DOI: 10.5281/zenodo.10213230

Afforestation of savannah using cocoa agroforestry: impacts on ecosystem services and effects of associated tree species on soil fertility

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ABSTRACT

Past studies showed a gradual expansion of forest over savannah in forest-savannah transition zones in Central Africa. While the natural encroachment of savannah by forest is more and more impeded by human activities, farmers in Cameroon have proven that afforestation of savannah is achievable using cocoa and specific technics to build up an associated tree canopy. Furthermore, mature cocoa agroforestry systems created on savannah (S-cAFS) or in forest (F-cAFS) exhibit comparable multi-strata structures. By combining measurements of cocoa yield, litterfall, soil quality, carbon storage and tree species diversity along an age gradient (1 to 70 years), we showed that those variables in S- and F-cAFS tended to comparable levels after several decades. Results also emphasized the ability of S-cAFS to increase most of the ecosystem services (including soil fertility and plant diversity) although the time needed to reach levels found in F-cAFS varied strongly amongst variables.

In addition to the previous study, we compared in a second time the impacts of the presence of shade trees on soil functions and cocoa yield in cocoa farms set up after savannah. To do so, we sampled 5 cocoa monocultures and 8 cAFS. Cocoa yield did not vary between these systems. Nonetheless, the soil P availability was improved in cAFS compared to monocultures. Within cAFS, unshaded cocoa conditions showed the lowest soil functions associated with the low leaf litter quality of cocoa plants. Tree species had contrasting effects on soil functions. Cocoa association with the fruit trees *Canarium schweinfurthii* and *Dacryodes edulis* did not improve soil fertility compared with unshaded cocoa, while associations with the legume tree *Albizia adianthifolia*, or the timber trees *Milicia excelsa* and *Ceiba pentandra* significantly improved soil N and P availability. These differences could be explained by the quality of the recycled litter, since low litter recalcitrance was strongly associated with increases in soil N and P availability, while soil pH and soil C contents increased with litter Ca restitution from *C. pentandra*.

Our results highlighted the positive impacts of cAFS establishment in savannah on soil fertility, species diversity and carbon storage in biomass and soil over time. Furthermore, we showed that using specific trees for soil quality and compatible with cocoa, and other trees for the provision of goods, can ensure cocoa AFS multifunctionality and sustainability. Future research will need to understand how plant diversity in these cocoa systems, can help to adapt to climate change.

Keywords: Cocoa agroforestry; ecosystem services; forest-savannah transition, litter traits, soil fertility

DOI: 10.5281/zenodo.10213230

1. Introduction and objectives

At the interface between tropical forest and savannah are areas of high ecological and social stakes in the Congo basin. These areas are a mosaic of vegetation types, with forest penetrating into the savannahs as gallery forests along river banks and as forest patches on plateaus and hills (Cuni-Sanchez et al, 2016). Long term woody encroachment and forest expansion into savannahs in the savannah-forest mosaic, have been widely documented in botanical, remote sensing and soil C isotope studies in Central Africa (Aleman et al, 2017; Gilet et al, 2001; Mitchard and Flintrop, 2013; Cuni-Sanchez et al, 2016; Sagang et al, 2022; Youta-Happi et al, 2003; among several authors). Aleman et al (2017) estimated that since the year 1900, Central African forests have expanded at the expense of savannahs (~ 1.4% net forest expansion, with ~ 135,270 km^2 of savannahs encroached). This result suggests that many savannahs previously considered to be degraded forests are instead relatively old. A recent study done by Sagang et al (2022) in the Mpem & Djim National Park (Centre Region of Cameroon) showed that savannah vegetation, which was initially dominant in the park, lost about 50% of its initial cover in less than 50 years in favor of forest, as a consequence of low fire occurrence due to protection.

