Roles of Agroforestry in sustainable intensification of small farMs and food SEcurity for SocIetIes in West Africa

WP2 **Ecosystem Services** - Task 2.1. **Provisioning services**
D 2.1.1. Impacts of trees on associated crops (80% completed)

D 2.1.1.1 - Burkina-Faso

D 2.1.1.1.1 *Pilostigma* impacts on *Sorghum* (*J-M. Douzet et al.*)

Methodology : *Piliostigma* is a non-nitrogen-fixing legume shrub that allows the stabilization of soil carbon content but not of soil nutriment nitrogen and phosphorus (Félix et al., 2019). A trial on increasing the stand density of *Piliostigma* intercropping with sorghum was set up in the 2iE Campus – Kamboinsé, Burkina Faso (12°28.031'N; 1°32.929'W) and monitored during the period 2012-2020. The experimental design was a factorial randomized block design with two factors and 4 repetitions: 1) Density of *Piliostigma* (0, 488, 976 and 1953, 2000 shrubs /ha) coppiced annually and the residues spread on the soil surface as mulch; 2) soil tillage (Zai) or not (No tillage). Only 2 densities (500 and 2000) were applied for non-tillage. The size of the plots was 13.6 x 20m. The distance between sorghum holes was 0.8 x 0.8m. The yields of each species were measured each year, and the root measurements were carried out in 2020 using mini rhizotrons.

Main results : Effect of the shrub intercrop on *Sorghum* straw and grain yield at harvest was not significant. Millet yields were very high in the first years and declined over the years in all treatments probably because of the decline in soil fertility following the long period of fallow before the trial set up (Fig. 1). In the recent years, more sensitivity of the cereal yield to the applied treatments seemed apparent. It is noticed that one cause of low yield differences between treatments could be the risk of a significant impact of the shrubs roots extending beyond the plots where the treatment was applied. The results collected on the root systems may allow examine this hypothesis.

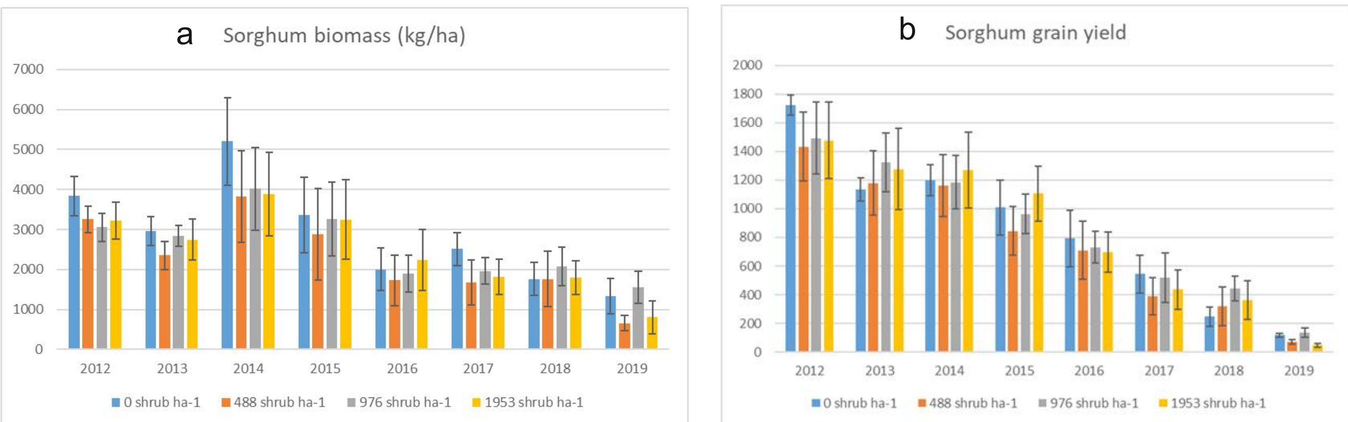


Fig. 1. Sorghum biomass (a), and grain yield (b) according to *Piliostigma* density at 2iE Campus trial - Kamboinsé, Burkina Faso (12-28.031'N; 1-32.929'W)

D 2.1.1.1.2 *Vitellaria paradoxa* (shea tree) impacts according to the distance from the tree

(*J. Sanou, J. Koala*)

Methodology : In Burkina Faso, cereal crops are grown in traditional low input systems, the most common of which are agroforestry parks with Vitellaria paradoxa (shea tree). Various studies showed that the tree proximity had a negative effect on the sorghum crop yield (Maïga 1987; Guinko, 1989; Kater et al., 1992; Kessler et al., 1992; Balaya, 2002b; Yaméogo, 2004). Bazié (2009) suggested that competition for light was mostly in cause. However, little work has examined the tree impacts on various traits of the agrosystems at the same time. Moreover how the tree impacts are related to the diversity of management practices in farmers' fields have not been sufficiently addressed. The aim of this study was to contribute to fill these gaps in order to identify innovative strategies for improving the performances of these agroforestry systems. The study was carried out in the rainy season 2019, in agroforestry parks selected in four villages of the Koumbia-Dano transect in Burkina Faso (Fig. 2).

- Djuié (11.198418°, -3.781958°): Bwba village with high population pressure and a large area with cotton crop. Hauts Bassins region,
- Gombélédougou (11.185946° -3.555146°), Bwaba and Mossi with large farms, mechanization for cotton crop, Hauts Bassins region
- Guéguéré (11.125016°, -3.178171°), Dagara village with good land and permanent crops, existence of women's groups on shea. South-West region,
- Lofing (11.1915998459°, -3.0529999733°): Dagara near Dano with poor land, lowlands and a multi-project area.

