figures 5 and 6.

Farmers also mentioned most of these species as being well adapted to drought, which can be seen as a valuable contribution from the indigenous knowledge systems to the design of climate change adapted CSL systems.

2.2.1 Niakhar

The site of Niakhar has a semi-arid climate, with an average rainfall of 500 mm/year. Soils are sandy and relatively poor in organic matter and nutrients. The main crops grown by local farmers are millet, groundnut and cowpea, and livestock is a very important part of the household's livelihood.

The team has chosen to work with on farm trials in three different villages in the site – Sanghaie, Sob and Diohine. The bush *Guiera senegalensis* and the tree *Faidherbia albida* were chosen as the key species for the studies in this site, due to their relative abundance and promising positive effect on crop yields and soil, while important knowledge gaps in the optimal management of these species in the agricultural systems still exist.

2.2.1.2. Effects of the distance and pruning of *Faidherbia albida* on the productivity of millet (on-farm trials in Diohine and Sob)

This experiment will use 30 mature *Faidherbia albida* trees per experiment and will count with the participation of a minimum of 10 farmers. The study will be developed in two different areas, one with a lower density of the species (village of Diohine) and one with a higher density (village of Sob).

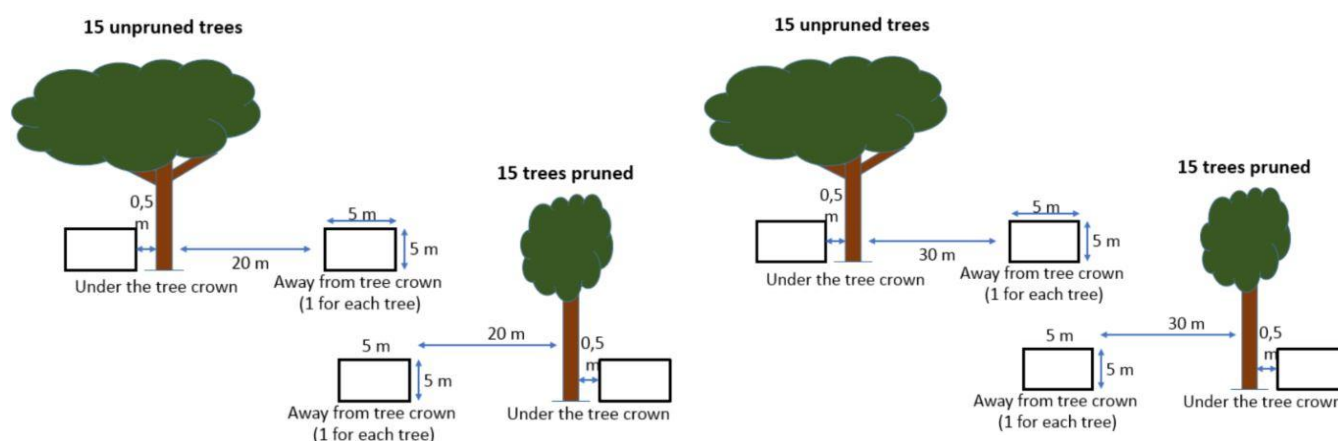
The experimental design includes two main factors: 2) Pruning of *Faidherbia albida* and 2) distance between crop and tree, in a total of 4 treatments. The studied factors and treatments are summarized in table 8, below.

Table 8. Studied factors and treatments in the experimental design in the on-farm trials in Diohine and Sob.

STUDIED FACTORS		TREATMENTS	
FACTOR 1	Pruning of <i>Faidherbia albida</i>	1) Pruned	2) Not pruned
FACTOR 2	Distance to tree	1) Under tree crown	2) 30 m away from tree crown (lower density), or 20 m away from tree crown (higher density)

Of the 30 mature *Faidherbia* trees included in each experimental set-up, 15 will be pruned while the other 15 not. For each of the trees, millet will be grown under the tree crown and away from the tree crown. In Diohine, with a lower tree density, millet productivity will be assessed 30 meters away from the tree crown, whereas in Sob, with a higher tree density, the distance will be of 20 meters, as seen in figures 5 and 6.

Figures 5 and 6. Experimental set-up in Sob (left) and Diohine (right).



2.2.2 Ouarkhokh

The site of Ouarkhokh is the most arid of the three sites in Senegal and in the whole project, with an annual rainfall of around 400 mm per year. The landscape presents a lower tree cover when compared to all other sites in the project, with relatively poor sandy soils bearing sparse vegetation, mostly bushes. The

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main crops grown in the area are groundnut, millet, watermelon and cowpea. Livestock is of a major importance for the local farmers.

