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Influence du précédent sur les trajectoires des systèmes agroforestiers à base de cacaoyers à Bokito (Centre Cameroun) étude à long terme sur une sélection de caractéristiques écosystémiques

Annemarijn Nijmeijer

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THÈSE POUR OBTENIR LE GRADE DE DOCTEUR DE MONTPELLIER SUPAGRO

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École doctorale GAIA – Biodiversité, Agriculture, Alimentation, Environnement, Terre, Eau
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Legacies of past land-use in complex cocoa agroforestry systems in Bokito (Central Cameroon): long-term effects on ecosystem multifunctionality

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Le 27 novembre 2017

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FRENCH SUMMARY

Influence du précédent sur les trajectoires des systèmes agroforestiers à base de cacaoyers au Centre Cameroun (région de Bokito) : étude à long terme sur une sélection de caractéristiques écosystémiques

Introduction

La culture du cacao est une des pratiques conduisant au changement d'usage des terres agricoles et de conversion de milieux naturels dans les zones tropicales. Au cours des dernières décennies la demande en cacao a fortement cru provoquant une augmentation de la production qui est passée de 1.2 M t de fèves sèches en 1961 à 4.5 M t en 2014. Dans le même temps, la surface cultivée en cacao est passée de 4.4 M ha à 10 M ha (FAO, 2017). Sachant que la productivité mondiale de fèves stagne depuis 1989, oscillant entre 434 kg ha⁻¹ et 513 kg ha⁻¹, l'accroissement de la demande en cacao augmente la pression sur les surfaces où la cacaoculture est possible (Vanhove et al., 2016). Le cacaoyer étant une plante tropicale originaire des sous-bois de l'Amazonie, sa culture est limitée entre 20 °N and 20 °S de latitude pour une altitude maximale de 600 m (Verlière, 1981). La température moyenne optimale varie entre 20 et 30°C (avec des différences saisonnières peu marquées) et le niveau de précipitation doit être compris entre 1000 et 2000 mm an⁻¹ (le cacaoyer est principalement cultivé dans des zones recevant plus de 1250 mm an⁻¹ avec un minimum de 100 mm mois⁻¹, et de 65 mm mois⁻¹ lors des saisons sèches) (Wood and Lass, 2001). Au niveau mondial, plusieurs millions d'hectares de forêts ont été défrichés et convertis pour soutenir cette production (Vaast and Somarriba, 2014). Entre 1960 et 1990, la Côte d'Ivoire a acquis le rang de 1er exportateur mondial au prix de défrichements très importants : on estime que 75% de la forêt du territoire ivoirien a été défriché le plus souvent pour laisser place à des monocultures de cacao pures ou très légèrement ombragées (Freud et al., 2000). Ces plantations monospécifiques ont une très faible valeur en termes de stockage de carbone et de biodiversité comparée aux écosystèmes forestiers dont elles sont issues (Tondoh et al., 2015). Cependant, une partie de la production cacaoyère est encore réalisée au sein de systèmes agroforestiers complexes sous forme de vergers de sous-bois, désignés par l'acronyme 'SAFc' dans la suite de ce texte. Dans ces SAFc, les cacaoyers co-existent avec d'autres plantes, annuelles ou pérennes, ayant le plus souvent un usage alimentaire, de fourrage ou de bois d'œuvre. Cette caractéristique permet aux SAFc de soutenir des niveaux de fonctions écosystémiques plus élevés que les systèmes monospécifiques (Andres et al., 2016). Leur niveau de biodiversité est inférieur à celui des forêts primaires mais il est supérieur à celui des monocultures (Schroth and Harvey, 2007). La plupart des cacaoculteurs préservent certaines espèces d'arbres pour des raisons qui leur sont propres. Ces raisons sont très variables et peuvent être d'origine écologique, agronomique, géographique, sociologique ou économique. Cependant les usages qui sont fait de la végétation peuvent généralement être assez clairement catégorisés. Par exemple Jagoret et al. (2014) et Saj et al. (2017) ont distingué quatre catégories d'usage : production de bois, favorisant la production cacaoyère, production de produits alimentaires (non issu des cacaoyers), usages culturels et cultuels (pharmacopée, religion, divertissement, outillage). Mais les SAFc possèdent également des fonctions

écosystémiques non-productives. Ces fonctions généralement considérées comme « secondaires » en agriculture car non directement associés à la production agronomique, s'illustrent de différentes façons : modification du vent et de la température générant ainsi un microclimat intra-parcellaire tamponné par rapport au milieu général (Verchot et al., 2007), amélioration de la structure et de la fertilité des sols (Schmitz and Shapiro, 2012). Isaac et al. (2005), facilitation de la redistribution hydraulique au sein des différents horizons de sols (van Noordwijk et al., 2014) ou encore accumulation de biomasse sur le long terme (Dixon, 1995; Saj et al., 2013; Schroth et al., 2002). Plusieurs études montrent par ailleurs des relations positives entre biodiversité et contrôle des maladies et ravageurs (Schroth et al., 2000) ou des herbivores (Bisseleua et al., 2009), avec des effets de bords depuis des îlots forestiers (van Bodegom and Price, 2015). La biodiversité relativement élevée au sein des SAFc pourrait également promouvoir le recyclage des nutriments grâce à l'apport de quantités importantes de litières foliaires, celles-ci pouvant posséder des caractéristiques très différent(e)s en termes de dégradabilité ou de quantité de nutriments (Okubo et al., 2012; Prescott, 2002). Ces fonctions écosystémiques « secondaires » sont la plupart du temps absentes des systèmes monocultureux du fait de leur faible diversité (Bhagwat et al., 2008; Bisseleua et al., 2009; Schroth and Harvey, 2007). A contrario, cette diversité semble représenter un des compromis majeurs au sein des SAFc car elle peut limiter la production cacaoyère de par la compétition interspécifique qu'elle engendre (Saj et al., 2017b; Somarriba et al., 2013). Ceci étant, il est régulièrement mentionné que pour de nombreux exploitants ces compromis sont compensés par le soutien à la sécurité et à la diversité alimentaire ainsi que par les revenus complémentaires qu'apportent les productions des végétaux associés (Gockowski et al., 2010; Saj et al., 2017a, 2017b; Schroth et al., 2002).

Problématique et objectifs

Le fonctionnement d'un (agro)écosystème à un instant t dépend de ses caractéristiques à cet instant mais également potentiellement des caractéristiques de l'(agro)écosystème qui l'a précédé. L'influence de ce précédent a été démontré pour tout un panel de fonctions écosystémiques comme le recyclage des nutriments, la séquestration de carbone, la communauté microbienne du sol et la respiration hétérotrophique (Dupouey et al., 2002; Freschet et al., 2014; Kallenbach and Stuart Grandy, 2015). En général, les compartiments les moins influencés par le changement d'usage des terres sont les horizons minéraux des sols (Dawoe et al., 2009; Laclau et al., 2003; Marques and Ranger, 1997). Mais les compartiments organiques, qu'ils soient aériens ou souterrains, incluant la matière organique des sols et leurs organismes vivants, semblent fortement influencés par le précédent (Bellemare et al., 2002; Jangid et al., 2011; Perring et al., 2016). Ceci reste vrai, sauf si d'importantes perturbations subies par le système conduisent à la constitution d'écosystèmes nouveaux (Hobbs et al., 2006).

Les SAFc sont en règle générale créés sur précédents forestiers primaires ou secondaires. Cependant, des installations sur savane ont été mentionnées et étudiées par quelques chercheurs ces dernières années, notamment au Centre Cameroun (Jagoret et al., 2011; Ruf et al., 2004). Les écosystèmes forestiers et savaniques possédant des caractéristiques et des fonctionnements clairement différents, cette thèse cherche à mieux caractériser les influences respectives de ces deux précédents lors de l'installation puis de l'exploitation d'un SAFc, et d'en analyser la dynamique temporelle. L'installation d'un SAFc sur savane (S-SAFc) peut paraître désavantageuse comparée à une installation sous forêt (F-SAFc). Il y

a des différences majeures, par exemple, en termes de quantité, de qualité et de distribution spatiale et temporelle de la matière organique entre ces systèmes. Ces différences se traduisent par des dynamiques nutritionnelles (notamment en azote et en phosphore) déjà bien caractérisées (Sugihara et al., 2015). Ainsi, alors que les F-SAFc profitent d'une « rente forestière » en termes de potentiel de fertilité des sols au moment de l'établissement du couvert cacaoyer, ce potentiel se construit dans le temps pour les S-SAFc.

L'objectif principal de cette thèse est d'identifier les effets du précédent usage des terres (savane et forêt) sur différentes fonctionnalités caractéristiques des agroforêts à cacaoyers à Bokito (Centre Cameroun). Hormis l'étude de ces effets sur le long terme (plusieurs dizaines d'années), nous voulons acquérir une meilleure idée des conditions de la durabilité de ces systèmes et des dynamiques structurelles et compositionnelles qui y sont associées.

Pour ce faire, trois sous-objectifs sont déclinés :

1) Identifier les similitudes et les différences de structures et de fonctionnalités entre S-SAFc et F-SAFc ainsi qu'avec leurs précédents respectifs.

Nous posons les hypothèses suivantes :

- Les pratiques de gestion des planteurs maintenant une importante diversité végétale jouent rôle un significatif dans le niveau de multifonctionnalité des SAFc.
- La conversion d'une forêt en F-SAFc est « abrupte » et induit des différences directement visibles entre le SAFc et son précédent ; la conversion d'une savane prend plus de temps, car elle demande que les arbres associés se développent, et induit des différences dans un premier temps peu visibles mais dont l'intensité va croissante avec l'âge du SAFc.
- Les S-SAFc stockent en moyenne moins de carbone dans le compartiment aérien que les F-SAFc. Les S-SAFc stockent en moyenne plus de carbone que leur précédent, les F-SAFc moins que leur précédent.

2) Identifier, pour quelques services et fonctions écosystémiques, le pas de temps sur lequel les différences entre S- et F-SAFc se maintiennent.

Nous posons les hypothèses suivantes :

- L'influence du précédent a un impact à long terme sur la trajectoire et le niveau des fonctions écosystémiques étudiées.
- cette influence est détectable plus longtemps au sein des S-SAFc qu'au sein des F-SAFc.
- Les S-SAFc présentent sur le long terme des niveaux de stockage de carbone dans la biomasse aérienne et dans la matière organique des sols comparables aux niveaux des F-SAFc.

3) Identifier si les différences structurelles et compositionnelles observées entre S- et F-SAFc se traduisent par des dynamiques de processus écosystémiques différenciables et, le cas échéant, le

rôle des arbres associés dans ces processus.

Nous posons les hypothèses suivantes :

- La quantité totale de litière issue de la chute des feuilles ainsi que la proportion de feuilles de cacaoyers dans les SAFc diffèrent en fonction du précédent mais ces différences s'estompent avec le temps.
- La dynamique intra-annuelle de chute des feuilles est négativement corrélée à la pluviométrie.
- Si les espèces associées au sein des SAFc augmentent la diversité fonctionnelle de la litière en général, la perte de masse de la litière issue du cacaoyer pourrait s'en trouver augmentée de par des effets non-additifs indépendants du microclimat parcellaire.

Matériels et Méthodes

Afin de répondre à ces objectifs, 32 parcelles de SAFc ont été sélectionnées en juillet 2015 au Centre Cameroun, plus précisément dans les villages de Bakoa et de Guéfigué, appartenant à l'arrondissement de Bokito (4°30 latitude N and 11°10 longitude E; 7125 km²). Il s'agit d'une zone de transition forêt-savane qui s'étend sur une bande d'environ 150 km de large orientée nord-sud à la frontière de la forêt semi-caducue du Cameroun (Guillet et al., 2001). Cette région est caractérisée par une mosaïque de forêts et des savanes herbacées brûlées annuellement et dominées par l'espèce vivace *Imperata cylindrica* (Jagoret et al., 2012). Les précipitations annuelles moyennes y varient de 1 300 à 1 400 mm et la saison sèche principale dure plus de trois mois, de mi-novembre à mars (Jagoret et al., 2012). Ces conditions climatiques ne sont pas considérées comme optimales pour la production de cacao. Les sols de Bokito sont à dominante ferrallitique légèrement desaturés (Elangwe, 1979). La topographie de la région est composée de collines aux pentes douces et s'étalant d'une altitude de 400 à 550 m. Les plantations cacaoyères y sont agroforestières et complexes, comptant de nombreux arbres associés où se côtoient espèces fruitières et à bois (Jagoret et al., 2011; Saj et al., 2013; Sonwa et al., 2007).

Quatorze parcelles ont été sélectionnées sur précédent savane (S-SAFc) et 14 autres sur précédent forêt (F-SAFc) avec une distribution régulière de leurs âges allant de 1 à plus de 60 ans. Cinq parcelles témoins par précédent (savane et forêt secondaire) ont été sélectionnées pour comparaison avec les SAFc. Dans chaque parcelle, différentes variables ont été mesurées sur les compartiments aérien et souterrain des plantes, et sur la litière : la structure et la composition de la végétation de type arborée, les biomasses aériennes et souterraines de cette végétation et les rendements accessibles en cacao marchand ont été estimés. Par ailleurs un protocole de récupération des chutes de litières a été mené sur une durée d'une année complète pour étudier leurs dynamiques intra-annuelle ; les stocks de litière au sol ont été estimés deux fois durant cette même année ; pendant 7 mois, une étude de décomposition de la litière issue des feuilles a été effectuée. Des échantillons composites de sol ont également été prélevés aux profondeurs de 0-15 cm et de 15-30 cm pour analyses physico-chimiques. Enfin, dans chacune des 32 parcelles, les racines fines ont été prélevées sur une profondeur de 0 à 10 cm et ont été étudiées jusqu'au 3ème ordre de ramification.