Fig. 2. Position of the four villages investigates by the Ramses II project along the Koumbia-Dano transect, Burkina Faso

In each village, 4 fields were selected based on the intensity of pruning of the branches and the average distance between the trees in the field. In each of these plots, five (5) trees were selected for the study. For each tree, three (3) plots were delineated (at 1/2 radius of the crown, at the edge of the crown and halfway to the nearest tree, (Fig. 3). In each plot, a three-line area with 5 holes was used for observations and measurements. Excavations were made at a depth of 1 m, below the crown and outside the crow of the trees and roots biomass evaluated for successive soil layers: 0-20 cm, 20-50 cm, 50-80 cm and 80-100 cm. The list of measured variables is presented in Table 1. More details can be found in the masters degree reports of the students.

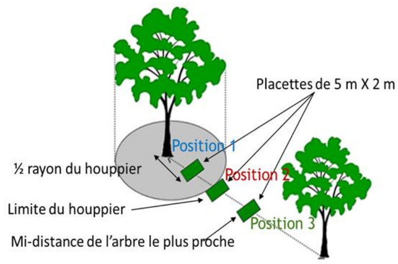


Fig. 3. Agronomic monitoring device at tree scale

Table 1. Collected data in sampled parklands located along the Koumbia-Dano transect in Bukina Faso

Variable categories	Available results
Socio-economic	Farm typology
	Perception and choices
	Ethnicity
	Land tenure
	Trees regeneration practices
Spatial	Location of each sampled parkland
	Georeferencing of each sampled tree
	Tree density in the sampled parkland
	Minimum distance between trees in the sampled
Practices and parkland management	Duration of the plot cultivation
	Associations and rotations over the last 5 years
	Frequency- and date of the last- pruning
	History of organic manure management
	Tool for soil tillage
	Age of the (last) fallow
Tree biometric traits	Trunk circumference at 1.5m
	Crown diameter
	Height
Crop traits and yield components	Plant growth and phenology
	Grain/straw yield
	Grain/straw yield components
	Parasites status (striga, mildew or other)
Underground traits	Vertical and horizontal distribution of root biomass
Tree health	Parasite status / presence of hemiparasite
Tree impacts on weeds	Tree impacts on weed floristic diversity
	Tree impacts on weed biomass
Tree impacts on physical environment	Soil moisture (0-10 cm and 10-30 cm)
	Photosynthtetic Active Radiation (PAR) under shea crown / in open area
	Air temperature under shea under shea crown and in open areas
	Rainfall under shea crown and in open-air areas

Main results : Rainy season 2019 was a rainy year. The rainfall collected in 3 to 5 rain-gauges installed in the open parts of fields, ranged from 675 mm (Djuié) to 780 (Loffing). The tree proximity had a negative effect on the sorghum yield in the Haut Basin regions (Djuié and Gombélédougou) where the yield was about three times lower du to the tree proximity. No significant negative effect of the tree proximity on the crop yield was recorded in South-West regions (Fig. ???). Root/shoot ratios were higher under the crown than outside, suggesting that the light constraint has affected more the shoot growth than the root growth (Fig ???).

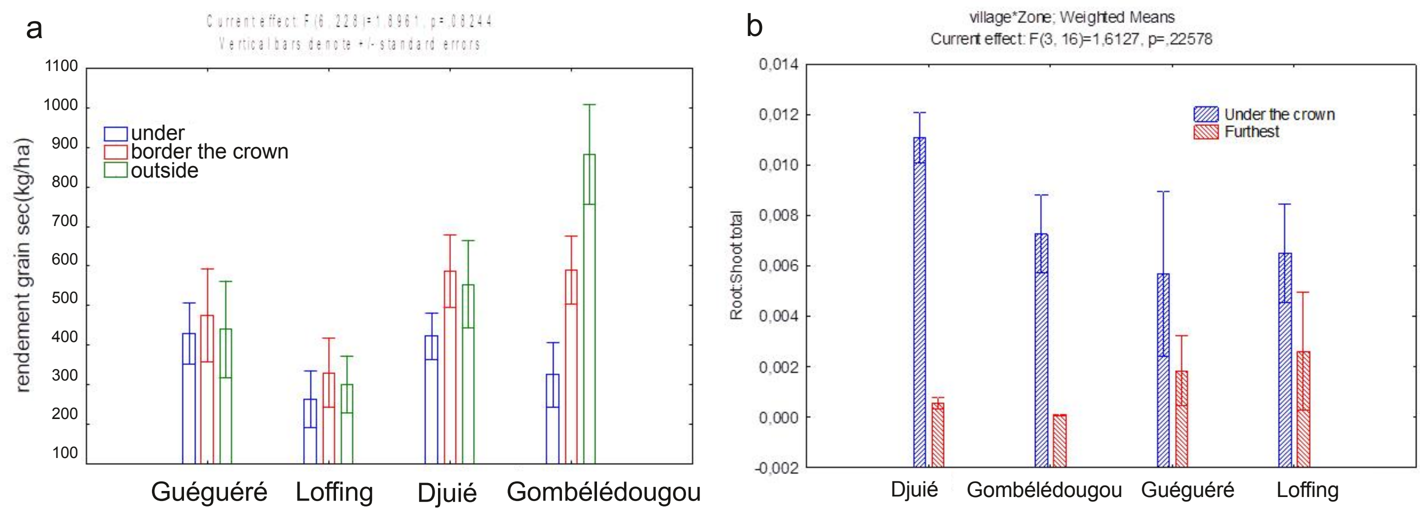


Fig. 4. Average yields of *Sorghum* grains (a) and root/shoot ratio of sorghum (b) in shea (*V. paradoxa*) according to the distance from the tree, and to the village along the Koumbia-Dano transect in Bukina Faso