The trees *Combretum glutinosum* and *Acacia radiana* and the bush *Guiera senegalensis*, species that are well adapted to the local conditions, have been chosen for the studies in this site.

2.2.2.1 Effects of the density of *Combretum glutinosum* under different fertilization treatments on the productivity of groundnut (on-farm trial in Ouarkhokh)

The trials will be set up around the village of Ouarkhokh, near Dahra, with a minimum of 10 participating farmers (the definitive number is not yet clear). *Combretum glutinosum* is a tree species native to the area, drought-resistant and valuable as forage for cattle, and thus considered ideal for the local context. The proposed study intends to fill knowledge gaps about the effects of the tree on crop yields.

The experimental design includes two main factors: 1) Density of *Combretum glutinosum* and 2) fertilization with organic and mineral fertilizers, in three different levels and in combination with biomass of *Combretum* – a total of 6 treatments. The studied factors and treatments are summarized in table 9, below.

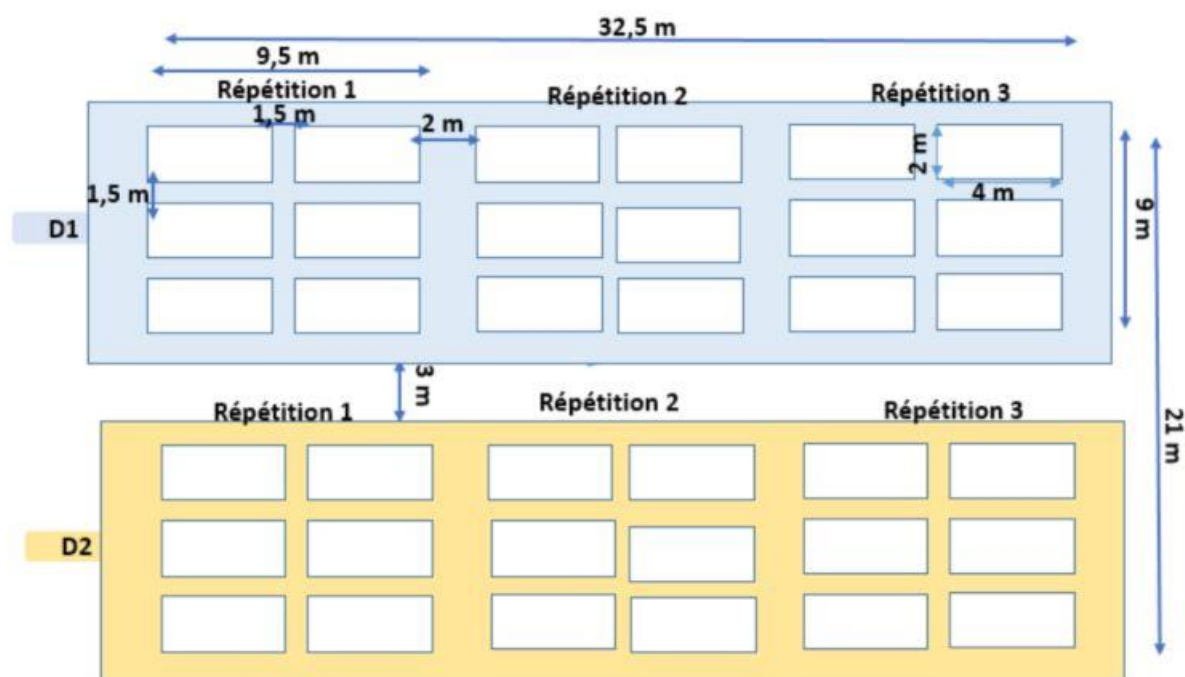
Table 9. Studied factors and treatments in the experimental design in the on-farm trials in Ouarkhokh.

STUDIED FACTORS		TREATMENTS		
FACTOR 1	Density of <i>Combretum glutinosum</i>	1) Lower	2) Higher	
		1) OF with <i>Combretum</i> biomass (5 ton/ha)	2) OF with <i>Combretum</i> biomass (5 ton/ha) + MF (50% of RD)	3) OF with animal manure (5 ton/ha)
FACTOR 2	Fertilization treatments adapted to the local reality	4) OF with animal manure (5 ton/ha) + MF (50% of RD)	5) MF (100% of RD)	6) No fertilization (control)

*OF – Organic fertilization; MF – Mineral fertilization; RD – Recommended dose

The experimental plots are implemented in a split-plot design to include the two above mentioned factors and three repetitions for each treatment in two blocks, as demonstrated in the figure 7.