Principaux résultats et points essentiels de la discussion

Les résultats montrent que, pour la plupart des variables étudiées, l'influence du précédent était observable plus longtemps après une installation sur savane. La quantité de carbone contenu dans la biomasse aérienne (CBA) est la plus élevée en forêt (118 t ha⁻¹) et la plus faible en savane (8 t ha⁻¹). Les systèmes créés sous forêt (F-SAFc) contiennent 40% de moins de CBA que les forêts témoin et il n'est pas observé de dynamique de stockage sur le temps long. Le CBA des S-SAFc augmente avec le temps et atteint la moyenne du CBA des F-SAFc (72 t ha⁻¹) après environ 75 ans d'exploitation. Le taux de carbone organique des sols (COS) se révèle dépendant de la profondeur du sol et de la teneur en argile. Dans les F-SAFc, le taux de COS ne démontre pas d'évolution significative avec le temps ni de différence avec celui des forêts témoin. Dans les S-SAFc, en considérant une période de 80 ans depuis l'afforestation, le taux d'accumulation annuelle du COS dans l'horizon 0-15cm est estimé entre 7,3‰, dans les sols à faible teneur en argile (10-15%), et 9,5‰, dans les sols contenant 20-25% d'argile. Aucune évolution de ce taux n'est notée dans l'horizon 15-30 cm. L'impact du précédent savane sur les fonctions étudiées se traduit par un maintien de son influence jusqu'au moins 10 ans voire 15 ans après l'installation. Ces effets sont particulièrement visibles sur la biomasse, la production de litière et son stock ainsi que sur les paramètres de fertilité du sol. A contrario, la conversion de la forêt en F-SAFc semble mener à des changements rapides dans le système aérien mais les caractéristiques du sol ne varient pas ou peu. Les rendements accessibles en cacao sont comparables pour les deux types de SAFc tout au long de la chronoséquence étudiée. L'association faiblement négative entre la biomasse des plantes pérennes et les rendements du cacaoyer dans les F-SAFc souligne potentiellement les compétitions interspécifiques qui s'y manifestent. A l'inverse, dans les S-SAFc, l'association positive entre la biomasse des plantes pérennes et les rendements en cacao mettent l'accent sur la stratégie "gagnant-gagnant" des agriculteurs. En effet, seule l'association du cacaoyer avec des arbres associés permet la mise en place de ce système notamment en maîtrisant l'enherbement et l'ombrage (Jagoret et al., 2012). La production de litière d'origine aérienne des SAFc au Centre Cameroun se révèle relativement plus élevée que dans d'autres régions du monde mais n'atteint pas celle des forêts témoin échantillonnées. La production de litière d'origine aérienne des S-SAFc atteint le niveau de celle des F-SAFc au bout de 15 ans. L'étude de la décomposition de la litière feuillue, permet de confirmer que les feuilles de cacao produisent une litière de mauvaise qualité, cette dernière se décomposant moins rapidement que la litière issue des feuilles d'arbres associés. Cependant, il n'a pas pu être démontré d'effets clairs sur la décomposition des feuilles de cacaoyer quand les deux types de litières se sont mélangés. Par ailleurs, des pics inattendus de production de litière aérienne (feuilles en particulier) sont observés, vraisemblablement causés par une saison sèche particulièrement longue et intense lors de l'année d'étude. Si tel est le cas, ce constat soutient l'hypothèse de la vulnérabilité du cacaoyer face au changement climatique, notamment une augmentation de la fréquence et de l'intensité des épisodes de sécheresse.

Dans l'ensemble, nos résultats montrent l'impact élevé de la conversion de la savane en SAFc : les influences de cette dernière sur les fonctions écosystémiques étudiées ne s'effritent qu'au-delà de 14 ans. La gestion par les planteurs des S-cAFS qui en sont issus donne naissance cependant naissance à des systèmes originaux aux caractéristiques similaires aux F-SAFc sur le temps long. Une attention plus particulière pourrait être accordée aux SAFc les plus jeunes (0-14 ans) et à maturité (15 à 30 ans) afin

de mieux renseigner sur les trajectoires des changements écosystémiques qui s'y déroulent. Par ailleurs, des études topographiques et archéologiques pourraient aider à expliciter certaines des différences observées en termes de texture et de teneur en certains éléments des sols. De plus, dans cette zone, mais aussi plus généralement dans les régions africaines de transition forêt-savane, il serait pertinent d'avoir une meilleure appréciation des superficies actuellement occupées par les S-SAFc et celles qui seraient potentiellement mobilisables. Une telle initiative permettrait d'évaluer dans quelle mesure l'afforestation des savanes pourrait être mise en œuvre sans pour autant provoquer de concurrence avec d'autres productions agricoles locales qui s'appuient sur les (agro)écosystèmes savanicoles. Enfin, l'afforestation de la savane tel qu'il est pratiqué à Bokito semble une stratégie locale très pertinente, basée sur de fortes connaissances empiriques, et capable de valoriser la multifonctionnalité des SAF tout en proposant des systèmes stockeurs de C dans les compartiments aériens et souterrains. Les S-SAFc semblent donc pouvoir contribuer à l'atténuation du changement climatique, et constituer de bons exemples de systèmes agricoles répondant à l'échelle de la parcelle aux critères des initiatives telles que le « 4 pour 1000 » ou encore « d'agriculture climato-intelligente » (CSA). Un tel constat plaide pour un approfondissement des connaissances sur le fonctionnement de ces agrosystèmes à cacaoyer. Pour aller dans ce sens, la question de la vulnérabilité accrue des SAFc en zone de transition forêt-savane face au changement climatique doit être posée. En effet, outre les réelles synergies qui sont désormais régulièrement décrites dans ces systèmes, des compromis y sont aussi à l'œuvre. Ainsi, la concurrence pour l'eau entre arbres associés et cacaoyers peut y être potentiellement prégnante, en particulier si l'augmentation de fréquence et d'intensité des saisons sèches se vérifie. Un travail sur les capacités de résilience et d'adaptation des SAFc face à des conditions climatiques changeantes semble donc nécessaire. Il permettrait de mieux apprécier les conditions environnementales et les caractéristiques structurelles et compositionnelles des SAFc qui permettraient une préservation de la production cacaoyère, entre autres productions, réaliste et acceptable pour les planteurs.

INTRODUCTION



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"inflorescent"

Ecosystem functioning

Boundaries of ecosystem functioning are set by several state factors including: a specific climate, the soil bedrock, the topography, the biota present in a place and the time. Elements influencing these factors depend on the scale at which they are observed. Globally, climate would be the strongest determinant, separating the biomes. In terrestrial ecosystems, regional variation is highly related to the soil parent material and the subsequent soil type which, combined to local climatic conditions, highly influence primary production. Topographical differences both influence microclimate and soil development at a local scale and finally diversity is mainly determined by the potential biota on a specific site. Time is a special factor since, depending on the timeframe, it interacts on all levels. Next to these factors are several interactive controls of importance for overall ecosystem functioning. These controls include the availability of resources such as light availability. Other interactive controls include the physical and chemical properties influencing the rates of ecosystem processes, such as pH and temperature, the biotic community, and the disturbance regime, in which human activities play a special role (Chapin et al., 2011). Since none of the ecosystem functions are isolated, the extent of human activities has an impact on all ecosystems. Human activities impact ecosystem functions either directly or indirectly as underlined for instance by the climate change currently observed (Chapin et al., 2011). Disturbances, natural or anthropogenic, lead to long term fluctuations in ecosystem structure and functioning. The frequency, type, size, timing, and intensity of a disturbance determines its impact and could eventually lead to land-cover or land-use change (Chapin et al., 2011).

Land-use change

Land-use change is by definition not the same as land-cover change. Land-cover change includes all biophysical changes observed on the earth's surface while land-use change demands the action of humans and their intentions (Meyer and Turner II, 1992). Land-use change can be the result of changes in fixed factors and the interactive controls like changes in a disturbance regime. The biggest impact on today's ecosystem functions is caused by anthropogenic activity that alters about 50% of the earth's ice-free land surface (Turner et al., 2007). A considerable part of the land-use changes occurred in a relatively short time, during the two to three last centuries (from the XVIIIth century). The most direct and substantial alterations are caused by agricultural activities, on around 40 %, of the land, leaving a patchwork of agricultural fields, pastures, and remnant unmanaged ecosystems (FAO, 2016; Foley et al., 2005; Turner et al., 2007).

Land-use change can be divided in two major forms (Meyer and Turner II, 1992). First, land-use change can be undertaken without radically changing the physical environment or dominant plant functional type. In this case, ecosystem processes, community structure, and population dynamics are significantly affected as for example when a natural forest is transformed into a managed forest. Secondly, land-use change can also comprise land-use conversion that switches an ecosystem type to another characterized by a different physical environment or plant functional type. This is the case for example when forest is changed into pasture (Lambin et al., 2003).

The land-use conversion that has the biggest impact in terms of spatial extent and consequences for ecosystem functioning is deforestation. Over the past 5000 years globally nearly 50% of the total forest area has been lost. For a long period, deforestation happened mainly in the temperate zone but since the XIXth century, it has largely spread to tropical regions concomitantly to the expansion of agricultural areas (FAO, 2016). In those tropical regions, one of the most used techniques for land preparation for agriculture is known as slash-and-burn. It often involves the complete clearing of forest for crops. The cleared land is cultivated for several years before being left into a fallow (of varying durations). This process leads to major above- and belowground carbon losses. Recent studies have estimated that around 130 Peta gram C from the first 2 m of soil got lost (Sanderman et al., 2017), due to vegetation destruction, leaching and rainfall-induced soil losses (Don et al., 2011; Hosonuma et al., 2012; Kotto-Same et al., 1997; van Noordwijk et al., 2002). Since population in most tropical African countries is still increasing and around two-third of the population in tropical zones depend to some extent on agricultural activities, the pressure on land available for agriculture is still growing (Herrero et al., 2010). This leads, besides increased clearing of forested areas, to increased frequencies of shifting cultivation practices (Defries et al., 2010; Zhang et al., 2002). Initially, after 1 to 3 years of cropping, a fallow period of 30 to 40 years followed, which allowed the regrowth of a secondary forest and rebuilding of the soil supporting it. Simultaneously to increase of land pressure, fallow periods shortened. Often fallow periods are so short that seed sources of mid-successional species get eliminated, impairing successional tree regrowth. This leads to landscapes dominated by active cropland or early successional weedy species (Kafle, 2011; Ngobo et al., 2004; Rahman et al., 2012; Styger et al., 2007; Yemefack et al., 2002). Next to the conversion of forest also tropical grasslands are frequently exploited for agricultural purposes. The UNDP (2003) estimated that over half of the tropical grasslands and savannahs had to make place for agricultural land.

Cocoa cultivation

Cocoa cultivation is one of the commodities leading to land-use modification and land-use change in the tropical regions. Over the past decades, the demand for cocoa steadily increased, provoking an increase in production from 1.2 M t in 1961 to 4.5 M t dry beans in 2014. The area needed to support the increase in production augmented from 4.4 M ha to 10 M ha (FAO, 2017). As yields per ha have stagnated since 1989, with average production between 434 kg ha⁻¹ and 513 kg ha⁻¹, increasing cocoa demand puts additional pressure on land available for the cocoa production (Vanhove et al., 2016).

Theobroma cocoa

The cocoa tree (*Theobroma cacao L.*), is a native Amazonian forest understorey tree species that has been cultivated since the Mayas discovered it around 500 years AD (Motamayor et al., 2002). Nowadays, the seeds of the cocoa trees are of commercial interest and mainly used for the production of chocolate. Cocoa is a dicotyledonous evergreen species that belongs to the family of the Malvaceae. The tree can become around 10 meters high, and after four years the tree starts flowering and producing fruits.

Leaves are petiolate (with leaf stalk) and arranged either spirally on orthotropic (upright) branches or alternate on plagiotropic (sideways) branches, 15-50 cm long and 4-15 cm broad. Flowers are produced as inflorescences on the trunk and older branches (cauliflory), usually born on small flower-cushions (tubercles) and are small in size (Figure 1a). The florescence is monoecious with bisexual flowers that are 1-1.5 cm in diameter, with white to reddish petals and pale-yellow sepals. Main flowering takes place during the rainy season (Boyer, 1973). The presence of a crown of staminodes around the stigma and the anatomical structure of the petals that are surrounding each anther entirely, ensure a physical barrier against self-pollination. Therefore, outcrossing rates are relatively high (30- 100%) (Figure 1a) (Efombagn et al., 2009; Silva et al., 2011).

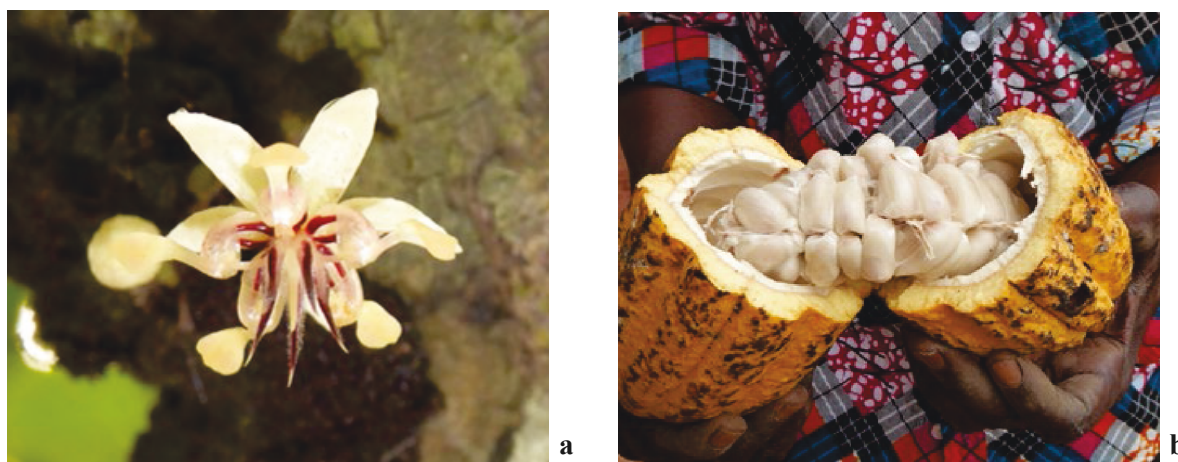


Figure 1: *Theobroma cacao* a) flower detail b) cocoa pod and cocoa beans - © A. Nijmeijer

Theobroma cacao is an entomophilous species as pollination is achieved by insects. The most important pollinators are very small midges of the genus *Forcipomyia*, who effectuate 25-50% cross pollination. Pollination efficiency is low, usually less than 10%, but is compensated for by the large number of flowers produced. After successful fertilization, full pod size is achieved after 4-5 months with another month required for ripening (Wood and Lass, 2001). Flowers are highly sensitive to drought, with only 72% of non-pollinated flowers surviving a second flowering day during a dry season and all pollinated flowers dropping after 5 days. Whereas, during the rainy season between 94 and 95% of the flowers lasts at least 5 days (Frimpong-Anin et al., 2014).

Fruits are berry-like drupes, commonly called cocoa pods (Figure 1b). The shape varies from globose to cylindrical and pointed, with sizes 10-32 cm long and 6-12 cm broad and ripening from yellow to orange. Each fruit contains 20-60 seeds, called cocoa beans, arranged in five rows and embedded in whitish, sugary and acid pulp (Figure 1b) (Wood and Lass, 2001). The root system of a cocoa tree issued from seed consists of a tap-root of 120 to 200 cm which ensures a good anchorage against storms and adequate water supply during the dry season (Wood and Lass, 2001). The tap root has an extensive system of lateral roots that are mainly located in the top 20 cm of the soil (Hartemink, 2005). The lateral roots grow far beyond the limit of the tree's canopy forming an intricately woven mat. At the tip of the main lateral roots there are bunches of fine rootlets that are especially abundant where plant residues are rotting (Wood and Lass, 2001). For the cultivation of cocoa, roots need some room, therefore soils

should preferably be easy penetrable up to at least 1.5 meters, with sandy-clayey texture and a top layer containing at least 3% of organic matter (Wood and Lass, 2001).