D 2.1.1.2 - Senegal

D 2.1.1.2.1 *Faidherbia albida* impacts

A - On millet crop according to the distance from the tree (*C. Clermont-Dauphin, M. Ndienor, A. Ba, L. Leroux O. Roupsard, C. Jourdan et al.*)

Introduction : Several studies have shown an increased yield of cereals near *Faidherbia albida* trees in the Sahelian zone (Barnes and Fagg, 2003; Boffa, 1999, Louppe et al, 1996). However, little work has examined the processes involved. Moreover, as already underlined by Sileshi et al, (2016), the variability of the tree impacts as related to the diversity of farmers management practices has been scarcely examined.

Methodology : In order to fill this gap, a regional agronomic diagnostic approach was carried out using a network of 83 stations sampled in farmers' fields distributed in five villages of the IRD observatory of Population/ Health/Environment at Niakhar (Fig. 5). The stations were representative of the diversity of pruning intensity, tree trunk circumference and tree density and diversity at landscape scale. Each station comprised a couple of *F. albida* trees and a couple of millet subplots distributed as shown in Fig. 6 : a subplot near the tree, and another at the halfway distance between the two trees. Table 2 shows the characteristics of the observation stations. Over the network technical management of millet was the most typical for the region. It was characterized by the absence of chemical and/or organic fertilization, the sowing of the Souna III variety from farm seeds and a succession of the usual technical interventions during the cycle for the thinning and weeding of the crop stand. Fig. 7 shows the farm calender during the millet cycle and the elaboration periods and observations of each component of the millet yield. The list of the measured variables and their modalities is presented in table 3.

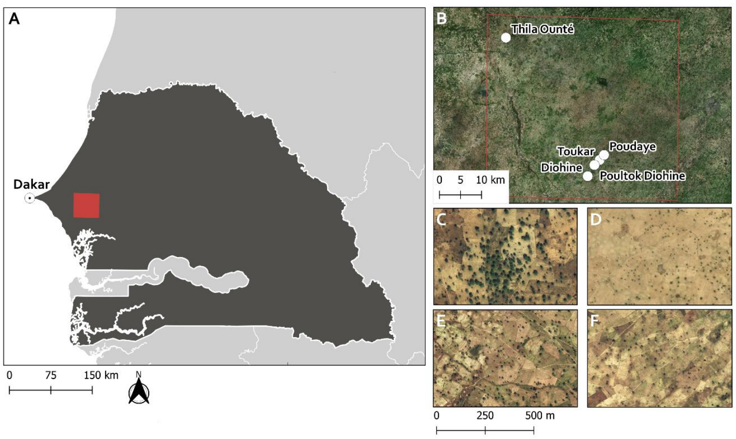


Fig. 5. localisation of the project site (A), of the five villages investigated by the project (B), and of monitorired parklands (C - F). Aerial view of the tree densities at Thila Ounté (C), Poudaye-Toucar (D),Touca-Poultock Diohine (E) et Diohine (F)

Fig. 6. Dispositif set up within each "station" which is itself composed of a couple of *F. albida* trees

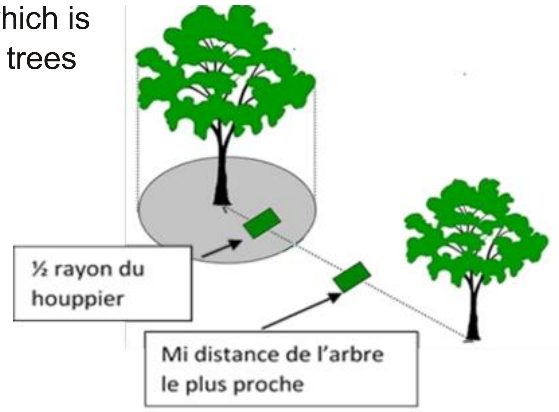


Table 2. Tree stand characteristics in the parklands where *Faidherbia abida* impacts were monitored in Senegal

Villages	**Average tree density** (Nbre/ha)	**Average percentage of *Faidherbia albida*** (%)	**Average tree species richness** (nbr of species)
Diohine	4,9	75,9	1,9
Poudaye-Toukar	8,9	100,0	1,7
Poultock-Toukar	7,2	97,8	1,6
Thila-Ounte	14,0	80,4	3,5
Average over all	**6,9**	**85,8**	**1,9**

Table 3. Device set up to study *Faidherbia abida* impacts in Senegal

Villages	**Number of stations***	**Average distance between trees (m)**	**Crown index (proxy for rate of pruning)** **	**Tree girth at 1.30 m (cm)**	**Soil type**
Diohine	16	78 ± 6	28 ± 2	233± 10 [b]	Arenosol
Toukar	16	44 ± 7	31 ± 3	173 ± 11 [c]	Arenosol
Poudaye-Toukar	8	33 ± 3	37 ± 5	164 ± 14 [c]	Arenosol
Poultock-Toukar	8	63 ± 8	64 ± 6	205 ± 13 [bc]	Arenosol
Thila-Ounte	20	28 ± 5	59 ± 3	282 ± 17 [a]	Arenosol
Sob	15	26	- (data not available yet)	159 ± 6 [c]	Arenosol

* A "station" is a couple of *F. albida* trees and a couple of millet plots distributed as shown in Fig. 6.