However, forest-savannah mosaics are increasingly subject to local agricultural practices, and the natural expansion of forests at the expense of savannahs is currently disrupted by human activities such as cropping and changes in the fire regime of savannah ecosystems. That leads to degraded grassy savannahs, annually burnt and periodically cultivated with food crops. This situation is observed in Cameroon, where the forest-savannah transition zone extends over a strip of about 150 km wide North–South at the border of the semi-deciduous forest (Gilet et al, 2001). Nevertheless, despite unfavorable conditions in herbaceous savannah (low soil fertility, weed competition and risks of bush fire), farmers in this zone have proven that afforestation of savannah is achievable using cocoa and specific technics to build up a tree canopy. As described by Jagoret et al (2012), farmers have set up for decades diversified cocoa agroforestry systems (cAFS) on savannah, by controlling *Imperata cylindrica*, intercropping cocoa with staple crops, providing initial shade to cocoa with banana and/or palm trees, and introducing different types of shade trees. Based on a temporal analysis of aerial photos (years 1951 and 2001) of the village of Kedia located in the savannah-forest mosaic in the Centre Region of Cameroon, Camara et al (2012) showed that 60% of the cAFS were created over large areas (780 ha) in savannah. The authors explained that the expansion of cAFS into grassy savannahs traditionally devoted to annual food crops, was a farmer innovation in response to the lack of forest reserves to be cleared for cocoa cultivation.

Nevertheless, we generally observe that full-grown cocoa agroforests created on savannah and in neighboring forest exhibit comparable multi-strata structure, which raises a question: do cocoa agroforests created on savannahs have the same performances and sustainability as cocoa plantations created in neighboring forests? In order to get evidence on that aspect we implemented a first study to assess the impacts of previous land use (forest or savannah) of cAFS on cocoa production and other ecosystem services on the long run (Nijmeijer et al, 2019a,b ; Saj et al, 2021).

Furthermore, in poor soils such as those in degraded savannahs, the effects of associated shade trees on soil fertility, cocoa nutritional status and yield are expected to vary strongly depending on shade tree species (Isaac et al, 2007; Wartenberg et al, 2019). The objective of our second study was to assess the impacts of agroforestry and different shade tree species, on soil fertility and cocoa yield, in relation to tree functional traits (Sauvadet et al, 2020).

2. Methodology

2.1 Study site

The study was carried out in the villages of Bakoa and Guéfigué, located in a forest-savannah transition zone in the Bokito subdivision (4°30 N, 11°10 E), Centre region of Cameroon. In this area,

DOI: 10.5281/zenodo.10213230

the landscape consists of hills and plateaus with gentle slopes at altitudes ranging from 400 to 550 m a.s.l. This area is characterized by a mosaic of different land uses: herbaceous savannahs, forests, cocoa agroforests (Figure 1) and croplands (Jagoret et al, 2012; Nijmeijer et al, 2019 a,b). Annual average temperature is about 25°C, and annual rainfall ranges from 1,300 to 1,400 mm with a main dry season lasting from mid-November to the beginning of March (Jagoret et al, 2012; Nijmeijer et al, 2019b). Soils are Orthic Ferralsol (Sauvadet et al, 2020).

Figure 1: Cocoa agroforestry system set up at the border of a savannah in Bakoa (Bokito district of Cameroon), Photo Jean-Michel Harmand

2.2 Ecosystem services provision of cocoa agroforestry systems according to previous land uses

We selected 16 plots of cAFS set up on savannah (S-cAFS) and 16 plots set up after secondary forest (F-cAFS) whose age was distributed along a gradient from 1 (farmers just having started the planting of cocoa) to over 70 years old. Plot size was of 40 m x 60 m (2400 m²). Forest and savannah patches were used as controls. Twenty-four ecosystem functions were measured in these systems, related to the following five ecosystem services: carbon storage, species conservation, crop production, nutrient cycling and finally soil quality maintenance (Figure 2).

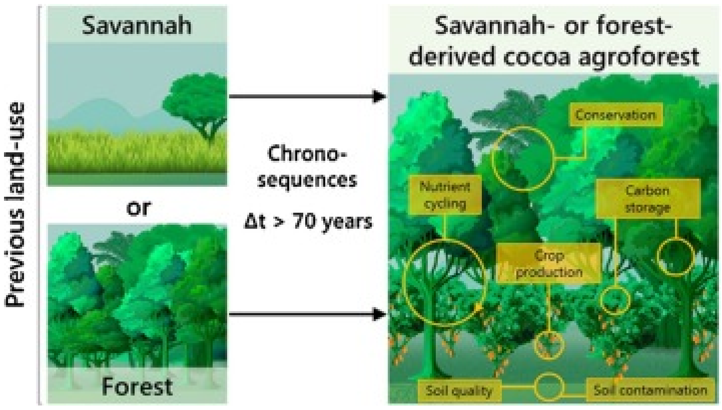

Figure 2: List of ecosystem services assessed in two sets of cocoa agroforestry systems and set-up on savannah or after forest in the Centre Region of Cameroon (Bokito district). From: Nijmeijer A, et al 2019b. Agr. Ecos. Env. 275: 100-111 https://doi.org/10.1016/j.agee.2019.02.004