Figure 7. Randomized split-plot design of the on-farm trials with *Combretum glutinosum* in Ouarkhokh.



2.2.2.2. Effects of *Guiera senegalensis* density, with and without organic and mineral fertilization, on the productivity of groundnut (on-farm trials in Ouarkhokh)

The trials will be set up around the village of Ouarkhokh, near Dahra, with a minimum of 10 participating farmers. The bush *Guiera senegalensis* is present in the area and provides a potential useful resource for farmers to enrich their relatively poor soils, through the incorporation of its biomass.

The experimental design includes two main factors: 2) Density of *Guiera senegalensis* and 2) fertilization with organic and mineral fertilizers, in three different levels and in combination with biomass of *Guiera* – a total of 6 treatments. The studied factors and treatments are summarized in table 10, below.

Table 10. Studied factors and treatments in the experimental design in the on-farm trials in Ouarkhokh.

STUDIED FACTORS		TREATMENTS		
FACTOR 1	Density of <i>Guiera senegalensis</i>	1) Lower	2) Higher	
FACTOR 2	Fertilization treatments adapted to the local reality	1) OF with <i>Guiera</i> biomass (5 ton/ha)	2) OF with <i>Guiera</i> biomass (5 ton/ha) + MF (50% of RD)	3) OF with animal manure (5ton/ha)
		4) OF with animal manure (5ton/ha) + MF (50% of RD)	5) MF (100% of RD)	6) No fertilization (control)

*OF – Organic fertilization; MF – Mineral fertilization; RD – Recommended dose

The experimental plots are implemented in a split-plot design to include the two above mentioned factors and three repetitions for each treatment in two blocks, as demonstrated in the figure 8.

The diagram illustrates the layout of the experimental setups for two conditions, D1 and D2. Both setups consist of a large rectangular area (50.5 m wide and 9.5 m high) containing three repetitions of a 2x2 grid of square targets. The targets are white squares on a blue background (D1) or orange background (D2). The dimensions and layout are as follows:

- Overall Dimensions:** 50.5 m wide and 9.5 m high.
- Repetition 1:** A 2x2 grid of targets. The width of the first repetition is 15.5 m.
- Repetition 2:** A 2x2 grid of targets. The width of the second repetition is 15.5 m.
- Repetition 3:** A 2x2 grid of targets. The width of the third repetition is 15.5 m.
- Spacing:** The distance between the right side of one repetition and the left side of the next is 1.5 m.
- Target Dimensions:** Each target is a square with a side length of 4 m.
- Target Spacing:** The distance between the right side of one target and the left side of the next target in the same row is 7 m.

The site of Tambacounda, in the south-east of the country, is the most humid of the sites in Senegal, with an average rainfall of around 800 mm per year. The main subsistence crops grown in the area are millet, sorghum and maize, with cotton and groundnut grown as cash crops. A growing part of the rural population has been engaging in agro-pastoralism, carrying out both farming and livestock rearing.

2.2.3.1 Effects of the density of *Piliostigma reticulatum* and different combinations of organic and mineral fertilizers on the productivity of cotton (on-farm trial in the village of Koussanar)

The trial will be set up near the village of Koussanar, near Tambacounda. *Piliostigma reticulatum* is a locally common bush, providing a readily available source of organic matter that can be used in the local agricultural systems. The potential of *Piliostigma reticulatum* on the productivity of cotton, a cash crop important for the locals, is poorly understood and was therefore selected to be addressed in this site.