Production zones and past land-use

Cocoa cultivation is limited to a zone between 20 °N and 20 °S and an altitude inferior to 600 m (Verlière, 1981). Optimal temperatures range from 20 to 30 °C (with small seasonal differences) and precipitation from 1000 to 2500 mm (mostly grown in areas with more than 1250 mm with minimum precipitation of 100 mm per month and no dry seasons with less than 65 mm monthly) (Wood and Lass, 2001). Today, the world cocoa seed production is around 4.5 million tons per year and it is expected that the demand for cocoa keeps increasing (FAO, 2017; International Cocoa Organization, 2012; Schmitz and Shapiro, 2012). Of this production 73% comes from countries in West Africa and is mostly produced by local smallholders (Laven and Pelders, 2010). To sustain this production every year hectares of tropical forest are cleared to make place for full sun or very slightly shaded cocoa plantations (Tschardt et al., 2011; Vaast and Somarriba, 2014; Vanhove et al., 2016). From 1960 to 1990, only in Ivory Coast, 75% of the forest had been cleared to make place for the installation of slightly shaded or full-sun cocoa plantations (Freud et al., 2000). These monoculture plantations have a much lower value in terms of carbon storage and biodiversity on these plantations is negligible compared to the initial tropical forests (Tondoh et al., 2015). Though, a part of the cocoa production is still taking place in complex cocoa agroforestry systems that are shaded cocoa plantations, hereafter referred to as cAFS. Within cAFS, cocoa trees are planted among other annual and perennial food species, timber trees and fodder trees. This makes that cAFS hold a higher levels of ecosystem functions compared to monoculture systems (Andres et al., 2016). Yet, competition for water and resources in these systems is regularly mentioned as the biggest trade-off which limits cocoa production (Somarriba et al., 2013).

High tree diversity and ecosystem multifunctionality in cAFS

All agroforestry systems could in several ways help for the conservation of biodiversity. Jose (2012) described these ways into the following five points: 1) provision of a habitat for disturbance tolerant species; 2) preservation of germplasm sensitive species; 3) conservation of natural habitat due to the sustainability of agroforestry systems; 4) formation of corridors between habitat fragments; and 5) conservation of biological diversity by providing other secondary ecosystem functions that prevent the degradation and loss of surrounding habitat. Cocoa AFS are of special interest since these systems occur in the tropical region where terrestrial diversity is the highest on the globe (Perfecto and Vandermeer, 2008). The number of species that are preserved in cAFS depends on management, cultural differences, location and farm history (Schroth and Harvey, 2007). Biodiversity of perennial plants in cAFS is lower compared to primary forests but higher compared to monoculture systems (Schroth and Harvey, 2007). Most farmers have their own reasons to keep certain tree species in their cAFS. The local uses of tree species have been categorized by Jagoret et al., (2014) and Saj et al., (2017) according to the service they deliver: useful wood production, useful for cocoa growing, useful for food production, useful for other

uses (e.g. medicinal, cultural and unknown). But cAFS provide several other non-provisional ecosystem functions, these secondary functions include among other things, a climate buffer by modifying wind speed and buffering the temperature (Verchot et al., 2007), the improvement of the soil structure (Schmitz and Shapiro, 2012), soil fertility (Isaac et al., 2005), the facilitation of hydraulic redistribution among soil horizons (van Noordwijk et al., 2014) and long-term biomass accumulation (Dixon, 1995; Saj et al., 2013; Schroth et al., 2002). Several other studies mention positive relations between biodiversity and pest control (Schroth et al., 2000), herbivory suppression (Bisseleua et al., 2009) or edge effect from local forest patches (van Bodegom and Price, 2015). The rather high biodiversity in a cAFS may also improve nutrient cycling thanks to increased litterfall with different leaf litter traits (Okubo et al., 2012; Prescott, 2002; van Bodegom and Price, 2015). These secondary ecosystem functions are often absent in monocultural systems due to the lack in biodiversity, (Bhagwat et al., 2008; Bisseleua et al., 2009; Schroth et al., 2000; Schroth and Harvey, 2007; van Bodegom and Price, 2015). A major trade-off could be the limitation of cocoa yield due to competition with associated trees (Saj et al., 2017b). Though, several studies mention that for many of the farmers such trade-offs may be balanced by the support to food security and diet diversity and/or the complementary incomes coming from associated vegetation by-products (Gockowski et al., 2010; Saj et al., 2017a; Schroth et al., 2002). Nevertheless, debates stay around the effectiveness of cAFS in terms of ecosystem functioning compared to monocultural systems, and primary and secondary forests (Blaser et al., 2017; Wartenberg et al., 2017). However, forest area available for the installation of cAFS is not always present, obliging farmers to create a cAFS on another land-use type that is locally available such as savannah (Jagoret et al., 2011). For proper comparisons, it would be interesting to include these other past land-use types as well.

Production

For farmers cocoa yield is the most important service of a cAFS since they depend on its production as income resource. Of smallholder farmers in Africa, around 75% of their revenues comes from the yield of cocoa (Gockowski et al., 2010; Jagoret et al., 2011). A stochastic frontier model (a model that allows to calculate the actual to expected maximum production) showed that cocoa production in the same area could reach up to 2 to 3 t ha⁻¹ (Binam et al., 2008). Though, the global average production has been estimated between 434 kg ha⁻¹ and 513 kg ha⁻¹ (Vanhove et al., 2016). Besides modelling of potential yields, do research methods on cocoa production vary from survey to on-field research methods resulting in highly variable production estimates. On-field research methods often examine the accessible cocoa production, not keeping into account secondary losses during harvesting for example. This results in accessible yields are higher compared to the final obtained yields by farmers (Saj et al., 2017b). More than once it has been reviewed that differences in accessible and obtained yield are not so much a problem of associated trees and biodiversity as well as a question of adequate management strategies of farmers (Aneani and Ofori-Frimpong, 2013; Clough et al., 2011; Jagoret et al., 2011).

Still, cocoa production in cAFS may be limited due to competition for water, nutrients and light with associated species. On the other hand, those systems are found to be productive over a much longer period compared to full-sun systems (Saj et al., 2017b) and secondary production from associated trees might complement incomes and/or support to food security and diet diversity (Gockowski et al., 2004;

Jagoret et al., 2014). A study in Bolivia showed that overall production in cAFS was significantly higher compared to monoculture systems (Schneider et al., 2016).

Biomass, carbon storage and climate mitigation

Considering the ecosystem multifunctionality, biomass and carbon storage in cAFS is one of the key ecosystem functions, especially as service in the light of climate change mitigation. Tropical forests, in which most of cAFS are installed, are considered as one of the main potential terrestrial carbon sinks. Yet, these are under major pressure due to logging, mining and agriculture (Lewis et al., 2009; Schimel et al., 2015). Agricultural activities carried out on forest-cleared lands in the tropics lead generally to major above- and below- ground carbon losses due to vegetation destruction, leaching and rainfall-induced soil losses (Don et al., 2011; Hosonuma et al., 2012; Kotto-Same et al., 1997; van Noordwijk et al., 2002). The conversion of a tropical forest into a cAFS will also unmistakably result in a reduction of stored above- and below- ground carbon (AGC and BGC), and soil organic carbon (SOC) (Don et al., 2011; Oke and Olatiilu, 2011; Schroth et al., 2002; Smiley and Kroschel, 2008; Steffan-Dewenter et al., 2007). At least a certain number of trees need to disappear to make room for the cultures that are installed. However, depending on the number and size of the associated trees, carbon storage of cAFS is generally high compared to monocultures or other agricultural land-uses.

In the Congo basin, potential aboveground carbon (AGC) stock of primary forests lies between 204 and 255 t ha⁻¹ (Kotto-Same et al., 1997; Palm et al., 2005a). The AGC of secondary and disturbed forests lies around 150 t ha⁻¹ (Kotto-Same et al., 1997; Norgrove and Hauser, 2013; Silatsa et al., 2016; Vargas et al., 2008) and cAFS have been found between 47.5 t ha⁻¹ and 126 t ha⁻¹ (Kotto-Same et al., 1997; Norgrove and Hauser, 2013; Saj et al., 2017a; Silatsa et al., 2016). Even though, this is lower than secondary or primary forest, AGC in cAFS would be higher compared to AGC in monoculture cocoa systems, 15 t ha⁻¹ (Dawoe et al., 2016). Large trees, with a DBH > 30 cm are the main contributors to AGC (Saj et al., 2013; Schroth et al., 2016a). Mirroring what is observed for AGC, soil organic carbon (SOC) is also highly sensitive to conversion from forest to agricultural land: conversion from primary forest to monoculture systems causes losses of SOC that are much higher (25-30%) compared to the conversion of a forest to an agroforestry system (*ca.* 7%) (Don et al., 2011).

Overall, agriculture is one of the biggest contributor to greenhouse gas emissions, both directly and indirectly: directly, through agricultural practices as the use of fertilizers, in special nitrogen, livestock and machines (Snyder et al., 2009) and, indirectly, via land-use change as a result of clearing new land for agricultural purposes (Vermeulen et al., 2012). At the same time, climate change is threatening agricultural productivity due to changes in precipitation and temperature intensities and ranges (Kurukulasuriya and Rosenthal, 2003). For the West African cocoa belt, higher temperatures during the dry season are predicted to negatively influence the cocoa production, especially for monocultures or simple cAFS close to the forest-savannah transition zones that do not have a climate buffering canopy (Oyekale et al., 2009; Schroth et al., 2016b). By 2020, agricultural production of rain-fed cultures including cAFS in Africa might be reduced up to 50% (Schmitz and Shapiro, 2012). Studies on the effects of climate change, the opportunities to adapt to climate change and the possibilities for climate

mitigation are numerous. More specifically, projects are launched concerning society's food production as this could influence the severity of, and will be seriously affected by, climate change. Some examples include global initiatives such as the "Climate Smart Agriculture" (CSA) (Saj et al., 2017b), which aims at achieving food security, mitigation of - and adaptation to - climate change altogether (Lipper et al., 2014) or the "4 per mille", which focuses on carbon storage in soils (Minasny et al., 2017). Since cAFS store more carbon compared to monoculture systems these could be of special interest in the light of climate change mitigation. Besides, could a greater variety of food producing species assure local food security and diversify local diets. Nevertheless, the adaptability of cAFS to climate change should be well examined.

Nutrient pools and cycling

The functioning of cAFS depends both on nutrient pools and cycling. Pools are found in live or dead above- and below-ground biomass, soil fauna, soil organic matter and available nutrients in soil solution. Nutrient cycling in a system depends on fluxes, including the litter production of above and belowground plant parts, and the subsequent decomposition, followed by the uptake of nutrients by plants. Since an ecosystem is in contact with its surroundings, gains and losses that are external to the system make part of its overall functioning. Gains into cAFS consist mainly of microbial fixation, rainfall and dry deposition and, in case used, fertilizer additions. Losses on the other hand are ascribed to leaching, erosion and yield removal (Young, 1997). In cAFS the presence of an elaborate root system of associated trees is known to help reduce runoff and erosion (Meylan et al., 2013; Sentis, 1997). Therefore, the production of litter and decomposition are indicated as the most important component in nutrient cycling in unfertilized cAFS (Attwill and Adams, 1993; Lian and Zhang, 1998; Martius et al., 2004).

Leaf litter fall and decomposition

Leaf shedding patterns in tropical regions are very variable notably due to differences in tree leaf life span strategies, from evergreen, to deciduous and semi-deciduous. In cAFS, this process of leaf shedding changes per location, climatic circumstances and with the tree species associated to cocoa as a result of farmers' management strategies (Addicott, 1978). Leaf litterfall dynamics in cAFS with a separate dry period are often linked to this period (Boyer, 1972; Costa et al., 2016; Dawoe et al., 2009)

In general, the interspecific variation in green leaf traits and their subsequent leaf litter quality are thought to be the most important predictor of leaf litter decomposition (Cornelissen, 1996; Cornelissen et al., 2003; Murphy et al., 1998). High quality leaf litter is characterized by short living, nutrient rich and carbon poor leaves which tends to decompose faster than low quality leaf litter (Bakker et al., 2011; Santiago et al., 2005). Furthermore, decomposition of leaf litter is influenced by environmental variables such as microclimate (Bradford et al., 2016; Moorhead et al., 1999; Raich et al., 2006; Wall et al., 2008). Concepts on leaf litter decomposition in communities of different species includes the mass ratio hypothesis: the effect of a species on a given ecosystem process is proportional to its relative abundance in a community (Garnier and Navas, 2012). This would mean that common weighted mean values of

mixed species litters should highly correlate with ecosystem functioning (Quested et al., 2007). Yet, this does not take into account the potential interactions as a result of the functional diversity of leaf litter during. Indeed, non-additive effects due to functional diversity of litter have been shown in the form of nitrogen transfers from leaves with high- to leaves with low- concentrations (Handa et al., 2014).

Soil fertility

Soil fertility parameters as soil nutrient stocks are of fundamental importance for the growth and functioning of an agroforestry system. Though, it stays difficult to link soil indicators to soil functions and sustainability due to the high variability in soils. Nevertheless, sets of baseline soil physical and chemical indicators such as soil texture, bulk density, sum of bases, pH and carbon, are used to describe differences among plots (Rousseau et al., 2012). First of all, soil fertility is highly dependent on the texture of the soil, which determines the ability of a soil to store nutrients and water. For example, sandy soils have a good drainage but risk leaching of water and nutrients while clayey soils store in general more nutrients and have a large moisture holding capacity but water is less easily available to plants (van Vliet and Giller, 2017).

Cocoa AFS set up on primary and secondary forests are thought to make use of the ‘forest-rent’, a fertility built up in the soil of forests over the years (Dawoe et al., 2009). Furthermore, those soils have the advantage of an extra litter input with a variety of litter quality from the shade trees. Therefore, soil fertility parameters, such as nutrient stocks, are thought to be better in cAFS compared to monoculture systems (Beer et al., 1990; Duguma et al., 2001; Wall and Hytönen, 2005). However, other studies do not find this positive link between cAFS and soil parameters compared to monoculture systems (Blaser et al., 2017; Wartenberg et al., 2017). Even if cAFS alter soil fertility less than cocoa monocultures, it is thought that cAFS contribute to the decline of the overall soil fertility over time due to nutrients that get exported from the cAFS with the production of cocoa and that are not replaced (van Vliet and Giller, 2017). Several studies link the production of cocoa to a decrease in the pH of the soil, which would negatively impact cocoa production (Hartemink, 2005; Snoeck et al., 2010) while other studies revealed contrasting results concerning the pH and the conversion of forest to cAFS (Dawoe et al., 2009; Isaac and Kimaro, 2008). Soil productivity and fertility depends for a large part on soil texture and the soil organic matter (SOM) quantity, quality and dynamics (Hartemink, 2003). Zuidema et al. (2005), argue that cocoa under sub-optimal rainfall regimes benefits most in a relative loamy soil. Furthermore, SOM is linked to a great variety of soil functions and is a great reserve of carbon and essential elements for plant growth (Schroth and Sinclair, 2002). A decrease in SOM due to land-use change is therefore an indicator that soil fertility is declining as well (Dawoe et al., 2009).