In each plot, we measured the diameter at breast height and height of all perennial plant species. Aboveground carbon was estimated using allometric equations, such as the one from Chave et al (2005). In each plot, we measured annual litterfall by using litter collectors randomly placed in the

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total area and displaced once a month. We estimated accessible cocoa yield, based on the counting of pods 5 times a year. Soil was sampled on the 0-15 cm layer and we measured soil organic C, organic N, $pH_{(H2O)}$ and other soil parameters (for more details, see Nijmeijer et al, 2019 a,b).

2.3 Shade tree species effects on soil functions and cocoa yield

To study the impact of agroforestry and associated tree species on soil functions, cocoa nutritional status and yield in relation to tree traits, we identified locally different cocoa plots created on savannah: 5 cocoa monoculture plots (≈ 10 years old) and 8 S-cAFS aged from 20 to 60 years old (Figure 3). The 8 cAFS were chosen in the previous study design according to the presence of five associated shade tree species, with contrasting characteristics, regularly occurring in these systems in this area: *Canarium schweinfurthii* and *Dacryodes edul*is (fruit trees, evergreen), *Milicia excelsa* and *Ceiba pentandra* (timber trees, deciduous) and *Albizia adianthifolia* (N_2-fixing tree, deciduous).

Soil was sampled on the 0-10 cm layer under shaded (for cAFS) and unshaded cocoa (for cAFS and monoculture). We measured soil organic C, organic N, NO_3^-, NH_4^+, Olsen P content and $pH_{(H2O)}$. For each modality, we also measured accessible cocoa yield, cocoa leaf macronutrients contents, litterfall, litter macronutrients and tannins contents (for more details, see Sauvadet et al, 2020).

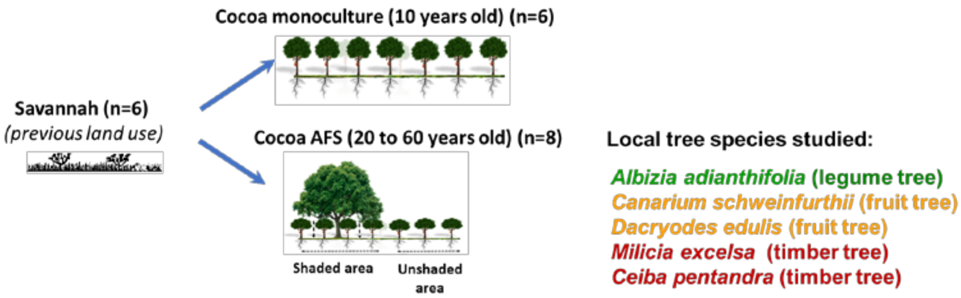

Figure 3: Study design of the effect of agroforestry and associated shade tree species on soil functions and cocoa yield in the Centre Region of Cameroon (Bokito district). (Adapted from Sauvadet et al, 2020. J. Applied Ecol. 57 (3):476-487. https://doi.org/10.1111/1365-2664.13560

3. Results and discussion

3.1. Previous land use effects on cAFS functions

In our site conditions, aboveground carbon (AGC) was highest in the secondary forests (118 Mg C ha^{-1}) and lowest in the woody savannahs (8 Mg C ha^{-1}) (Figure 4). Cocoa plantations established after forest (F-cAFS) showed a mean AGC 40% lower than that of forest but this AGC stock was highly variable among the sampled cocoa plots, partly depending on the intensity of forest clearing (Nijmeijer et al, 2019a). The AGC of plantations established after savannah (S-cAFS) increased with time and reached the mean AGC of cAFS established after forest (F-cAFS) (72 Mg C ha^{-1}) after 75 years (Figure 4). Large associate trees (diameter at breast height > 30 cm) accounted for 70-80% of total AGC in these systems. For F-cAFS and mature S-cAFS, cocoa trees accounted for less than 10% of AGC (6.61 Mg C ha^{-1}) (Nijmeijer et al, 2019a).