** Crown index is calculated as the ratio of crown surface to potential crown surface as predicted by the regression with the circumference of the tree trunk at 1m30, following Louppe et al, (1996): (Y = 65 + 449 g, with Y= tree crown area of non pruned trees (m2) and g= trunk circumference at 1m30

Table 4. Collected data in sampled parklands located along the Niakhar transect of villages in Senegal

Variable categories	Available results
Spatial	Location of each sampled parkland
	Georeferencing of each sampled tree
	Tree density and diversity in the sampled parkland
	Distance between the sampled and the nearest tree
Practices and parkland management	Crop history over the last 5 years
	Frequency- and date of the last- pruning
	History of organic manure management
	Tool for soil tillage
	Nature and dates of technical interventions on millet (2019)
Tree traits	Trunk circumference at 1.5m
	Crown diameter and orientation
	Height
	Sex of the tree (farmer declaration)
Crop traits and yield components	Plant growth and phenology
	Grain/straw yield
	Millet hill* density at harvest
	Number of spike/hole
	Number of grains/spike
	Weight of 1000 grains
	Parasites status (% striga, % mildew, % miners)
Crop water stress status	Predawn leaf potential of millet 30 days after lifting
	Midday leaf potential of millet 30 days after lifting
	Predawn leaf potential of millet 56 days after lifting
	Midday leaf potential of millet 56 days after lifting
Underground traits	Vertical and horizontal distribution of root biomass
Tree health	Parasite status / presence of hemiparasite
Tree impacts on physical environment	Soil moisture 0-20 cm soil depth 30, 56, and 70 days after lifting
	Soil temperature 0-20 cm 30 days after lifting
	Soil bulk density at sowing : 0-10, 10-20 and 20-30 cm soil depth under crown / in open area
	N and C total at sowing 0-10 cm soil depth
	P olsen and K, Ca, Mg available at sowing 0-10 cm soil depth

* hill: "*several seeds or plants planted in a group rather than a row*" (Merriam-Webstezr dictionnary)

Main first results : the millet yields were often two times higher near the tree than at mid distance between two trees (Fig. 8). However some variability exists between situations. LAI measurements carried out at flowering or days after (what about Sob sites?) shows that differences of LAI between the pairs of plots were often non-significant (Fig. 9a). Differences in LAI between sites maybe partly related to the differences in dates of measurements. The root:shoot ratio, which is a proxy of the pearl millet carbon allocation strategy, was always higher away from *F. albida* than under its crown cover, which indicated a greater investment in resource acquisition at the expense of yield (Fig. 9b). This is because water and nutrient conditions were worse away from the trees. The root system interactions between the tree (*F. albida*) or the shrub (*G. senegalensis*) with the crop (pearl millet), data