Land-use legacies and cAFS past land-use

Ecosystem functioning depends on both the current ecosystem ecological features and the legacies from past land-use. Legacies related to previous land-use are demonstrated for an array of ecosystem functions, including nutrient cycling, carbon storage, microbial community and heterotrophic respiration

(Dupouey et al., 2002; Freschet et al., 2014; Kallenbach and Stuart Grandy, 2015). In general, one of the least sensitive compartments of an ecosystem to land-use change are the mineral soil horizons (Dawoe et al., 2009; Laclau et al., 2003; Marques and Ranger, 1997). But, all organic components, above- and below- ground, including soil organic matter and living organisms, seem to be highly influenced by past land-use (Bellemare et al., 2002; Jangid et al., 2011; Perring et al., 2016). Hence, land-use legacies might be overruled if current disturbances are strong enough, ultimately leading to novel ecosystems (Hobbs et al., 2006). Usually, cAFS are set up in primary or secondary forests. However, few studies found cAFS to be installed on savannah land (Jagoret et al., 2011; Ruf et al., 2004). These different past land-uses shall result in different land-use legacies, which therefore would differentially influence cAFS ecosystem functions during installation and maintenance. The installation of a cAFS on savannah (S-cAFS) could have drawbacks compared to cAFS set up in forests (F-cAFS). Indeed, there are major differences in the quantity, quality and distribution of organic matter in savannah and forest systems resulting in differences in nitrogen and phosphorus dynamics (Sugihara et al., 2014). Where F-cAFS have already a fertility potential present in terms of organic matter content at the moment of plot establishment (Snoeck et al., 2010), this potential needs to be created over a longer period for S-cAFS.

Cocoa AFS set up in tropical forests

For the installation of cAFS in a forest, farmers start with slash-and-burning of a part of the forest leaving certain trees in place in order to provide shade during the first years after planting (Gockowski and Sonwa, 2011). The effect of the conversion of forest into cAFS is in most cases negatively influencing most ecosystem functions. Though incorporation of ash from the burned biomass into the soil results in a direct boost in soil fertility (Palm et al., 2005a). The productivity of a F-cAFS is thought to depend on the inherent soil fertility of a forest soil and the ash incorporated into the soil (Dawoe, 2009). If a complete canopy cover of large associated trees has been left intact soil fertility could sustain for a longer time due to the restitution of nutrients back into the system in the form of litterfall and litter decomposition. Depending on the production and the amount of nutrients that get removed from the field, F-cAFS have shown to be productive for over 80 years without chemical fertilization (Jagoret et al., 2009, 2011).

Cocoa AFS set up on savannah

In theory, savannah areas are less suitable for the production of cocoa compared to forest areas, due to poor soils, unsuitable rainfall regimes and the lack of shading during the establishment of a plantation. Soils of tropical forests are often phosphorus (P) limited while savannah soils often lack available nitrogen (N) (Sugihara et al., 2015; Vitousek, 2015). These low levels of N in savannah soils could also be the result of inhibitors released by roots of savannah grasses, inhibiting soil-nitrification (Lata et al., 2004). Most stable savannah areas are entirely off limit for cocoa production due to annual rainfall of less than 650 mm (Sankaran et al., 2005). Savannahs that have annual precipitation above this rate are considered in a transition state, meaning that these areas receive enough water for canopy closure to occur. Disturbances in the form of fire or herbivory are required to control canopy closure and maintain the savannahs (Sankaran et al., 2005). Even in case rainfall regimes are sufficiently high the establishment

of cAFS on savannah is rare. So far only two regions describe the establishment cAFS on *Imperata cylindrica* dominated savannahs. The first study comes from a reforestation project of family farms in Indonesia, and the second from Cameroon (Jagoret et al., 2012). In the Centre region of Cameroon, annual savannah burning by local communities that use these areas for hunting and agricultural practices prevent these areas from natural reforestation (Jagoret et al., 2012). As a side effect of those annual burnings, those savannah systems assume great losses of nutrients (Kugbe et al., 2012).

The establishment of a S-cAFS and the elimination of *I. cylindrica* is realised either by creating a shading regime of 80% or more or is started with a cycle of annual crops. The shading regime is often realised in the form of oil palms in dense stands, which is especially effective after a ground level cut of *I. cylindrica* (Jagoret et al., 2011; Palm et al., 2005a). In general, it is thought that afforestation of savannah areas with agroforestry systems shall have a positive effect on above- and below- ground ecosystems' multifunctionality. It could even have a role in climate mitigation through the increase in aboveground carbon sequestration (Figure 2) (Carvalho Leite et al., 2014; Hu et al., 2008; Montagnini and Nair, 2004; Zomer et al., 2008). Even though afforestation of savannah has also shown to negatively affect the native labile SOM layer (Jackson et al., 2002), another study observed that this loss of carbon was compensated by an increase in new plant-derived carbon (Epron et al., 2009).

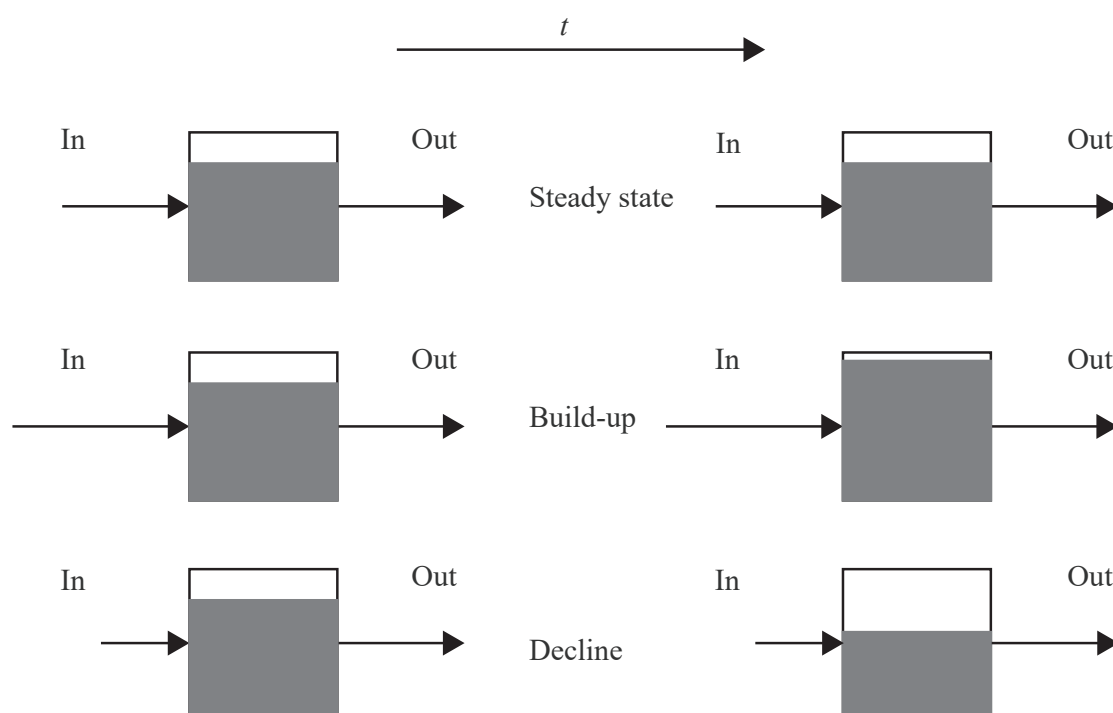


Figure 2: States of an ecosystem, Steady: inflow and outflow are equal, no build-up or decline over time, Build-up: overtime an augmentation is observed of one or more ecosystem variables, Decline: over time a decrease of one of more ecosystem variables is measured - White box as represent ecosystems and the grey squares the variable parts of an ecosystem (after Hartemink et al 2003)

Thesis Objectives

Ecosystem functioning depends on a variety of factors and disturbances. Human disturbances provoke large changes in ecosystem functioning that often lead to land-use change. In the tropical regions of West and Central Africa cocoa cultivation is a main cash crop that leads to land-use change of tropical forests. Cocoa-AFS, which ecosystem multifunctionality is greater than that of monoculture systems, are still widely spread over this region and mainly cultivated by smallholder farmers. Previous research in Central Cameroon showed, beside the installation of cAFS in forest, the possibilities of afforestation of savannah land with economically valuable cAFS. However, not much is known on the impact of the past land-use on the cAFS performance and on the duration of the effect.

Research objectives

The main objective of this thesis was to identify the effect of past land-use on current ecosystem multifunctionality of cocoa agroforestry systems in Bokito (Central Cameroon). Besides the long-term effects we wanted to get a better insight in the sustainability of those systems and the dynamics driving this sustainability.

To do so the following sub-objectives were defined:

1) Identify the structural and functional differences and similarities between S-cAFS, F-cAFS and with their precedent land-uses.

It is hypothesized that:

- Farmer's practices maintaining high plant diversity play an important role in ecosystem multifunctionality.
- Land-use change of F-cAFS is rapid, inducing direct differences with its past land-use; land-use change of S-cAFS takes more time and induces less changes in ecosystem function within the first years but will have larger effects after longer periods.
- S-cAFS have a lower mean biomass content compared to F-cAFS.
- S-cAFS mean AGC is higher compared to the savannah control plots and lower compared to F-cAFS.

2) Identify the time span these differences sustain in cAFS.

It is hypothesized that:

- Past land-use affects ecosystem functions on long time scales.
- Legacies of past land-use are longer visible in the S-cAFS compared to F-cAFS.
- S-cAFS exhibit comparable AGC and soil organic carbon (SOC) as F-cAFS in the long-term.

3) Identify if differences between F-cAFS and S-cAFS result in differences in ecosystem dynamics and the role of associated trees in these processes.

We hypothesized that:

- Associated species leaf litter percentages differ depending on their past land-use but will be similar for full grown cAFS.
- Litterfall dynamics is negatively related to rainfall.
- If associated species in cAFS increase the functional diversity of the litter, mass loss of the cocoa leaf litter could increase due to non-additive effects independent of the microclimate.

MATERIAL AND METHODS

Study site

In Central Cameroon, complex agroforestry systems are created for over a century but had its main development in the 1950s (Jagoret et al., 2012). Although, the production levels are often claimed to be lower compared to intensive production systems, cAFS provide farmers with a steady production of cocoa over decades with only scarce use of chemical or organic fertilization (Jagoret et al., 2011). These farms are mainly family-based and often passed down from generation to generation (Jagoret et al., 2012). For most farmers cocoa production is the main source of income, though, up to 25% additional revenues can be obtained from production of the associated perennial plant species in their cAFS (Gockowski et al., 2010). Sonwa et al. (2007) found that the most important associated trees were food producing tree species. Additionally, compared to other local cropping systems (annual and other perennial systems such as coffee), these systems are significantly more diverse in species richness and support to some extent biodiversity conservation (Gockowski and Sonwa, 2011; Saj et al., 2017a; Sonwa et al., 2007; Zapfack et al., 2002). One region of Central Cameroon, Bokito, is of special interest since local farmers set up their cAFS not only on partially cleared forest but also on savannah (Figure 3) (Jagoret et al., 2012).

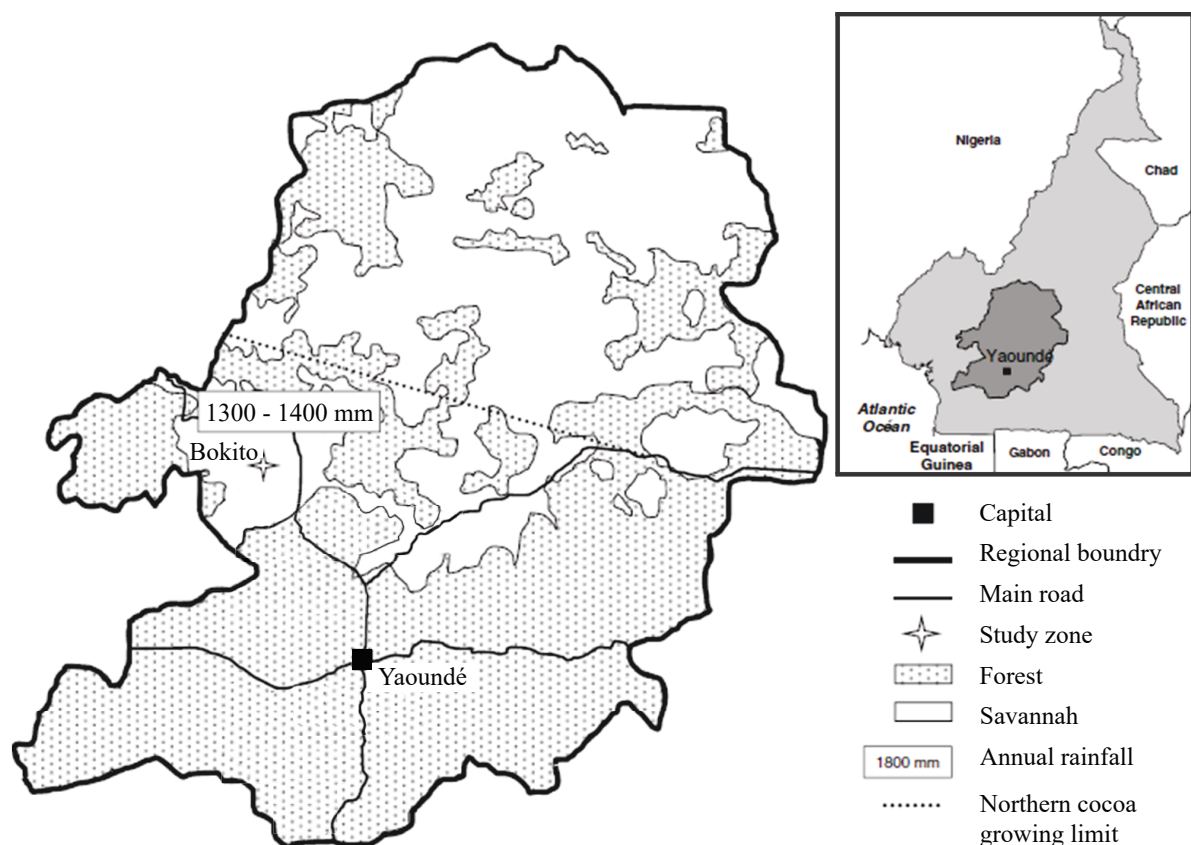


Figure 3: Study region in Centre Cameroon (After Jagoret et al., 2011)