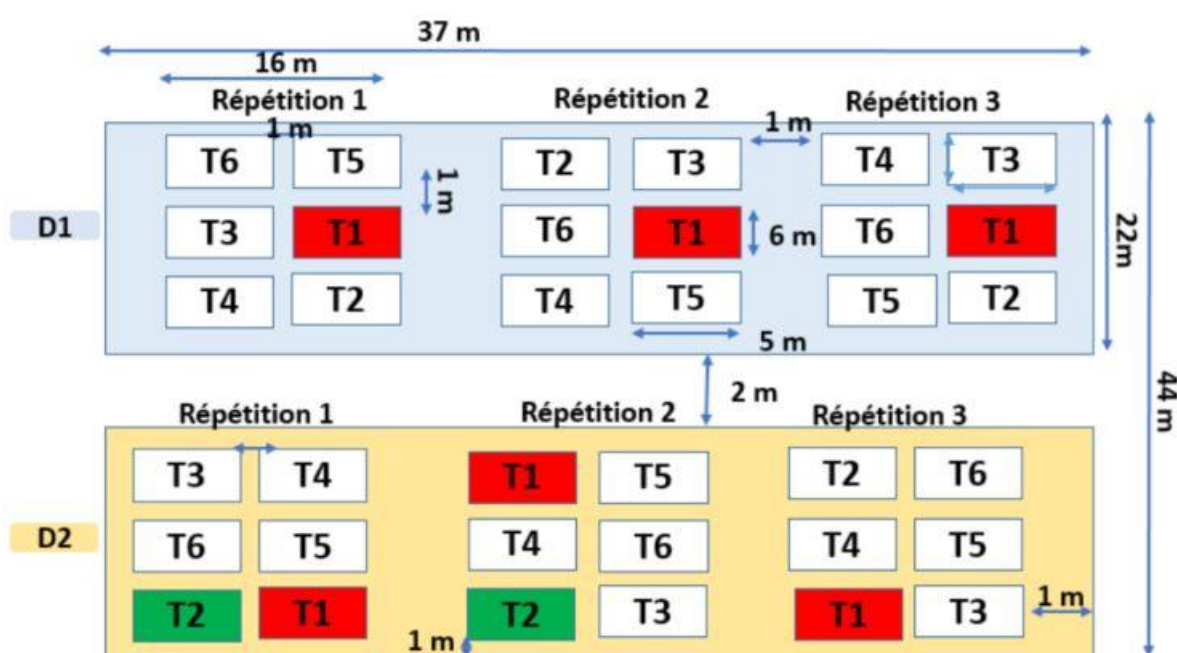
The experimental design includes two main factors: 2) Density of *Piliostigma reticulatum* and 2) fertilization with organic and mineral fertilizers – a total of 4 treatments. The higher density (D1) uses 50 plants of *Piliostigma* per hectare while the lower density (D2) uses 25. The studied factors and treatments are summarized in table 12, below.

Table 12. Studied factors and treatments in the experimental design in the on-farm trials in Koussanar.

STUDIED FACTORS		TREATMENTS		
FACTOR 1	Density of <i>Piliostigma reticulatum</i>	1) Lower	2) Higher	
FACTOR 2	Fertilization treatments adapted to the local reality	1) OF with <i>Piliostigma</i> biomass (5 ton/ha)	2) OF with <i>Piliostigma</i> biomass (5 ton/ha) + MF (50% of RD)	3) OF with animal manure (5ton/ha)
		4) OF with animal manure (5ton/ha) + MF (50% of RD)	5) MF (100% of RD)	6) No fertilization (control)

*OF – Organic fertilization; MF – Mineral fertilization; RD – Recommended dose

The experimental set-up is implemented in a split-plot design to include the two above mentioned factors and three repetitions for each treatment. The experimental design is shown in the figure 11.

Figure 11. Randomized split-plot design of the on-farm trials with *Piliostigma reticulatum* in Koussanar.

2.3 Burkina Faso

The literature review in Burkina Faso has counted with 108 references, with a total of 44 species covered. The analysis shows that the Shea tree (*Vitellaria paradoxa*) and Nere (*Parkia biglobosa*) are the most well studied species in the context, followed by the bushed *Piliostigma reticulatum* and *Guiera senegalensis*. Interestingly, most of the studies (59%) focused on feeding for animals and humans, likely highlighting the need for more studies to provide insights regarding impact of tree and bush species on soil fertility indicators and crop yields.

Most female farmers consulted during the initial phase of the project mentioned the shea tree as very important for them and for their own income and autonomy. The study in the Gampela research station, for example, will seek to generate knowledge on best practices to stimulate the growth and successful implementation of this and other species in the fields, under different treatments.

2.3.1 Yilou

To the north of the capital Ouagadougou, the site of Yilou is the driest site in Burkina Faso, with an annual rainfall of around 600 mm/year. Soils are poor in nutrients and the landscape is dominated by open savanna ecosystem, with a prevalence of tree species such as *Vitellaria paradoxa*, *Parkia biglobosa* and *Lannea microcarpa*. The main crops are sorghum, millet, maize and cowpea. Groundnuts and sesame are grown as cash crops. Livestock is an important complement to the agricultural activity.

2.3.1.1. Impact of different management practices in agroforestry systems on soil and crop yields (observational studies in Yilou and Saria)

This study will assess existing agroforestry systems in the areas of Yilou and Saria, providing insights regarding the impact of different management practices on soil fertility indicators and crop productivity.