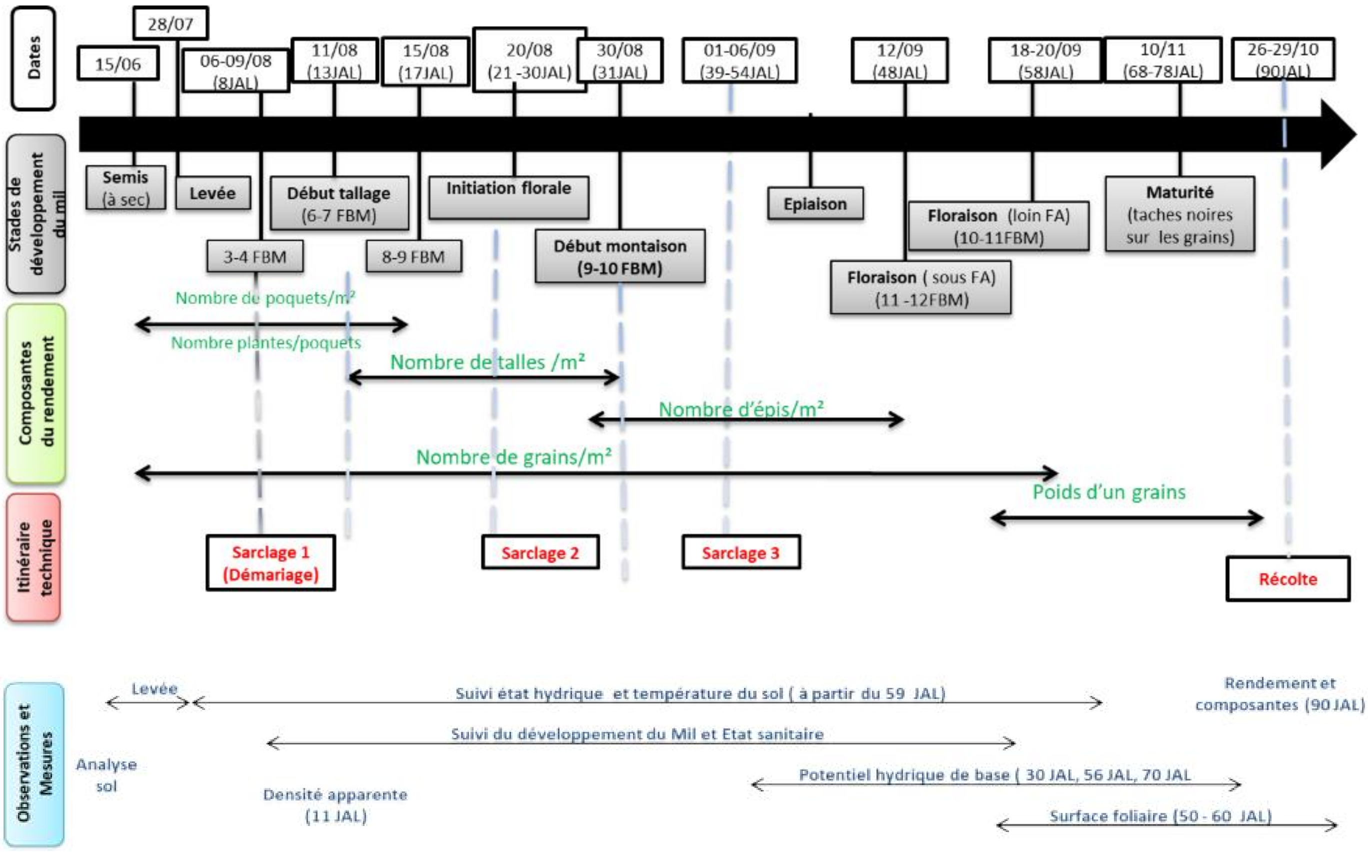


Fig. 7. Farm calender during the millet cycle and the elaboration periods and observations of each component of the millet yield during 2019 campaign

are still recording with scanners and (mini) rhizotrons and will be analysed through AI neuronal network in 2021. However, previous recordings were analysed prior to this project and results were shown and discussed in D 2.2.3. on the tree functioning.

Four master degree reports from UCAD University of Dakar were realized (Sane A; Diouf A., Mboh M., Diatta F.).

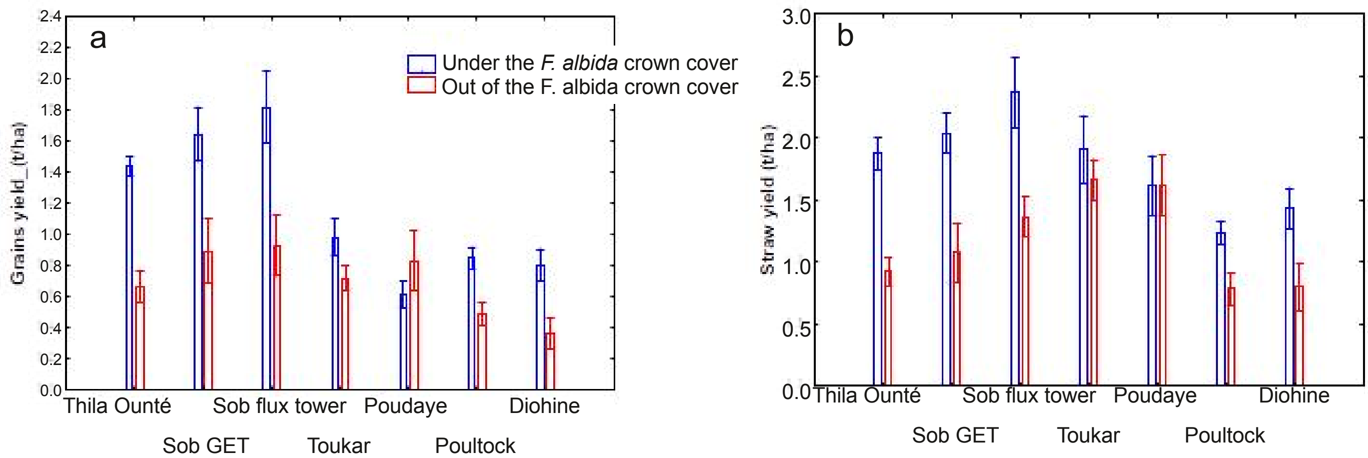


Fig. 8. Grain (a) and straw (b) millet yield under and outside the *F. albida* crown cover in the sampled villages in Senegal

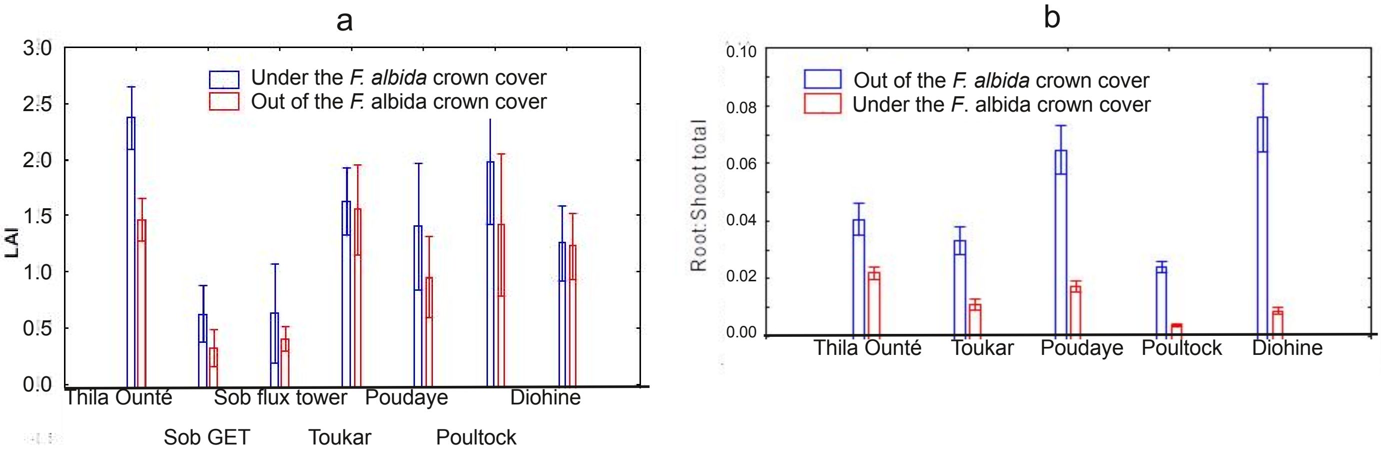


Fig. 9. Leaf Area Index (LAI) (a) and root/shoot ratio (b) under and outside the *F. albida* crown cover