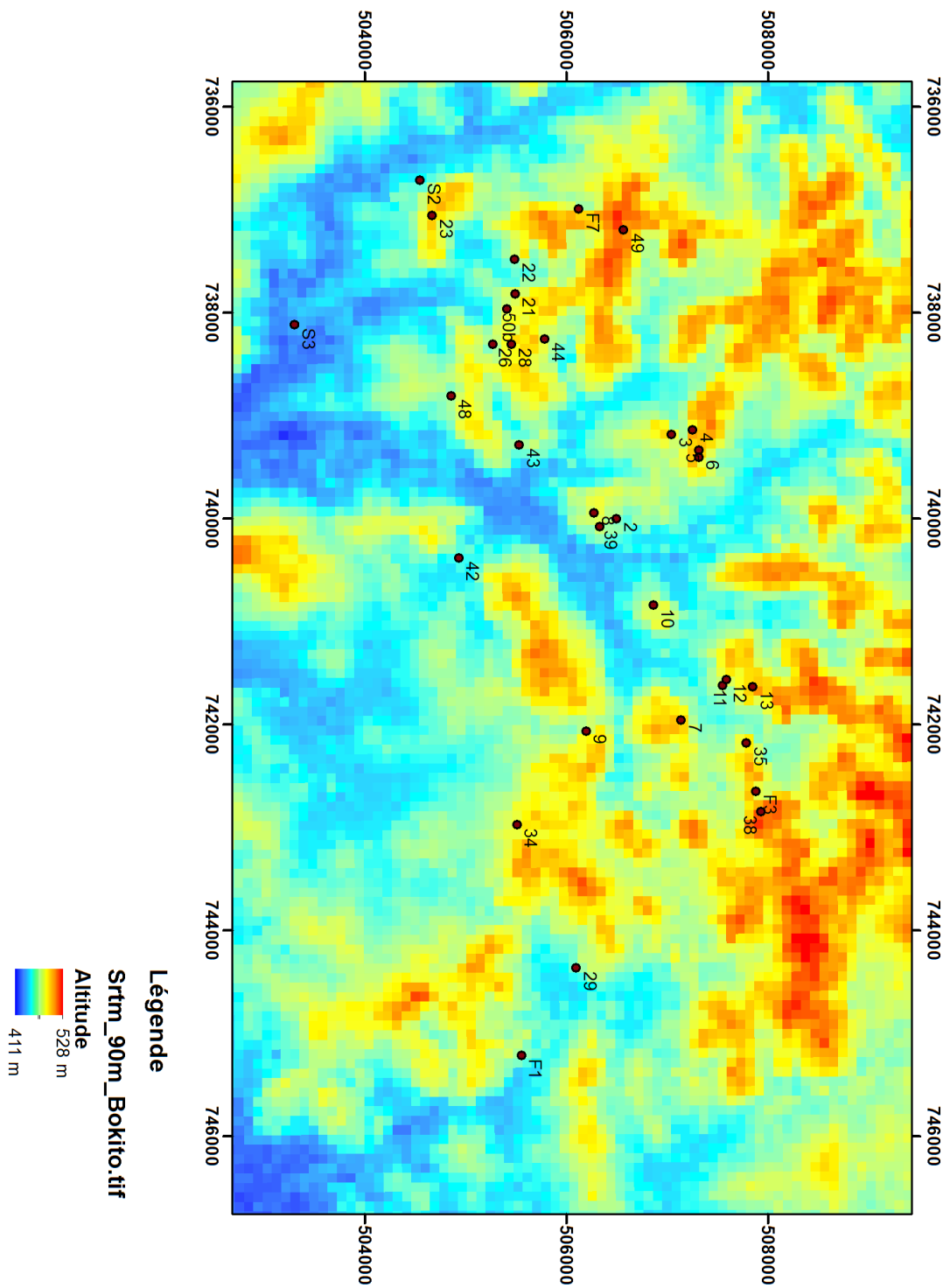


Figure 4: Altitude map Bokito with the plot indication; numbers corresponding to S- and F-cAFS, numbers starting with an S or F correspond to savannah and forest control plots (black dots; *Freycon 2017*)

Topography and soil characteristics

The region is characterised by two types of topography, with mainly a hilly environment varying from 411 to 528 m with gradual slopes < 10% (Figure 4) and a plateau near study plots 29 and 34. This region is dominated by slightly desaturated ferralitic soils (Elangwe, 1979). Soils are heterogeneous in texture colour and in number and size of stones. The depth of the bedrock is changing from site to site depending on the position of the plot, starting at -10 to -80 cm (Freycon, 2017). The stones mainly comprise of quartz and a black mineral or garnet. The soil texture varies from sandy to sandy-lime soils. Especially on the plateau, soils are very sandy whereas on hillsides they have higher clay content. Soil texture varies also with soil depth. Soil colour varies from orange to yellow with in general darker soils on the surface compared to deeper soil layers. The soil organic matter content of the savannah is lower than the required 2% for the growth of cocoa (Jagoret et al., 2012).

Climatic characteristics

The climate in the forest-savannah transition area makes it not very suitable for the production of cocoa. The annual rainfall, 1300 – 1400 mm, is lower than the recommended needs of cocoa trees. Furthermore, the dry season (<100 mm rainfall per month) exceeds the maximum recommended dry period of three months (Jagoret, 2011). A longer dry period could decrease soil moisture availability too much (Wood and Lass, 2001; Zuidema et al., 2005).

Cocoa agroforestry in Bokito

An earlier study in Bokito showed that the production of S- and F-cAFS was very comparable, 354 kg ha⁻¹ for F-cAFS and 321 kg ha⁻¹ for S-cAFS respectively (Jagoret et al., 2012). Compared to cAFS in other parts of Central Cameroon, cAFS in the Bokito region have relatively more (non-native) fruit trees and less native forest trees (Figure 5a) (Saj et al., 2013). Similar cocoa growing systems have been described in Nigeria (Degrande et al., 2006; Oke and Odebiyi, 2007), Côte d'Ivoire (Herzog 1994), Ghana (Asase and Tetteh, 2010) and even Brazil (Johns, 1998). In Bokito, 45% of the cocoa plantations are over 60 years old. In addition, about 22%, of plantations have been categorized as young (up to 20 years) indicating that even now young farmers are starting these complex agroforestry systems (Jagoret, 2011). Plantation management is minimal, about 91% of cocoa plantations are weeded 2–3 times a year and 64% of cocoa plantations are chemically treated 0–3 times a year against black pod rot (Jagoret et al., 2011). A great part of the cAFS are set up in the forested area. The conversion of the forest into cAFS in Central Cameroon is, as in other parts of the world, mainly achieved by slash-and-burn techniques (Figure 5b) (Achard et al., 2002; Nepstad et al., 1999; Palm et al., 2005b). Farmers keep several species of interest that have a shading effect in the first years after establishment. Those species are kept for food, wood or fertility reasons and could provide some additional income (Jagoret et al., 2012). The afforestation of savannah in this area is a complex process since the savannahs are mainly dominated with the highly resistant *Imperata cylindrica* (Figure 5c) (MacDonald, 2004).



a



b



c



d

Figure 5: a) Cocoa agroforestry systems in Bokito b) Forest at the moment of conversion to cAFS c) Savannah unburnt in June 2015 d) Savannah after burning in February 2015 -© A. Nijmeijer

This weedy herbaceous species is hard to eliminate from an agricultural field due to a combination of survival strategies including an extensive rhizome system, adaptation to nutrient-poor soils, drought tolerance and high genetic plasticity (MacDonald, 2004). Annual intentional vegetation fires that prevent natural forestation of the area (Figure 5d)(Sankaran et al., 2005), are used to clear land for cattle keeping, agriculture and hunting practices (Kugbe et al., 2012). Though, those annual burning will have a negative impact on the accumulation of nutrients (Knicker, 2007).

Study approach

Two approaches are often used while studying ecosystem functions and dynamics: (i) a long-term observation design - that is difficult to handle in practice, or (ii) the contemporaneous observation of various sites with different ages but similar climate, bedrock, topography, and biotope, ie. the reconstruction of a chronosequence (Amundson and Jenny, 1997). For this study, we adopted the second strategy and the temporal monitoring was adopted to study the dynamics of ecosystem components over time for several sites covering a large range of cAFS in the region of Bokito. Thirty-Two S- and F-cAFS whose age varied from 0 (year of plantation of the cocoa trees) to 80 years old and five forest- and five savannah- control plots were selected. Within the selected plots, the main variables investigated were: tree stands including aboveground and fine root biomass, species richness and diversity, soil physico-chemical properties at two soil depth (0-15 and 15-30 cm), cocoa accessible yields (obtained by on-field pod counting), litterfall and litter stocks, leaf litter decomposition (Figure 6). Details of the methods and analyses are described in the materials and methods sections of each research chapter of the thesis.

The first chapter focussed on the carbon stocks and contents in the c-AFS and their past land-uses. In the second chapter the persistence of land-use legacies in c-AFS are analysed using the measured variables. Furthermore, we tested if the studied variables were depending on plot age, soil clay content or farmers' management (including biodiversity and associated tree biomass). In the third chapter c-AFS and forest litterfall dynamics and leaf litter decomposition were analysed.

Forest



Savannah



Forest-cocoa agroforestry systems

Savannah-cocoa agroforestry systems

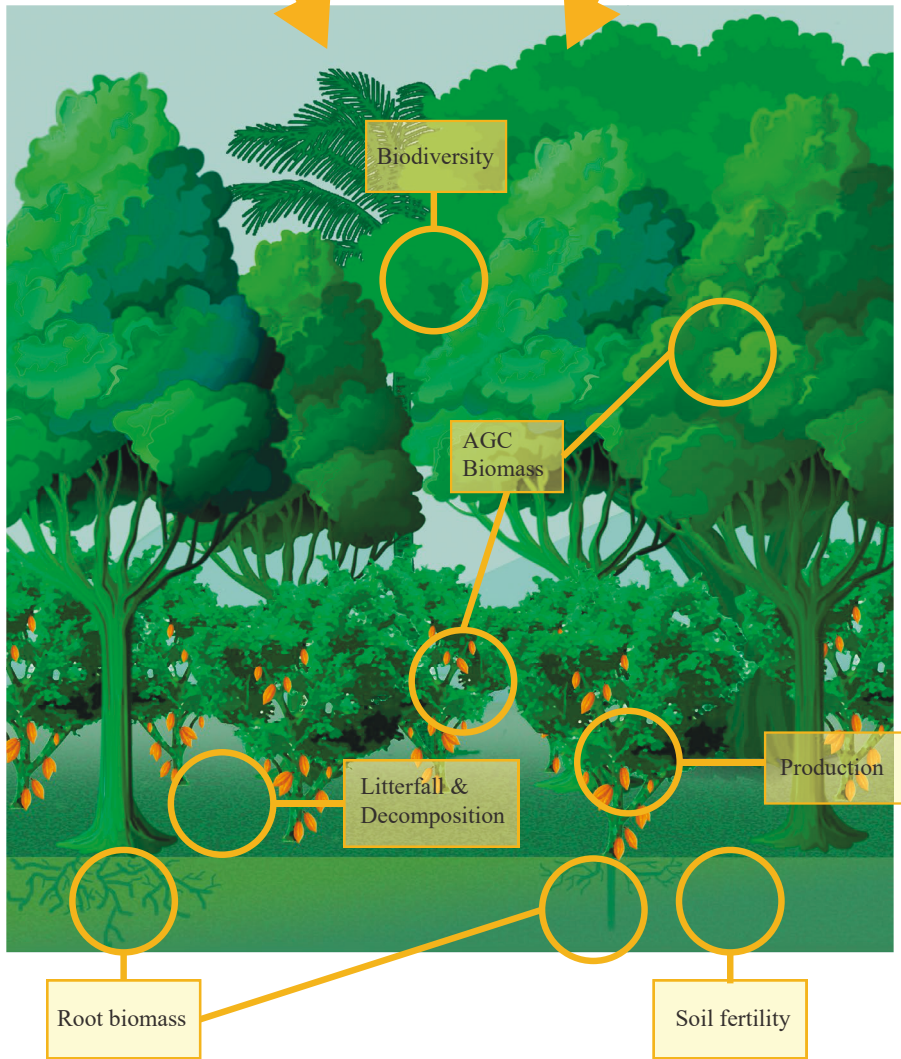


Figure 6: Study design; with on the top the past land-uses, forest and savannah that are converted in cocoa agroforestry systems (cAFS). Studied variables that explain parts of the ecosystem multifunctionality, the legacies of land-use change and annual dynamics are indicated with the yellow circles.

CHAPTER 1



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"Growth"

Carbon dynamics in cocoa agroforestry systems in Central Cameroon: afforestation of savannah as a sequestration opportunity.

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Abstract

Afforestation of savannah is suggested as a mean to help addressing climate change mitigation through increased (C) carbon storage. Previous studies in Central Cameroon evidenced farmers' ability to realize afforestation by creating cocoa-based agroforestry systems (cAFS) in forest-savannah transition zones. In the same region, we studied a cAFS 80 years chronosequence to assess their C dynamics- and maintenance-abilities. We selected both cAFS created after forest and savannah, and we used local forest and savannah patches as controls. AGC was highest in the forests (118 t ha⁻¹) and lowest in the savannahs (8 t ha⁻¹). Systems created after forest (F-cAFS) revealed a mean AGC 40% lower than that of forests and did not evolve with time. The AGC of cAFS created after savannah (S-cAFS) increased with time and reached the mean AGC of F-AFS (72 t ha⁻¹) after ca. 75 years. SOC concentration depended on depth and clay content. The SOC concentration of F-cAFS did not evolve with time and revealed no difference with forest. In S-cAFS, considering a time of about 80 years after afforestation, the average annual increase in SOC concentration in the 0-15 cm layer ranged from 7.3‰ in soils with a low clay content (10-15%) to 9.5‰ in soils containing more than 20-25% of clay. No change in SOC concentration was found for the 15-30 cm layer. Overall, S-cAFS revealed to store and maintain significant levels of C both in the biomass and in the soil. Such an afforestation thus appeared as a valuable local strategy to combine cocoa and other perennial plant productions with C storage while avoiding deforestation.