The specific research objectives can be summarized as follows:

- Conduct an analysis of the recent evolution of local agroforestry systems;
- Characterize the structure of agroforestry systems;
- Identify the different management methods of agroforestry systems;
- Evaluate the impacts of the management methods on soil fertility and crop productivity.

The study's research hypotheses are that:

1. The dynamics of agroforestry parks are progressive;
2. The structure of agroforestry parks is stable;
3. The use of agroforestry parks varies according to the phytogeographic zones and ethnic groups of the country;
4. The different management methods of the parks contribute to the reduction of the productivity of the agroforestry parks.

2.3.2 Saria and Gampéla Research Stations

Geographically located in the center of the country, the site of Saria has an annual rainfall of around 800 mm/year. The landscape is dominated by open savanna with a dominance of *Vitellaria paradoxa*, *Parkia biglobosa* and high numbers of the introduced species of *Azadirachta indica*, or Neem tree. The main crops

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are millet, maize, sorghum, groundnuts, bambara pea and cowpea. Livestock is very common in the area and an important complement to people's nutrition and income.

2.3.2.1 *Impact of Piliostigma reticulatum and Guiera senegalensis on soil characteristics and crop yield (on-farm studies in 5 villages)*

Farmers from the villages of Nassoulou, Gourongo, Nandiala, Saria and Poa-Yaoguin will participate in the study, which will be carried out in farmers' fields and use existing bushes.

In each farmers' field, four bushes of *Piliostigma* and four bushes of *Guiera* will be selected with the assistance of the farmers, and the following parameters will be analyzed:

- Determination of total bush biomass;
- Soil physical and chemical properties below and away from each bush;
- Crop productivity and health around and away from each bush;
- Root profiles (including mycorrhization) of crops around and away from the bushes;
- Determination of crop biomass and yield.

The study considers the following hypothesis:

1. The proximity of the shrub and mulch areas have a positive effect on soil fertility (physical, chemical, biological) and sorghum yield development;
2. Shrubs maintain good soil health under their influence;
3. The presence of shrubs improves the availability of water and the absorption of water and nutrients by the sorghum plants;
4. Bio-pests have a low impact on the development of grain and straw yields of sorghum associated with shrubs and mulch areas;
5. Shrubs presence increases the intensity of mycorrhization of sorghum plants in different treatments;
6. Shrubs presence significantly increase sorghum yield;
7. High density of shrub stumps and their management have a positive effect on soil fertility indicators and sorghum yield depending on the species.

2.3.2.2 *Effects of tree management, fertilization and watering intensity on different tree species for agroforestry systems adapted to the Sahelian area (on-station trial in Gampéla)*

The trial will be implemented in 2022 in the research station of Gampéla, around 30 km east of Ouagadougou, and it will be managed by the University of Bobo.

The objective of the trial is to assess tree survival, growth rates, biomass production and mineralization rates for different trees that are considered promising for agroforestry systems in the local context, such as *Balanites aegyptiaca*, *Vitellaria paradoxa*, *Gliricidia sepium*, *Combretum glutinosum*, *Piliostigma reticulatum* and *Faidherbia albida*, among others. The trees will be planted in a fenced split-plot design, with three repetitions per species.

The team envisages also the association of cereal crops (sorghum, maize or millet) two years after the implementation of the trees, in order to evaluate their impact on crop yield. The final protocol is not yet completed.

2.3.2.3 Crop-Native Evergreen Woody Shrubs Long-term Experiment, Kamboinsé

This trial compares impact of different densities of *Piliostigma reticulatum* on crop production and soil quality. It also has two other treatments that are very important for water capture and conservation: no-till and Zai pits.