DOI: 10.5281/zenodo.10213230

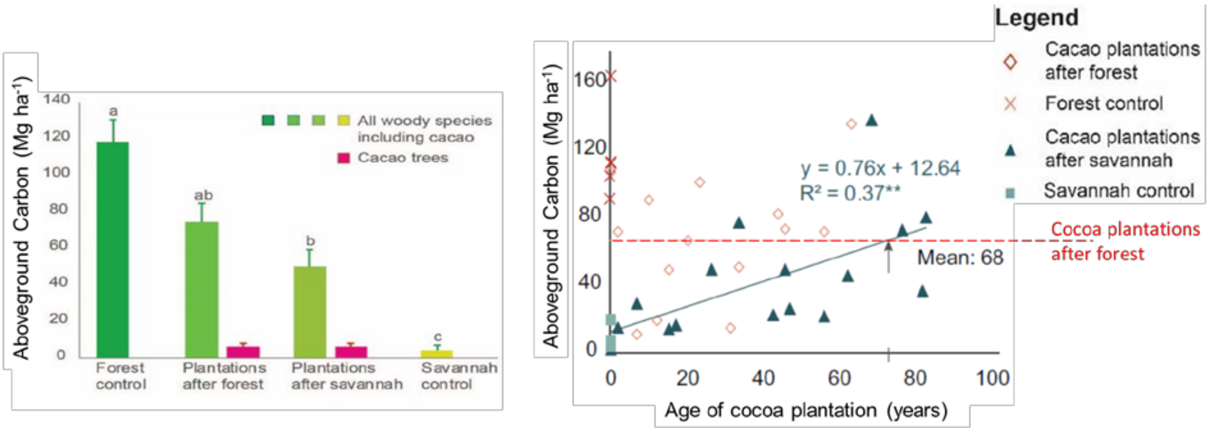

Figure 4: C storage in aboveground biomass of Forest, Savannah, cocoa plantations set-up after forest (F-cAFS) or after savannah (S-cAFS) in the Centre Region of Cameroon (Bokito district). On the left graph, bars with the same letter indicated that values are not significantly different. Adapted from Nijmeijer et al, 2019a. Agroforest. Syst., 93: 851–868. ***https://doi.org/10.1007/s10457-017-0182-6***

Soil organic carbon (SOC) content in the 0-15 cm layer in F-cAFS showed no difference with Forest (~18 mg kg^{-1} soil) and we could not detect any change in SOC content of F-cAFS over time but there was a high variability in plot values. Considering a time of about 80 years after afforestation of savannah, in S-cAFS, SOC increased with time from 12 mg kg^{-1} soil in savannah and at an average annual rate ranging from 7.3‰ to 9.5‰ depending on the soil texture (Figure 5) (Nijmeijer et al, 2019a).

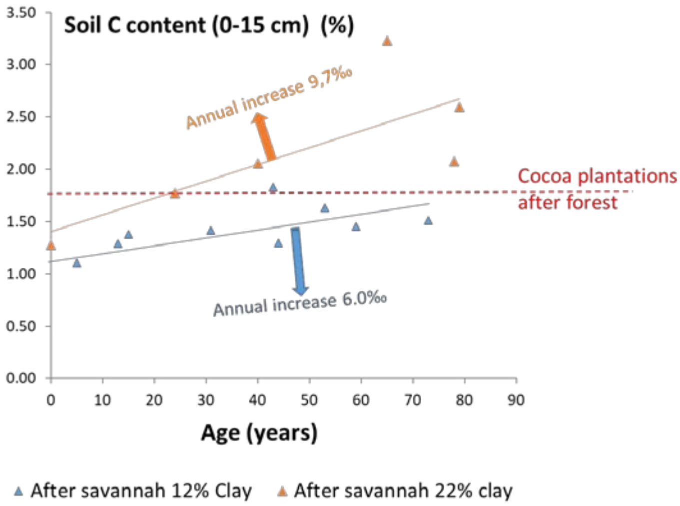

Figure 5: Soil C content of cAFS set up after savannah (S-cAFS) in relation with the age of the system for two categories of soil texture: 12% and 22% of clay content. The red dotted line indicates the average soil C content of cAFS set-up after forest (F-cAFS). Adapted from Nijmeijer et al, 2019a. Agroforest. Syst., 93: 851–868. *https://doi.org/10.1007/s10457-017-0182-6*

Finally, the conversion of degraded savannah ecosystems into cAFS results in a net increase of AGC stock and soil C content over time (Nijmejer et al, 2019a). Likewise, it is clear that the potential for climate mitigation through carbon storage in aboveground biomass of cAFS is a major advantage of cAFS over cocoa monocultures.