Keywords: Cocoa agroforestry; Afforestation; Carbon sequestration; Climate change mitigation

1. Introduction

Food production is especially susceptible to, and will be seriously affected by, climate change (CC). Therefore, many R&D initiatives as “4 per mille” (Minasny et al. 2017), “Climate Smart Agriculture” (CSA; Lipper et al. 2014) and the “Adaptation of Africa Agriculture” (AAA; 2016) aim at combining food security with CC mitigation and adaptation on the agricultural global agenda. At the same time agriculture contributes to CC through the emission of greenhouse gases. This is for example the case in the humid tropics which comprise forests that are considered as one of the main terrestrial carbon (C) pool (Pan et al. 2011). These forests are especially threatened by slash and burn practices used for shifting cultivation (Kotto-Same et al. 1997) which lead to major above- and belowground C losses through vegetation destruction, leaching and rainfall-induced soil losses (Don et al. 2011; Hosonuma et al. 2012).

In Africa, population growth could be pointed out as a driver that increases the pressure on land available for agriculture which subsequently leads to increased frequencies of shifting cultivation practices (Zhang et al. 2002; DeFries et al. 2010). Shortened fallow periods impair tree regrowth and cause the expansion of savannah-like landscapes (Ngobo et al. 2004; Rahman et al. 2012). Besides, increased installation of perennial systems such as rubber, oil palm, cocoa and coffee agroforestry systems or monocultures contribute as well to deforestation (Kleinman et al. 1995). Consequently former tropical forest landscapes progressively disappear and are often replaced by areas containing a mosaic of short-cycle commodities, perennial cultures, savannah and forest patches (Gockowski et al. 2004).

Nowadays, afforestation or reforestation of savannah or fallow areas is opted as a climate mitigation opportunity (Zomer et al. 2008). Yet, the conditions for its implementation and mitigation efficiency are still to be found and studied (Nair et al. 2009). In regions with a high rainfall regime the main cause of savannah patches maintenance is their annual burning by local communities to support hunting practices and arable agriculture (Guillet et al. 2001; Sankaran et al. 2005; Yemefack et al. 2005). For local communities, afforestation of savannah-like fallow lands would only be interesting if the productions and other uses resulting from afforestation are more advantageous than the ones they obtain from these savannah areas. Furthermore, the afforestation option for climate mitigation is still under debate. Indeed, afforestation is expected to strongly increase aboveground carbon (AGC) (Hu et al. 2008). Yet, afforestation has also been shown to negatively affect the native labile soil organic carbon (SOC), even though this loss may be compensated by an increase in new plant-derived carbon (Epron et al. 2009).

In such a context, perennial cropping systems, like cocoa agroforestry systems (cAFS), one of the most significant way to produce cocoa in West and Central Africa, could be of interest (Gockowski and Ndoumbé 2004). These diversified perennial systems - while providing incomes for the farmer – exhibit higher carbon stocks in vegetation and soil as well as better soil fertility compared to annual monocropping systems (Beer et al. 1990; Duguma et al. 2001; Wall and Hytönen 2005). Cameroonian cAFS are known for their complexity (Jagoret et al. 2011, Sonwa et al. 2016). They regularly include an upper story of associated forest tree species, an intermediate strata with many associated fruit species including banana and palm trees and an understory of cocoa trees. Their plant biodiversity is often valued through a large variety of uses such as cocoa shading, timber, firewood, medicines or food production and

soil fertility maintenance (Jagoret et al. 2014; Saj et al. 2017). Farmers usually clear forest for cocoa cultivation, but they have also proven their ability to set up diversified cocoa AFS 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 in the system. These cAFS were found to exhibit cAFS designs equivalent to those created after forest as well as to be productive on the very long-term (Jagoret et al. 2012).

We herein report a study about long-term C dynamic in cAFS from Central Cameroon which were either created on savannah (S-cAFS) or forest (F-cAFS) land. We compared C storage abilities in aboveground biomass (AGB) and SOC concentrations of S- and F-cAFS to those of their previous land-uses. We tried to check if afforestation of local savannah areas by cAFS could store as much C in AGB as F-cAFS. Furthermore, we used an age gradient in order to bring more insight in the long-term evolution of the C levels in the studied systems. We hypothesized that (i) mean above ground carbon (AGC) of cAFS would be lower than that of forest controls; (ii) S-cAFS would have a lower mean AGC content compared to F-cAFS but that it would be higher compared to the savannah control plots; (iii) in the long-term S-cAFS were to exhibit comparable AGC stocks and SOC concentrations as F-cAFS.

2. Material and methods

2.1 Study site

The study was carried out in the villages of Bakoa and Guéfigué which are part of the Bokito district (4°30 latitude N and 11°10 longitude E; 7125 km²), located in the forest–savannah transition zone, which extends over a strip of about 150 km wide North-South at the border of the semi-deciduous forest in Cameroon (Guillet et al. 2001). The area is characterized by a patchwork of forest and herbaceous savannahs dominated by the perennial species *Imperata cylindrica* (Jagoret et al. 2012). Bokito's average annual rainfall ranges from 1,300 to 1,400 mm and the main dry season lasts over three months, from mid-November to March (Jagoret et al. 2012). Those climate conditions are not considered optimal for cocoa production. Bokito's soils are dominated by slightly desaturated ferralitic soils (Elangwe 1979). The area consists of hills with gentle slopes and an altitude between 400 and 550 m. The cocoa plantations in this region comprise mainly of complex cAFS that contain many associated trees, including fruit and forest tree species (Sonwa et al. 2007; Jagoret et al. 2011; Saj et al. 2013). In Bokito, 45% of the cAFS were found to be over 40 years old since cocoa cultivation in these regions had its main development in the 1950's (Ruf and Schroth 2004). In addition, 22% have been categorized as young (up to 20 years) indicating that farmers still carry on the setting up of complex cAFS (Jagoret et al. 2011). The previous authors reported an average cocoa production of ca. 335 kg ha⁻¹ with Amelonado being the most abundant variety. The management of the cAFS is minimal, about 91% of cAFS are weeded 2–3 times a year and 64% are treated 0–3 times a year against black pod rot (Jagoret et al. 2011).

2.2 Plots studied

In July 2015, we selected 32 cAFS plots divided into two groups. Sixteen cAFS had been created after savannah (S-cAFS) while 16 had been created after forest (F-cAFS). Each group contained 14

plots which ages were regularly distributed along a gradient from 8 to over 80 years. To complete the age gradient, we added 2 new plots per group that were, at the moment of the inventory in 2015, 0, where farmers started the planting process of cocoa, and 2 years old. Unfortunately, two F-cAFS plots were abandoned by their owners during our study and were excluded from the study of aboveground properties. Five control plots of savannah and five control plots of local degraded forest patches were selected for comparison with the S- and F-cAFS.

2.3 Vegetation structure

In each plot, we measured the diameter at breast height (1.3m; DBH) and height of all perennial plant species, including cocoa, associated trees, standing dead trees, palms and bananas with a DBH between 5 and 30 cm in an area of 800 m² (20 m x 40 m). Trees with a DBH larger than 30 cm were inventoried in a larger area of 2400 m² (40 m x 60 m) including the previous area of 800 m². For the cocoa trees, stem diameters were usually measured at 1.30 m except when they were smaller. In this case, the measurement was done under the first branch. Diameters at breast height were measured using a measuring tape or a caliper. When the tree stem was not round, the diameter was measured in two directions and the mean diameter was considered. The height of trees was measured either using a graduated stick (when lower than 7 m) or using a TruPulse 360 R Laser Rangefinder. In total, we measured 3036 cocoa trees and 670 associated individuals in the studied cAFS plots. In addition, we measured 304 and 92 perennial plants in the forest- and savannah- control plots respectively. We were unable to identify 11.6 % of the (associated) perennial plant species.

2.4 Above ground biomass

A non-destructive sampling method was used for the determination of total aboveground biomass (AGB). For the AGB of the associated and cocoa trees we used the allometric equation (1) from Chave et al. (2005) for tropical dry forests (<1500 mm yr⁻¹):

$$AGB = 0.112 * (\rho * D^2 * H)^{0.916} \quad (1)$$

Where ρ is the wood specific gravity (kg m⁻³), D the DBH (cm) and H the height (m) of the tree. The wood specific gravities were partly recuperated from a study of Saj et al. (2017) that was performed in the same region. If specific gravity was not available via this source it was obtained using the following database: Tree functional attributes and ecological database (World Agroforestry Centre; consulted between January and March 2016). In case of an unknown species, the mean gravity of all associated woody species and individuals was taken as replacement (excluding cocoa trees, palms and bananas). Since oil palms (*Elaeis guineensis*) do not show secondary growth (Hairiah et al. 2001), the AGB of palms in the plots were calculated using the simple regression model (2) developed by Asari et al. (2013):

$$AGB = 71.797 * H - 7.0872 \quad (2)$$

For bananas (*Musa* sp.) we used the model (3) developed by Hairiah et al. (2001):

$$AGB = 0.03 * D \cdot 2.13 \quad (3)$$

In savannah control plots, AGB of the herbaceous stratum was estimated at the end of the rainy season

(October, 2015), when the development of herbs was at an annual maximum. In each savannah plot, herbaceous vegetation was cut at ground level in ten randomly distributed 1 m * 1 m quadrants and fresh weight of each quadrant was measured. A fresh weighted subsample of each quadrant was taken back to the lab and dried at 60 °C for 72 hours and weighed for dry matter calculation.

Aboveground carbon (AGC) stocks of all plants was estimated by multiplying the biomass by 0.475, as an average value of carbon stocks in plants (Saj et al. 2013).

2.5 Soil organic carbon

Soil was sampled at depths of 0-15 and 15-30 cm. For each depth a composite soil sample - made from eight subsamples randomly distributed in each plot - was taken. Soil samples were air-dried and sieved at 2 mm. Analyses of soil chemical properties, were performed by the IITA soil laboratory in Yaoundé (11-2016; www.iita.org). To determine organic C, soils were further ground to 0.5 mm, subsequently chromic acid digestion and spectrophotometric analysis were executed (Heanes 1984). Particle size (three fractions) was identified by the hydrometer method (Bouyoucos 1951) and pH in water was determined in a 1:2.5 (w/v) soil:water suspension.

2.6 Data analyses

Non-parametric analyses of variance (Kruskal-Wallis) and multiple pairwise comparisons using the Steel-Dwass-Critchlow-Fligner test were used to test for differences between the four different systems studied (S- and F-cAFS, forest and savannah controls). The two soil layers (0-15 cm and 15-30 cm) were compared using the Mann-Whitney test. Since SOC highly depends on the chemical or physical protection by bonds between organic matter and colloids or clay or encapsulation of the organic matter with clay particles (Robert 2001; Gama-Rodrigues et al. 2010), we checked for correlations between clay content and SOC. To evaluate the effect of the cAFS age on the studied variables, mean height, basal area, AGC and SOC, simple and multiple regressions were used. Analyses of covariance (ANCOVA) were performed to evaluate differences between slopes. All the statistical analyses were performed using XLSTAT (Addinsoft, XLSTAT, 2016).

3. Results

3.1 Standing structure

The mean density of cocoa trees was of 1209 individuals' ha⁻¹ and no difference was found between the cAFS set up after savannah (S-cAFS) and those set up after forest (F-cAFS) (Table 1). F-cAFS and S-cAFS displayed 81% and 88% less (associated) small trees (< 30 cm) than the forest control, respectively. Although no significant difference was found between the different land uses, the densities of large trees (> 30 cm) graded in the following decreasing order: Forest control ≥ F-cAFS ≥ S-cAFS ≥ Savannah control (Table 1). The density of total perennial plants including cocoa-, small- and large trees as well as palms, bananas, and dead trees, was significantly higher in the cAFS, compared to the forest and savannah control groups that displayed the lowest values (Table 1). In the cAFS, the cocoa trees accounted for 84% to 90% of the density of total perennial plants. No difference was found for the

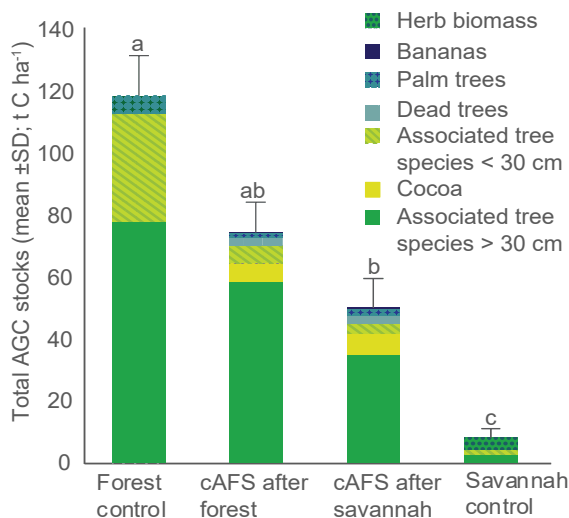


Figure 7: Total above ground carbon (AGC; mean \pm SD) stocks in local forest patches and savannah, cocoa based agroforestry systems after forest and after savannah (F-cAFS and S-cAFS, respectively). Shades represent the contribution of each plant category in the total mean AGC stock. Different lower case letters indicate statistically significant differences between the four different studied groups ($P < 0.05$)

(74.6 t ha⁻¹) than in forest control while mean AGC stock of S-cAFS (50.5 t ha⁻¹) was ca. 6.3-fold higher than in savannah (Figure 7). In savannah control, grass accounted for almost 45% of AGC. Except for savannah, large associated trees (DBH > 30 cm) were the most important contributors to AGC stocks. They accounted for 30%, 65%, 69% and 78% of the total AGC in savannah control, forest control, S-cAFS and F-cAFS, respectively. Cocoa trees contributed for 13% and 9.5% of the total AGC in S- and F-cAFS, respectively (Table 1).

3.3 The relationship between above ground standing structure and cAFS age

No correlations were found between the density (individuals ha⁻¹) of associated perennial plants and the age of the cAFS nor between the density of cocoa trees and cAFS age (data not shown). Mean height of associated trees significantly increased with cAFS age in S-cAFS but not in F-cAFS (Figure 8a). At ca. 50 years associated trees of S-cAFS reached the same mean height (ca. 13 m) as those of F-cAFS (Arrow in Figure 8a). Mean height of cocoa trees in F- and S-cAFS significantly increased with the age of the system ($p \leq 0.05$; Figure 8b). There was no correlation between basal area of associated trees and cAFS age (Figure 8c). On the contrary, strong correlations were found between the basal area of cocoa trees in S- and F-cAFS and cAFS age (Figure 8d). The AGC of all associated plants increased significantly over time in S-cAFS whereas it fluctuated around a mean of ca. 68 t ha⁻¹ in F-cAFS (Figure 8e). The AGC of cocoa trees in S- and F-cAFS significantly increased with time. At 72 years AGC of both S-cAFS and F-cAFS were found similar (Arrow in Figure 8e).

mean height of cocoa trees according to the two-previous land-uses (Table 1). The mean height of (associated) perennial plants varied from 4.3 m in the savannah to 13.5 m in S-cAFS and was found in both cAFS, to be ca. 9 m higher than the mean height of cocoa trees (Table 1). The maximum tree heights graded in the decreasing following order: Forest control \geq F-cAFS \geq S-cAFS > Savannah control. The basal area of total perennial plants including cocoa, was the largest in forest control (39.7 m² ha⁻¹), intermediate in F-cAFS (26.5 m² ha⁻¹) and S-cAFS (22.5 m² ha⁻¹), and the lowest in savannah (4.3 m² ha⁻¹).