B - On groundnut crop in Sob site (intensive flux measurements "*Faidherbia flux*") according to the distance from the tree (*O. Roupsard + 1 master student*)

Methodology : Most *F. albida* parklands in Senegal are cultivated every year with a biennial rotation of millet (cereal) and groundnut (legume) crops. Crop Net Primary Production was assessed at the plot scale during 2 years, for millet in 2018 (Roupsard et al. AGEE, 2020) and for groundnut in 2019 (MSc F.U. Agbohessou, Agbohessou et al. in prep.). Six (5) trees were selected on the "*Faidherbia Flux*" site at Sob village. For each tree, three (3) plots were delineated (at 1/2 radius of the crown, at the edge of the crown and halfway to the nearest tree). In each plot, grain and fodder yields, Leaf Area Index (LAI) and root biomass were measured. Here we present *F. albida* impacts on the groundnut crop only. The other data analysis are on going.

Results : Effect of tree proximity is not significant on grains yield but is positive on straw yield of millet (Fig.10ab). This low effect comparatively to a cereal crop as millet is probably because the peanut legume is capable to fulfil at least part of its demand of N from the atmospheric N fixation process. Therefore the legume is less dependant on the soil offer for this nutrient.
Root/shoot ratios were significantly higher far from- than close to- the tree (Fig. 10c). Similar results were found with millet (Fig.9b). These results are indicators of increasing stress (soil resources) with increasing distance from *F. albida* trees.

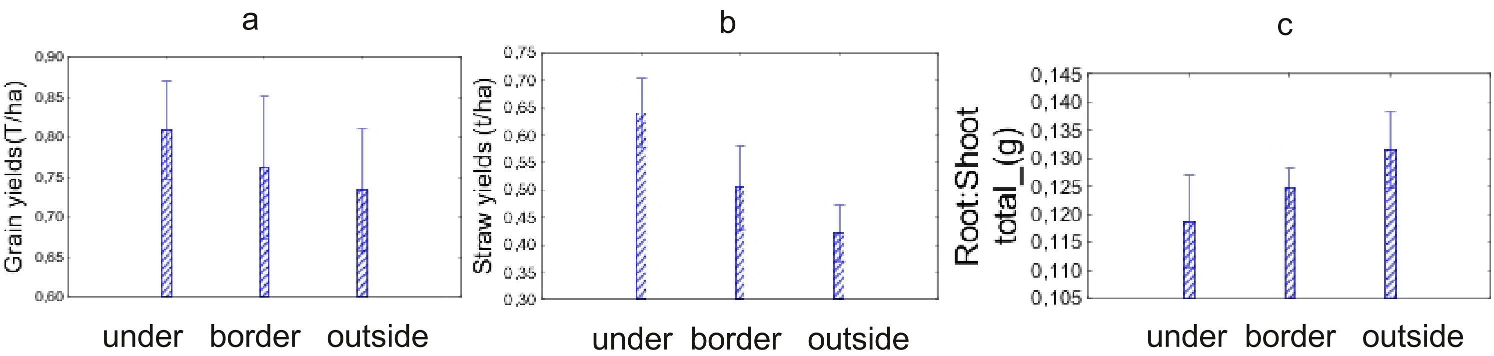


Fig. 10. Grain (a), straw (b) yield, and root:shoot ratio (c) of groundnuts according to the distance from *F. albida* crown cover: under, at the border, and outside, respectively, in Sob village, Senegal

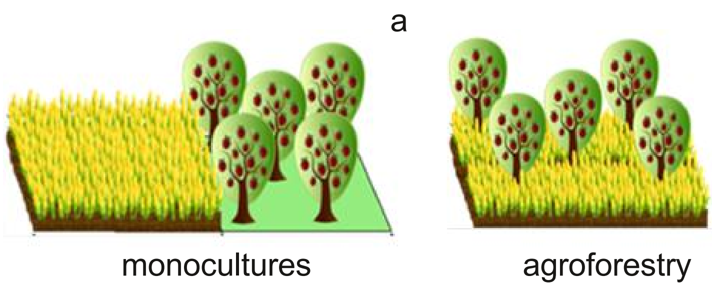
C - On crop yield, biomass and litter at the parkland scale in Sob site (intensive flux measurements "*Faidherbia flux*") (*O. Roupsard et al.*)

This study is an intermediary step toward the services spatialisation at the landscape scale (D.2.3.1)

Methodology : In order to upscale the crop yield, biomass and litter of the sample plots to the whole parkland - i.e. to estimate the Land Equivalent Ratio (LER) as an indicator of the productivity benefit of agroforestry (Fig. 11a) - a new method was used (Roupsard et al., AGEE 2020). It is based on drones (Fig. 11b), multispectral images and geostatistics. The spatial heterogeneity is generally large under agroforestry systems (e.g. yield, biomass, harvest index, litter, soil properties etc.), which makes scaling up complex. The principle is to take benefits of very high-resolution images acquired by drone in the multispectral (MS) domain to obtain reflectance in specific bands and compute various vegetation indices (VIs, e.g. NDVI), with a pixel size of around 4 cm^2 only, all over the entire plots (several ha). Second to correlate VIs with productivity variables (e.g. yield, biomass, LAI, litter etc,) in sample plots distributed systematically inside the plot (typically at various distances from the trees, with replicates). Third to analyze geostatistically the 2D semi-variance of pixel VIs as a function of the distance to tree trunks (for instance), and to infer the distance at which, the trees have no more impact on VIs, i.e. by extension, no more on the growth variables that correlate well with VIs. Fourth, to delineate areas in the plot which are beyond that limit, assumed to represent sole crop areas. Last, to compute the crop partial Land Equivalent Ratio, as the ratio of crop yield in agroforestry divided by sole crop yield. 2020).