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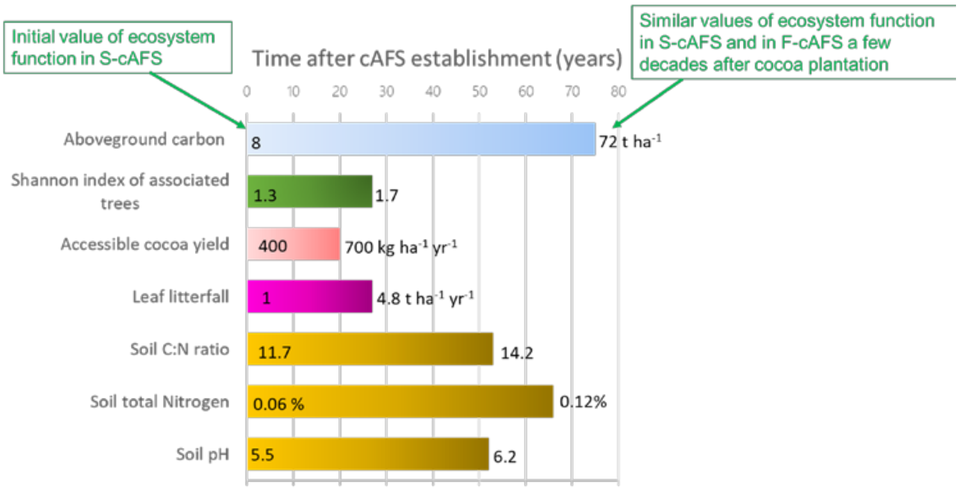

Figure 6: Effects of cocoa agroforests set-up after savannah on aboveground carbon stock, tree species diversity, cocoa production, litterfall, and some soil functions along an age gradient. On the left are initial function values of S-cAFS. On the right are function values of S- and F- cAFS at the same age. Adapted from: Nijmeijer A, et al 2019b. Agr Ecos Env 275: 100-111. https://doi.org/10.1016/j.agee.2019.02.004

Like AGC stock and soil C content, most other ecosystem functions in S-cAFS improved over time and tended to comparable levels of ecosystem functions in F-cAFS, although the time needed to reach levels in F-cAFS varied strongly amongst functions. As shown in Figure 6, twenty to 30 years were necessary to reach the same values for species diversity, cocoa yield and leaf litterfall while 50 to 75 years were necessary to reach the same values for some components of soil quality as for AGC stock (Nijmeijer et al, 2019b).

3.2. Shade tree species effects on soil functions and cocoa yield

Regarding cocoa yield, 10 years old cocoa monocultures were not more productive than 20-60 years old S-cAFS and we did not detect any shade tree species effect on yield (Table 1). Nonetheless, we could observe increased soil P availability and a trend of increase in cocoa leaf P concentration in mature S-cAFS compared to young cocoa monocultures (Table 1). Higher soil P availability in cAFS could be due to higher litter restitution than in cocoa monocultures. We could also observe this contrast within cAFS when comparing areas under or away from shade trees (Figure 7).

However, as detailed more extensively in Sauvadet et al (2020), the shade tree effects on soil functions depended greatly on the species. Amongst the five species studied, the fruit tree species *Canarium* and *Dacryodes* did not allow any improvement of the properties studied excepted total leaf litterfall, while the other species (the timber tree species *Milicia* and *Ceiba* and the legume species *Albizia*) increase the availability of N and P (Figure 7). Furthermore, the timber tree species improved soil pH, but also soil C content in the case of *Ceiba*, while the legume *Acacia* decreased soil pH.