3.2 Above ground carbon (AGC)

Total AGC stock varied widely among land uses. It was highest in the Control forest (118.4 t ha⁻¹) and lowest in savannah control (trees and herbs: 8 t ha⁻¹). Considering all the cAFS plots of different ages, mean AGC stock was around 40% lower in F-cAFS

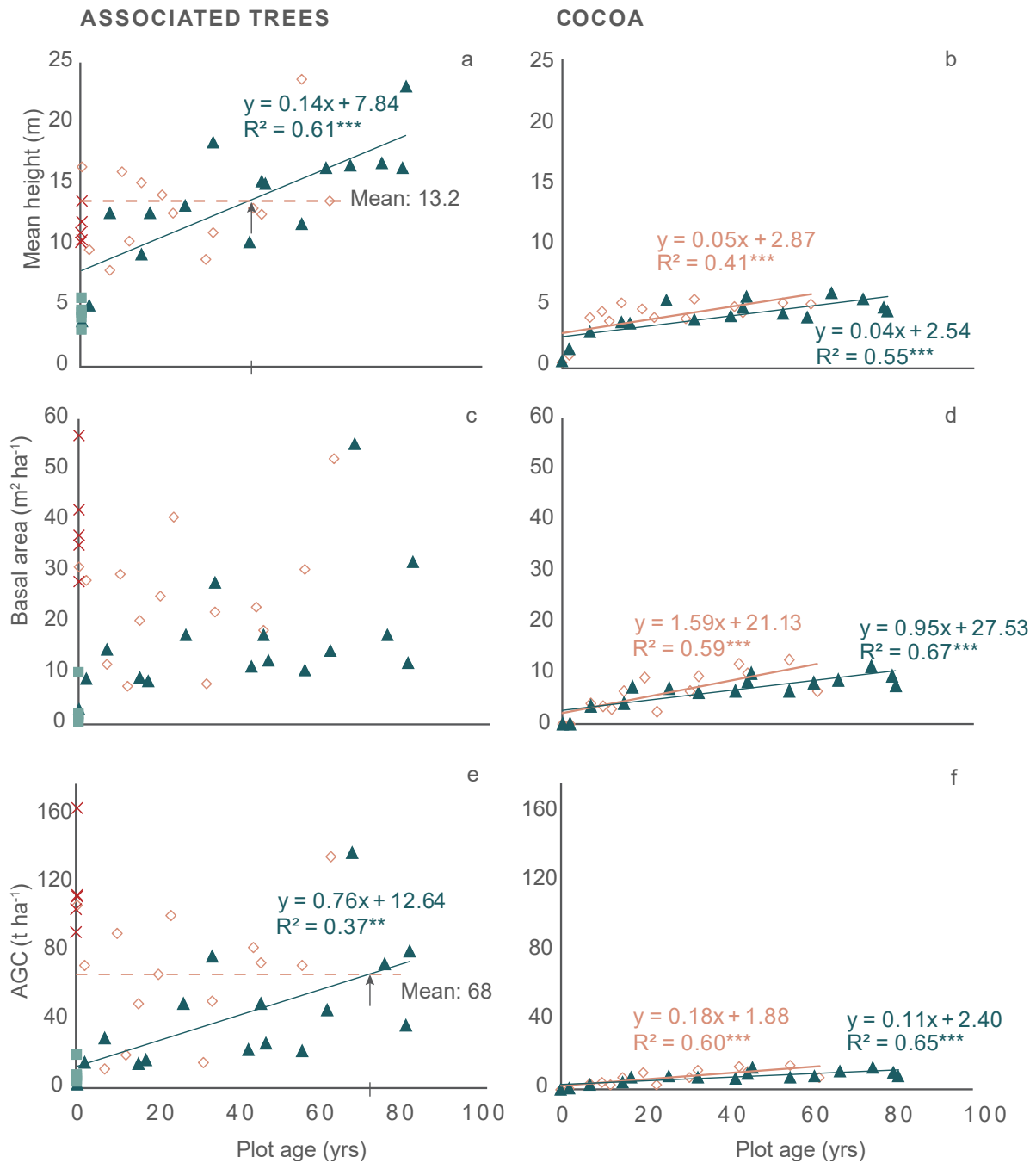


Figure 8: Correlations between age of the cocoa based agroforestry systems (cAFS) and A) mean height (m) of associated trees; B) mean height (m) of cocoa trees; C) basal area ($m^2 ha^{-1}$) of associated trees; D) basal area ($m^2 ha^{-1}$) of cocoa trees; E) total aboveground carbon (AGC, $t ha^{-1}$) of associated trees; and F) total aboveground carbon (AGC, $t ha^{-1}$) of cocoa trees. Solid lines give a correlation between age and the variable whereas dashed lines in (A) and (E) show the mean where no correlation was found. Where: \diamond cAFS after forests; \blacktriangle AFS after savannah; \blacksquare savannah control; \times forests control. $^{***}P < 0.001$; $^{**}P < 0.01$; $^*P < 0.05$; $\bullet < 0.1$

3.4 Soil properties

Some intrinsic soil properties differed between the different land-uses. Soil clay content was the highest in F-cAFS followed by forest and savannah (Table 2). Clay content of S-cAFS was lowest and significantly different from that of F-cAFS in the top soil (0-15 cm). For the 15-30 cm soil layer, no

significant differences in clay content was found. For both soil layers, pH was lowest in savannah (Table 2). Mean soil organic carbon (SOC) content of the upper 15 cm was significantly lower in the savannah compared to F- and S-cAFS (Table 2). In S-cAFS and F-cAFS, SOC was higher in the top soil (0-15 cm) than in the 15-30 cm layer. In F-cAFS, pH was higher in the 0-15 cm than in the 15-30 cm layer (Table 2). In the 0-15 cm layer SOC was positively correlated with soil clay content for S- and F-cAFS (Figure 9). According to the soil texture, S-cAFS could be divided in two groups of plots with significant different clay content: the first group having a low clay content between 10-15%, and a second group with a higher clay content between 20% and 25%. No change in SOC with age was found for F-cAFS whereas the two groups after savannah showed a clear increase of SOC content for the 0-15 cm layer. (Figure 9a,b). In S-cAFS' 0-15 cm layer, SOC exhibited a yearly increase of 7.3‰ and 9.5‰ under low clay- and high clay- content respectively (Figure 9b).

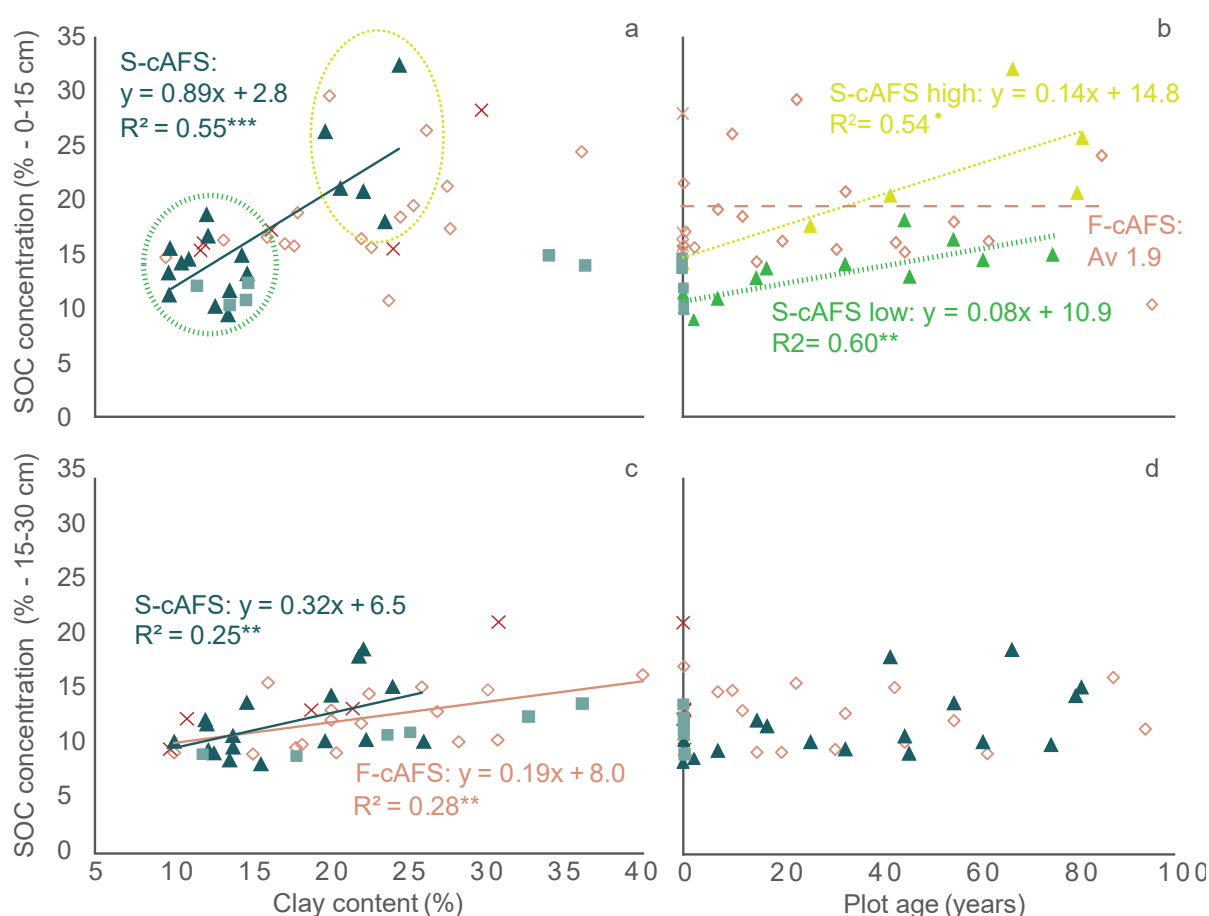


Figure 9: Soil organic carbon content (SOC, 0-15 cm and 15-30 cm) of the cocoa-based agroforestry systems after forest (F-cAFS) and after savannah (S-cAFS). Graphs show the correlation between the age of the cocoa agroforestry systems for S-cAFS and F-cAFS for A) 0-15 cm and C) 15-30 cm. The graphs B and D show the correlations between SOC and soil clay content (B) 0-15 cm and D) 15-30 cm). Solid lines give a correlation between age and the variable whereas dashed lines show the mean where no correlation was found. Dashed circle borders represent the division into two groups of plots of S-cAFS with a different clay content, where the vertical dashed line represents a group with a soil clay content between 10 and 15% and the dotted a group with a clay content between 20% and 25%. The different signs within the figure represent: \diamond F-cAFS after forests; \blacktriangle S-cAFS after savannah; \blacksquare savannah control plots; \times forests control plots. $^{***}P < 0.001$; $^{**}P < 0.01$; $^*P < 0.05$; $\bullet < 0.1$. The different shades of triangles represent the different groups based on the plots clay content.

Table 1: Stand characteristics

Stand characteristics (mean \pm 1 SD) of the studied groups. Significant differences at $P < 0.05$ between the different land-uses are indicated by different superscripts after SD.

	Cacao based agroforest set up after:			
	Savannah (S-cAFS)	Forest (F-cAFS)	Forest control	Savannah control
Stem density (individuals ha⁻¹)				
1) Cocoa trees	1174 \pm 380	1248 \pm 435	-	-
Small trees (DBH \leq 30cm)	61 \pm 42 ^a	92 \pm 71 ^a	523 \pm 109 ^b	177 \pm 175 ^{ab}
Large trees (DBH > 30cm)	28 \pm 14 ^a	35 \pm 25 ^a	60 \pm 18 ^a	14 \pm 18 ^a
Other perennial plants	47 \pm 59 ^{ab}	112 \pm 118 ^a	31 \pm 29 ^{ab}	7 \pm 8 ^b
2) Associated perennial plants	136 \pm 82 ^a	239 \pm 143 ^a	614 \pm 90 ^b	198 \pm 197 ^a
3) Total perennial plants	1310 \pm 354 ^a	1487 \pm 450 ^a	614 \pm 90 ^b	198 \pm 197 ^b
Height (m)				
1) Cocoa trees	4.16 \pm 1.5	4.14 \pm 1.6	-	-
2) Associated perennial plants	13.46 \pm 4.9 ^a	13.15 \pm 4.0 ^a	11.40 \pm 1.4 ^a	4.29 \pm 0.95 ^b
3) Total perennial plants	5.52 \pm 1.9 ^a	6.17 \pm 1.4 ^a	11.40 \pm 1.4 ^b	4.29 \pm 0.9 ^a
Maximum tree height	26.34 \pm 10.0 ^a	33.35 \pm 8.7 ^a	41.60 \pm 2.0 ^a	10.08 \pm 6.3 ^b
Basal area (m² ha⁻¹)				
1) Cocoa trees	6.64 \pm 3.2	6.17 \pm 4.1	-	-
Small trees (DBH \leq 30cm)	1.58 \pm 1.2 ^a	2.66 \pm 2.2 ^a	12.88 \pm 15.8 ^a	1.50 \pm 2.0 ^a
Large trees (DBH > 30cm)	11.46 \pm 12.8 ^{ab}	14.74 \pm 14.0 ^{ab}	23.60 \pm 3.6 ^a	1.30 \pm 2.1 ^b
Other perennial plants	2.82 \pm 2.0 ^a	2.94 \pm 2.9 ^a	3.25 \pm 2.2 ^a	0.17 \pm 0.3 ^b
2) Associated perennial plants	15.87 \pm 12.84 ^b	20.34 \pm 14.3 ^{ab}	39.74 \pm 10.7 ^a	2.97 \pm 4.0 ^c
3) Total perennial plants	22.50 \pm 14.3 ^a	26.51 \pm 15.7 ^a	39.74 \pm 10.7 ^a	2.97 \pm 4.0 ^b
AGC (t ha⁻¹)				
1) Cocoa trees	6.78 \pm 3.7	6.45 \pm 4.6	-	-
Small trees (DBH \leq 30cm)	3.28 \pm 3.5 ^a	5.89 \pm 4.7 ^a	35.31 \pm 52.7 ^a	1.76 \pm 2.4 ^a
Large trees (DBH > 30cm)	34.94 \pm 33.8 ^a	57.89 \pm 34.6 ^a	77.16 \pm 26.5 ^a	2.49 \pm 4.0 ^b
Other perennial plants	5.54 \pm 6.4	4.33 \pm 7.1	5.97 \pm 4.2	3.95 \pm 0.7
2) Associated perennial plants	43.77 \pm 35.0 ^b	68.15 \pm 36.6 ^b	118.45 \pm 28.0 ^a	8.20 \pm 6.3 ^c
3) Total perennial plants	50.55 \pm 37.2 ^b	74.59 \pm 36.8 ^{ab}	118.45 \pm 28.0 ^a	8.20 \pm 6.3 ^c

4. Discussion

4.1 Above ground carbon stock in agroforests

The potential AGC of primary forests in the Cameroonian part of the Congo basin lies between 204 and 255 t ha⁻¹ (Kotto-Same et al. 1997; Palm et al. 2005). The AGC of secondary and disturbed forests lies around 150 t ha⁻¹ (Kotto-Same et al. 1997; Vargas et al. 2008; Norgrove and Hauser 2013; Silatsa et al. 2016). With a mean AGC of 118 t C ha⁻¹ our control group of degraded forest patches contain less carbon stored than these references.