This same method is currently being applied to groundnut in the MSc thesis of Agbohessou YF (2020) and under publication.

Results : The study enabled to (i) estimate the distance of influence of agroforestry trees on Millet, to be around 18m, (ii) upscale yield, biomass, LAI and litter from sample quadrats to whole plots through correlations with VIs and compare estimated yield successfully with the actual whole plot yield (iii) estimate the crop-specific Land Equivalent Ratio directly within agroforestry fields (Fig. 12, and table 5).



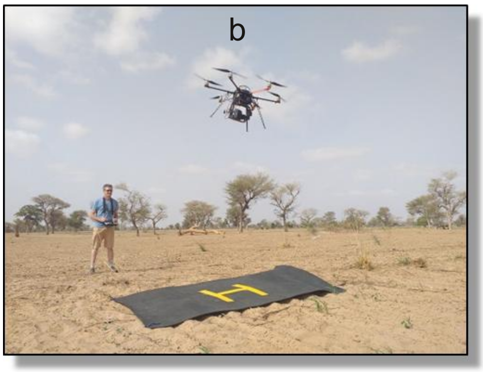


Fig.11. (a) Land Equivalent Ratio (LER) is the ratio of the yield from growing trees and crops together ((a) *right*) to that of the yields from each of the monocultures ((a) *left*) over the same period; (b) Drone as an up-to-date technologies and opportunities

Table 5. Computation of pearl-millet yield and crop-partial Land Equivalent Ratio (LERcp) from subplots to the whole-plot scale; comparison (error) between measurements (in subplots and at the whole-plot scale) and estimations via UAV-NDVI1 product. Yi is the yield in agroforestry used to compute LERcp.

	Method	Variable of interest	Value	Unit
Whole-plot characteristics	QGIS	Whole plot area	8994	m^2
	QGIS	Shelter area	62	m^2
	QGIS	Trunk basal area	2.4	m^2
	QGIS	Whole plot effective area	8929	m^2
	Manual	Subplots area	226	m^2
	QGIS	*F. albida* canopy projected area	862	m^2
	QGIS	*F albida* canopy cover	9.6	%
Harvest	Measured	Subplots harvest	17.6	kgDM grain
	Measured	Whole-plot bundle harvest (without subplots)	52.0	# bundles
	Measured	Whole-plot bundle harvest (without subplots)	1214.6	kgDM bundles
	Measured	Rate of conversion bundle-to-grain	0.52	/
	Measured	Whole-plot grain harvest (without subplots)	632.0	kgDM grain
	Measured	Whole-plot harvest	650	kgDM grain
	UAV-NDVI (Estimated)	Estimated Whole-plot harvest	811	kgDM grain
Yield	Measured	Millet yield as sole crop (5R)	0.48	tDM grain ha^{-1}
	Measured	Millet yield half-distance (2.5R)	0.76	tDM grain ha^{-1}
	Measured	Millet yield under tree crown (0.5R)	1.36	tDM grain ha^{-1}
	Measured	Whole-plot Yield	0.73	tDM grain ha^{-1}
	UAV-NDVI (Estimated)	Estimated Millet yield sole crop (dist > Range)	0.82	tDM grain ha-1
	UAV-NDVI (Estimated)	Estimated Millet yield agroforestry (Crown < dist < Range)	0.92	tDM grain ha-1
	UAV-NDVI (Estimated)	Estimated Millet yield agroforestry (dist < Crown)	1.21	tDM grain ha-1
	UAV-NDVI (Estimated)	Estimated Whole-plot Yield	0.91	tDM grain ha-1
	Error	Yield Error	19.9	%
LER_{cp}	UAV-NDVI (Estimated)	LER_{cp} with *Yi* = actual whole plot yield	1.10	/
	UAV-NDVI (Estimated)	LER_{cp} with *Yi* = whole plot yield for dist < Range	1.16	/
Millet + Weeds litter	UAV-NDVI (Estimated)	Estimated Litter (Crop + weeds)	1.05	tC ha-1