Table 1: Cocoa yield and nutritional status under the different cocoa systems and shade tree associations studied. Significant differences were tested by GLM followed by Tukey HSD post hoc tests and bear different letters for P-values < 0.05. Adapted from: Sauvadet et al, 2020. Sci. Total Environ. 57(3) : 476-487, https://doi.org/10.1111/1365-2664.13560

	Cocoa yield (number of pods per tree)	**Cocoa leaf P concentration** (%)	**Soil Olsen P** (mg P per kg soil)
Cocoa monoculture	22.4 ± 10.5 a	0.11 ± 0.02 a	3.6 ± 0.7 c
cAFS			
In unshaded cocoa area	21.7 ± 10.8 a	0.16 ± 0.06 a	9.3 ± 5.3 b
Under *Canarium*	25.8 ± 13.1 a	0.14 ± 0.02 a	10.9 ± 2.1 ab
Under *Dacryodes*	21.4 ± 9.4 a	0.16 ± 0.05 a	14.4 ± 5.7 ab
Under *Milicia*	23.7 ± 11.8 a	0.17 ± 0.03 a	17.2 ± 5.7 a
Under *Ceiba*	21.5 ± 9.6 a	0.17 ± 0.02 a	18.7 ± 7.2 a
Under *Albizia*	24.9 ± 15.1 a	0.16 ± 0.01 a	21.0 ± 10.6 a

The differences of soil functions observed under shade tree species could be linked to some extent to species litter traits. Indeed, cocoa showed the lowest leaf litter quality, which corresponded to a lower litter decomposition rate than that of associated tree species as shown by Saj et al (2021). The positive impact of Milicia, Ceiba and Albizia could be linked with the higher quality of their litters (low tannin content and high N and P contents), while the absence of effects of the fruit species Canarium and Dacryodes could be associated to their higher recalcitrance (Figure 8).

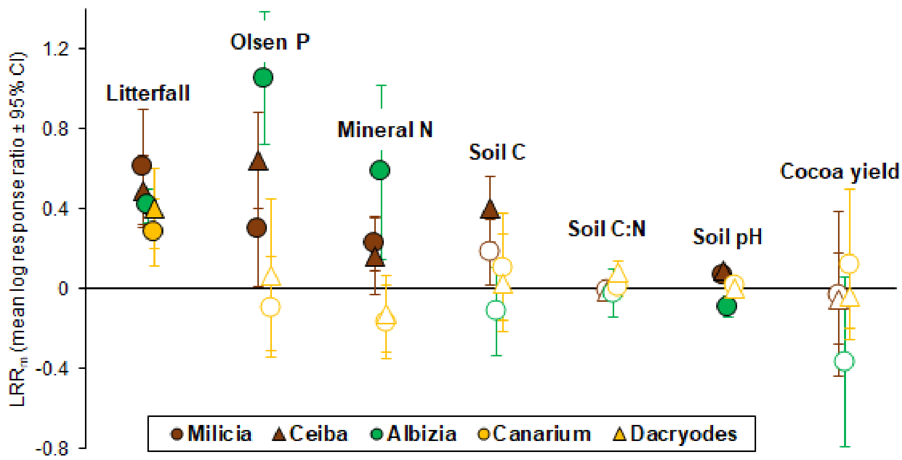

Figure 7: Effects of shade tree species on plant and soil properties. Data were calculated as log response ratio (LRRm) of shade tree associations as compared to the unshaded cocoa reference treatment. Full and empty symbols indicate significant and non-significant effects, respectively. Vertical bars correspond to 95% confidence intervals. Adapted from: Sauvadet et al, 2020. Sci. Total Environ. 57(3): 476-487, https://doi.org/10.1111/1365-2664.13560

On the other hand, the significant increase of soil C content under *Ceiba* could be linked with the higher Ca content of the recycled litter – almost twice higher than under other shade trees and unshaded cocoa (Sauvadet et al, 2020). This finding is in line with the common knowledge that litter Ca typically drives litter decomposability (Hobbie, 2015).

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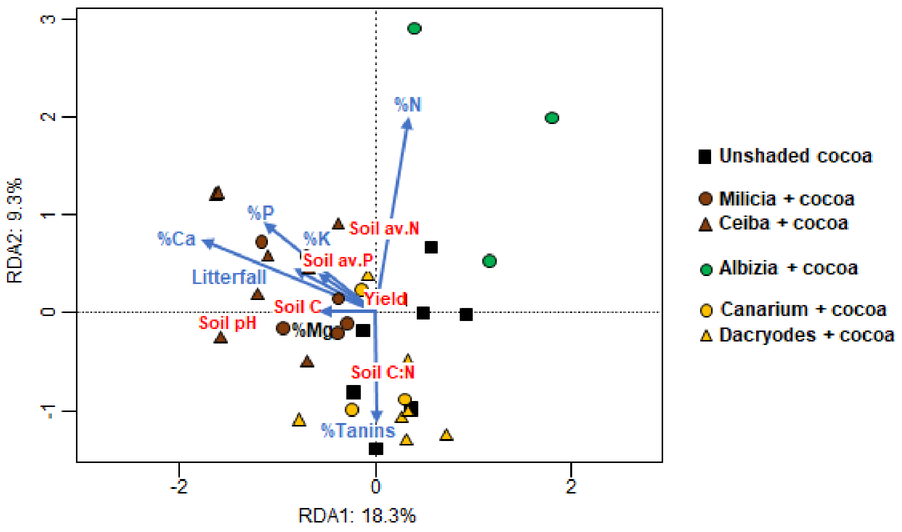