4 Shrubs' densities

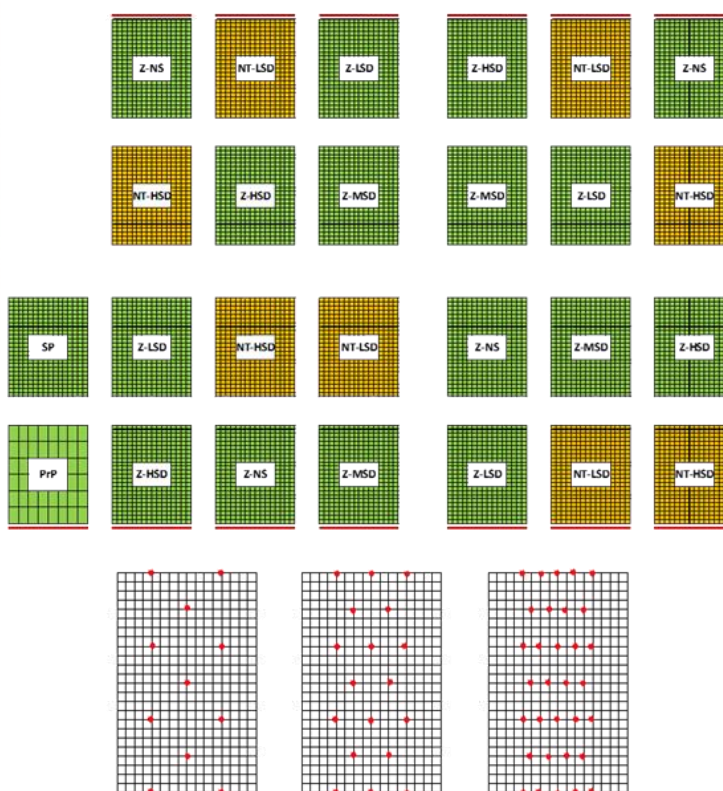
- 0 (No Shrub -NS)
- # 500 (Low shrub density- LSD) ha^{-1}
- # 1000 (Medium shrub density –MSD) ha^{-1}
- # 2000 (High shrub density- HSD) ha^{-1}

Combined with

2 soil tillage methods

- zai pits (Z)
- no-tillage (NT)

Crop residues are maintained as mulch



3. OBSERVATIONAL STUDIES

From the farmer visits, MARP reports, and literature review it became clear that information is limited on the functioning of existing complex Sahelian agroforestry systems. There is some information on the impact of common local species on crop productivity and soil quality, but the effects of several trees together in the field on crop and soil is not available. The difficulty involving assessment of several species interaction on crop and soil have prevented researchers from investigating such systems. Yet, such complex systems are the reality in most of the project sites.

These observational studies aim to observe different agroforestry systems over time and thus identify the main characteristics responsible for distinction in productivity and soil quality. It is hypothesized that tree/canopy density are the primary factors responsible, and with increasing density higher performance can be achieved. Tree species and age might be secondary factors which are intricately linked. The observation will be conducted on farmer managed fields which are preselected by the research team according to their tree/canopy density.

For this reason, the SustainSahel project decided to engage in observational studies in the three countries, capable of demonstrating the effects of tree density and composition in different farms in the project sites.

Around 30 farms have been selected in all sites, covering different levels of tree density and composition. Drone pictures of the selected farms have been taken and local PhD and MSc students will document the

activities of the respective farmers, as well as measure yield levels and soil indicators in order to provide data to infer on the effect of trees on the selected parameters.

The type of field management will be carefully documented, as well as crop yields, tree composition and abundance, and soil characteristics both in the proximity and away from trees. The use of drone images, in combination with satellite images, will allow for a landscape level analysis and modelling, thus providing new insights on the impact of trees at the field and landscape levels.

This survey will not collect personal data and only rely on the agronomic productivity and management of the fields. We would recommend to do a test survey in one village before.

The selected fields will be divided into groups according to parameters collected during the field survey. We will use tree/canopy density as a primary factor of distinction, but will add others (e.g., tree species or nutrient amount) if appropriate.

Regular data collection over time

To identify the effect of the factors like tree/canopy density (and maybe others) on the yield performance and soil quality, the selected fields will be observed over several seasons. In summary, there will be three data collection areas which are similar to the survey during the selection process, but are more detailed:

1. **Farmers' field management:** each field owner farmer will be asked to provide information on their field management.
2. **Field characteristics:** each field will be visited by the project staff and changes during the observational periods will be recorded
3. **Productivity and soil data:** during and at the end of the cropping season, yield and soil data will be collected from each field. This will also include information such as tree leaf or shrub mulch cover observations.

Statistical Approach

Even if we assume that tree/canopy density will be the primary factors influence yield performance and soil quality, we will use a cluster analysis to identify groups within the fields depending on several factors. A cluster analysis is a method of grouping a set of objects (in our case fields) in such a way that objects in the same group are more similar to each other than those in other groups. After discussion, we can decide on a model (linear mixed effect) to reflect the effect of field parameters on yield performance and soil quality parameters. The model will be tested with an analysis of variance (ANOVA) to determine possible significant effects between the groups.

4. REFERENCES

SustainSahel project, Deliverable D4.1 – A list of Suitable Shrub Species (May 2021)