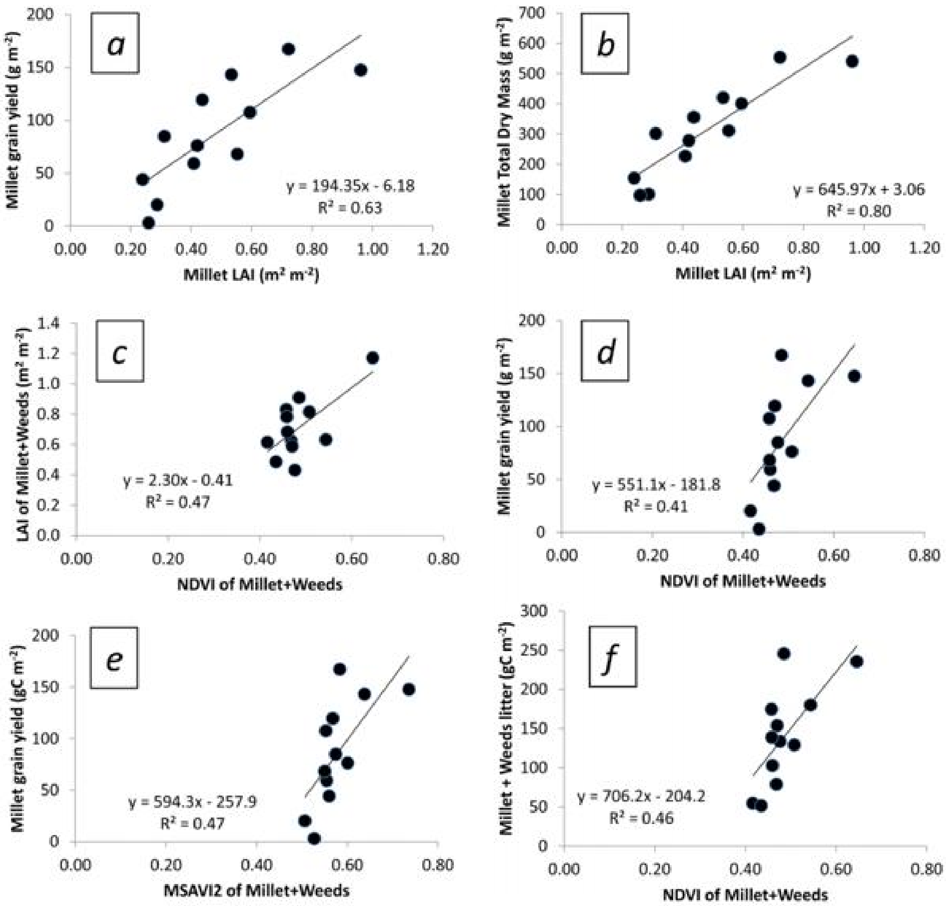


Fig. 12. Correlations between a single reflectance index (NDVI or MSAVI2) and some crop traits : millet grain yield (a), millet total dry mass (b), LAI millet + weeds (c), litter (f), within the harvested subplots (N= 12). Because the UAV could not sense the 0.5R plots, we used pixels from the tree surroundings where the 0.5R plot had been harvested, as proxy to compute NDVI or MSAVI2

D - Indicators (proxy) of the impacts of the tree cover on above-ground crop yields and performances (*C. Jourdan et al.*)

Methodology : The objective is to test the dry mass of the pearl millet clump as an indicator of total root biomass at a depth of 1m..

Results : Concerning the estimation of the belowground production of crops, we have tried to use the pearl millet stump dry mass (sun dry) to act as a proxy of the total root biomass spread out from 0 to a depth of 1m. The results were disappointing (Fig. 13), no relationship was found between poquet biomass and millet root biomass. This lack of relationship could be explained by the high variability of the biomass of the millet stump due to the large heterogeneity of millet plant development.

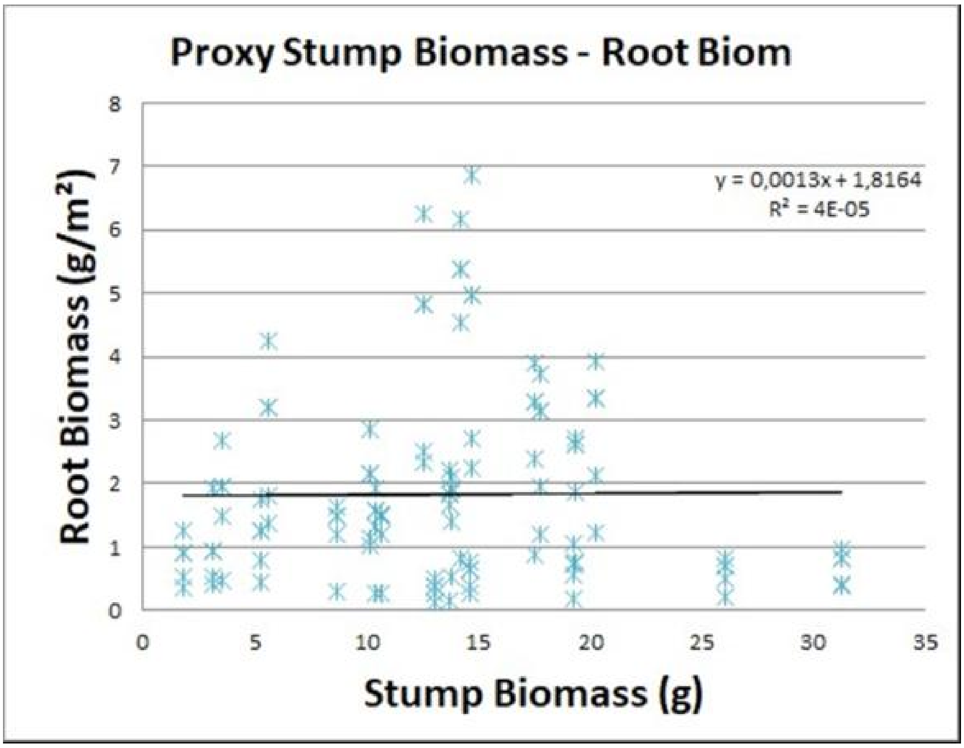


Fig. 13. Relation between millet stump biomass and root biomass on Sob site of intensive flux measurements ("*Faidherbia Flux*")

RAMSES - II