Figure **8**: Redundancy analysis of soil functions and cocoa yield (in blue) constrained by cocoa - shade tree litter characteristics (in black). Adapted from: Sauvadet et al, 2020. Sci. Total Environ. 57(3) : 476-487, https://doi.org/10.1111/1365-2664.13560

In our study we observed also that nutrient (N, P and K) recycling through litterfall under the different shade tree species was equal to or greater than nutrient removal by cocoa beans and husks harvest (data not shown). Therefore our results suggest that deep uptake of nutrients by associated tree species and their recycling through litterfall contribute both to increase top soil nutrient contents and to nutrient export by cocoa harvest.

4. Conclusion

Our results show that planting cocoa trees together with shade trees in degraded savannahs can increase soil fertility, species diversity, carbon storage in vegetation and soil carbon content over time. Furthermore, cocoa-based agroforestry systems set-up on savannah or after forest display convergent profiles of ecosystem functions in the long run (including cocoa production) (Nijmeijer et al, 2019 a,b). Like cAFS set-up after forest, cocoa systems set-up on savannah have shown a long economical life, resulting from the association with shade trees and from a rational management of cocoa and the whole system.

Our study highlighted the benefits of introducing shade trees on agroecosystem multifunctionality on poor sandy soils, where the putative balance between lower light availability and higher soil nutrient availability may maintain similar cocoa yield. Such benefits ranged from improved soil fertility and higher soil C content to higher cocoa nutritional status, which nonetheless depended on the tree species. High leaf litter Ca and low tannin contents of shade trees appeared particularly important to improve the local poor sandy soil conditions. These results underline the need to go beyond classical indicators of litter quality and soil functioning (Sauvadet et al, 2020) and the importance to consider long-term litter and nutrient cycling in assessment of agroecosystem sustainability.

5. Recommendations

Overall, it appears that cAFS set up on degraded savannahs are a clear example of a climate smart agricultural system that is to be better considered by both the stakeholders of cocoa value chain and those of forest-savannah territories. Farmers have been implementing afforestation of degraded savannahs with cocoa in some districts of the Centre Region of Cameroon, but this farmer innovation stays at local level and is poorly diffused.

Particular constraints prevail for the establishment and early growth of cocoa after savannah: the control of bush fires during the dry season is necessary; savannah with too sandy soil texture should be discarded to avoid too low soil fertility; the control of gramineous weeds due to low shade also is necessary. When implementing cocoa agroforestry systems into savannahs, using specific shade trees for the provision of goods, and other trees for soil quality, both compatible with cocoa, can ensure multifunctionality and sustainability of cocoa systems.

As often less than 100 mm of rainfall occur during the three months of dry season in this area, further studies are necessary to understand how plant diversity can help to adapt to climate change in the context of the forest-savannah transition zone in Central Africa.

Acknowledgements

The present studies were supported by different research projects: AFS4FOOD (EuropeAid/130-741/D/ACT/ACP), SAFSE (CIRAD, IRD), STRADIV (Agropolis Fondation no. 1504-003) and SoCa (BNP Paribas Foundation, no. 306735/00). This research was conducted within the Research and Training Platform ‘‘DP Agroforestry Cameroon’’ and within the framework of the CGIAR Research Program on Forests, Trees and Agroforestry (FTA). Soils and plants sampling and analysis and other technical operations received support from staff of IRAD (Institute of Agricultural Research for Development of Cameroon), CIRAD, ICRAF and IITA in Cameroon, and from CIRAD, IRD, INRAE, CNRS-CEFE in Montpellier, France and IRD in Dakar, Senegal.

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