Even though, in all cases the conversion of primary or degraded forests cAFS led to a decrease in AGC stocks, the mean AGC in our cAFS was, with 51 and 72 t ha⁻¹ for S- and F-cAFS, lower compared to other studies in Cameroon. Even after excluding the plots up to 15 years old, plots where vegetative growth is still high, the average total AGC of F-cAFS was 81 t ha⁻¹ which was lower compared to other results from Cameroon. For mature F-cAFS, between 10 and 40 years old, Kotto-Same et al. (1997) found 126 t ha⁻¹, Norgrove and Hauser (2013) found 111 t ha⁻¹ and Silatsa et al. (2016) 97 t C ha⁻¹. It is likely that our results underline the fact that (i) the potential of C storage in our studied zone may inherently be lower than that of the southern part of Cameroon because trees do not have the same growth potential due to lower precipitation rates; (ii) the remaining forests of the Bokito zone appear severely disturbed as a result of anthropogenic intervention; and (iii) the cAFS designs in the Bokito area comprise more fruit trees and less native forest trees relative to those in the southern parts of Cameroon (Saj et al. 2013). Furthermore, these discrepancies may as well be due to the allometric equations used to calculate AGC in above-mentioned studies which are known to overestimate C stocks, especially for the Congo Basin (Chave et al. 2005; Kearsley et al. 2013). Finally, the sampling designs of these studies differ from ours and therefore their means do not aggregate exactly the same information. Where we chose to use 800 m² to measure cocoa and associated perennial plants < 30cm and 2400 m² to sample trees > 30cm, others often use smaller plot sizes which increases the risk of overestimation. Only Saj et al. (2013) used Chave et al. (2005) allometric equation in the same area but with a slightly different sampling design. They found a mean live tree C content of 48 t ha⁻¹ in Bokito's cAFS, which seems closer to our results.

The use of the relative C loss due to the conversion of forest to F-cAFS could bypass a part of the

Table 2: Soil properties

Stand characteristics (mean ± 1 SD) of the studied groups. Significant differences at P<0.05 between the different land-uses are indicated by different superscripts after SD. Significant differences at P<0.05 between the different soil layers are indicated by different capital letters after SD.

	Cacao based agroforest set up after:		Forest control	Savannah control
	Savannah (S-cAFS)	Forest (F-cAFS)		
Clay (%)				
0-15 cm	15.1 ± 5.2 ^a A	21.6 ± 6.4 ^b A	18.7 ± 7.9 ^{ab} A	20.8 ± 11.2 ^{ab} A
15-30 cm	16.7 ± 5.2 ^a A	22.7 ± 7.4 ^a A	18.4 ± 8.6 ^a A	24.6 ± 9.1 ^a A
pH (water)				
0-15 cm	6.1 ± 0.6 ^{ab} A	6.4 ± 0.6 ^b A	6.4 ± 0.4 ^b A	5.4 ± 0.5 ^a A
15-30 cm	5.8 ± 0.5 ^a A	6.1 ± 0.6 ^a B	6.0 ± 0.5 ^a A	5.1 ± 0.2 ^b A
SOC (%)				
0-15 cm	1.7 ± 0.6 ^{ab} A	1.9 ± 0.5 ^b A	1.8 ± 0.6 ^b A	1.2 ± 0.2 ^a A
15-30 cm	1.2 ± 0.3 ^a B	1.2 ± 0.3 ^a B	1.4 ± 0.4 ^a A	1.1 ± 0.2 ^a A

differences that are caused by dissimilarities in research methods and help comparing studies from literature. Doing so, we found a mean biomass reduction of 40 % from the forest control group to the F-cAFS. When excluding young and productive F-cAFS, up to 15 years, the average total AGC level is ca. 81 t ha⁻¹, which is equal to a decrease of 31 % when compared to our forest controls. These results are very similar to the results from other regions in Cameroon, like the reduction of 38 % estimated by Kotto-Samme et al. (1997) and 34 % by Silatsa et al. (2016), but still lower compared to the reduction of 57% from a mature forest to a mature agroforest found by Njomgang et al. (2011). In agreement with our results, a study in South Cameroon underlines large trees to be the most important contributors to AGC with percentages between 63% for mature- and 80% for old cAFS (Silatsa et al. 2016). Altogether, our results underline on the one hand a significant decrease of AGC when forests are transformed in cAFS and, on the other hand, a significant increase in AGC when savannahs are transformed in cAFS.

4.2 Soil carbon content dynamics in agroforests setup on savannah land

In the upper soil layer (0-15 cm) a clear difference was shown for the SOC of savannah (1.2%), exhibiting the lowest carbon content, and the forest-based land-uses (ca. 1.9%). The mean SOC level of S-cAFS with 1.7% fell, in-between the previous mentioned groups. The lower SOC content in savannahs could be the result of the yearly burning. Such a perturbation is prone to decrease by 2 or 3 times the organic matter input to the soil when compared to unburned soils (Knicker 2007). The SOC values we found in Bokito's cAFS seem comparable or slightly lower when compared to other published data for cAFS. Takoutsing et al. (2016), in a study conducted in central Cameroon found, combining several land-uses, found a mean SOC content of 1.8% for the upper 10 cm and 1.4 % for the first 30 cm of cAFS. Duguma et al. (2001) found slightly higher percentages for the first 20 cm of soil levels between 2.4 and 2.7% in three different locations in cAFS in Cameroon. Also, the SOC content of the upper soil layer (0-10 cm) in cAFS in Ghana seem also to be a little higher (between 2.1 and 2.6%; Dawoe et al., 2014). On the other hand, the latter studies reveal a much stronger decrease of SOC from the upper soil layer to the soil layer underneath compared to our study. The accumulation of 7.3‰ yr⁻¹ and 9.5‰ yr⁻¹ of SOC in the upper soil layer of S-cAFS implies that it is getting closer to forest-like land-uses and could be confirmed with results from Jagoret et al. (2012), who found in the same area similar SOC accumulation rates of 9.5‰ yr⁻¹ with a clay content around 18%. For the upper soil layer the accumulation of SOC after afforestation of savannah is above the 4‰ per year that had been set as one of the climate goals during the COP21. However, for this initiative the entire soil profile should be considered or at least up to one meter (Lal 2016; Minasny et al. 2017). Since our 15-30 cm soil layer did not reveal a significant accumulation of SOC the S-cAFS do not seem to provide the accumulation needed for the 4/1000 initiative. Nevertheless, this could be of interest in savannah areas with originally low C content.

4.3 Carbon storage in cAFS' aboveground biomass and soil as a mean for climate change mitigation

Afforestation of savannah areas could not only decrease the pressure on primary forest but in addition it could have an important role in climate change mitigation through increased carbon sequestration (Montagnini and Nair 2004). We found that, on the contrary to the decrease in AGC due to the conversion

of forest into F-cAFS, the conversion of savannah into S-cAFS increased on average the AGC with 42 t ha^{-1} , which is equal to an annual accumulation of ca. $0.5 \text{ t ha}^{-1} \text{ yr}^{-1}$. With $8,2 \text{ t ha}^{-1}$ of C, our savannah control came close to the results of woodland or moist savannahs in other parts of the world (Barbosa and Fearnside 2005). To our knowledge there is no available data on the study of AGC evolution during the conversion of savannah into S-cAFS. Jackson et al. (2002) describe that woody invasion of savannah could have a negative effect on the total carbon storage in savannah especially in regions with higher precipitation rates ($>1000 \text{ mm yr}^{-1}$), like in our case, and a profound soil. Nevertheless, in our study SOC content in the first 30 cm of the savannahs in Bokito was relatively low, between 1.1 % and 1.4% in soils with low and higher clay content, respectively. This was likely related to that fact that local savannahs are regularly used as marginal cropland and burnt once a year. Our study showed that after installation of a S-cAFS it took ca. 30 years for the upper soil layer with a high clay content ($>20\%$) to get to the same mean level of SOC from F-cAFS (Figure 9a). Meanwhile, for the S-cAFS with clay content of 10 -15% it takes ca. 100 years to get at this point. Part of the variation of the SOC content of F-cAFS could probably be linked to the topographical position of the plots. For the AGC of S-cAFS ca. 75 years was needed to get at the same level as F-cAFS. Variations in AGC could be explained by differences in management practices, where a farmer chooses to leave associated trees in place or remove them from the cAFS (Jagoret et al. 2011). The main drivers for this long-term accumulation of AGC were the large associated trees confirming previous results by Saj et al. (2013) and Silatsa et al. (2016). Since in young S-cAFS the associated trees are not yet developed, their number and their importance in the young years of a S-cAFS is almost negligible. Annual accumulation of carbon in the studied systems is around $0.8 \text{ t ha}^{-1} \text{ yr}^{-1}$ which seems relatively low compared to other studies in the southern part of Cameroon, where carbon accumulation rates between 1.5 and $10 \text{ t ha}^{-1} \text{ yr}^{-1}$ have been described (Boyer 1973; Montagnini and Nair 2004). However, as shown in the study of Silitsa et al. (2016), the accumulation, and growth, rates are not linear and therefore, highly dependent on the time scale. While these authors found maximum carbon sequestration rates for cAFS to be between 12 and 20 years we used linear regression on an 80 years chronosequence. Finally, the farmers' management strategies, as tree pruning and the elimination of trees when shade gets too dense could be a reason for low accumulation rates in Bokito (Saj et al. 2013). This could also be a reason why no overall AGC accumulation has been found for the F-cAFS. For the cocoa trees in both systems, accumulation rates of $0.11 \text{ t C ha}^{-1} \text{ yr}^{-1}$ for S-cAFS and $0.18 \text{ t C ha}^{-1} \text{ yr}^{-1}$ for F-cAFS were obtained with no significant differences between both cAFS systems. The shade regime in F-cAFS could have a positive influence on the growth of cocoa as shown by Isaac et al. (2007), and the growth rate of full sun cocoa trees, like those in the first years on S-cAFS, could be inhibited by the high irradiation rate during the first years after planting (Isaac et al. 2007; Sonwa et al. 2016).

Finally, afforestation of savannah may help in other things in addition to climate change mitigation. The cAFS of Bokito, implemented on a land-use characterized by long drought periods (Jagoret et al. 2012), show cAFS to be more resilient to drought than expected. Conversion of monoculture cocoa production systems to multi-specific cAFS by planting shade trees could represent an alternative method of production in order to adapt to increasing irradiation and more intense drought events, thus improving production conditions and livelihood in the area, ultimately helping to avoid large population migrations

as seen in Ivory Coast (Wood and Lass 2001; Ruf et al. 2015; Schroth et al. 2016). More detailed information is needed on putative competition and facilitation processes between cocoa and associated tree species as the results are affected by rainfall quantity and temporal distribution. One advantage of cAFS is the diversification of farmers' income with the production of market valuable products by the associated trees (Jagoret et al. 2012; Saj et al. 2013). This makes farmers less dependent on the production of cocoa and more resilient when production fails one year. Overall, it appears that S-AFS are a clear example of a climate smart agricultural system (Lipper et al. 2014) that is to be better considered both by the industry and the cocoa scientific community.

5. Conclusion

Our study showed, over a period of about 80 years, a steady increase in both AGC and SOC after converting savannah to S-cAFS. Unique to this study is the length of our chronosequence which makes it possible to demonstrate that carbon content of S-cAFS gets similar to F-cAFS on the long-term. On the other side, conversion from degraded forest patches, our forest control, to F-cAFS led to a reduction of ca. 40% of carbon, with a minimum maintenance of AGC on the long-term and no decrease in SOC.

Besides their potential climate mitigating function, S-cAFS seem very compatible at the field level with both the 4 permille and the Climate Smart Agriculture initiatives. This makes further exploration to the functioning of these systems very promising. Nevertheless, more information is needed about adaptation to climate change (especially drought events) to confirm that this would be one of the solutions to cope with coming climatic difficulties. In the forest-savannah transition zone of Central Africa, it would be interesting to get a better insight of the area covered by these S-cAFS in order to check to which extent afforestation of savannahs could be expanded without leading to competition with other local commodities.

Acknowledgments

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CHAPTER 2



"Production"

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Ecosystem functions of complex cocoa agroecosystems in Central Cameroon – Insight into the legacies of past land-use

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Abstract

The functioning of an (agro)ecosystem may depend on its past land-use. Cocoa agroforestry systems (cAFS) in Central Cameroon can be set up either after forest or after savannah and can therefore inherit very different levels of ecosystem functions. Long-term legacies of several ecosystem functions of the two past land-uses were studied using chronosequences of over 80 years for cAFS created after savannah (S-cAFS) and forest (F-cAFS). The results were compared with data from forest and savannah control plots in the same area. Our study shows that most land-use legacies were longer observable for S-cAFS compared to F-cAFS. The high impact of the land-use change from savannah to S-cAFS made that legacies of the past land-use were fading after 14 years and resulted in significant changes especially for biomass, litterfall and -stock and soil fertility parameters. Contrastingly, the legacies from the forest conversion into F-cAFS led to rapid above ground changes but probably rather stable soil functioning. The diversity and richness of perennial plant species, African or exotic, were comparable for both cAFS in the long-term and underlined the active management practices undertaken by farmers to build-up and further maintain the complexity of S-cAFS. The accessible yields were comparable for both cAFS types all along the chronosequences. The positive relationship between the associated perennial plant biomass and the accessible yield for S-cAFS emphasized the win-win management strategies of farmers when cAFS are set up on savannah land. Contrastingly, this relationship was marginally negative in F-cAFS and putatively underlining interspecific competition effects.

Keywords: Land-use legacies; Cocoa agroforestry systems; Ecosystem functions; Biodiversity; Afforestation;

1.Introduction

Ecosystem functions depend on both current ecosystem ecological features and historical legacies. Disturbances, natural or anthropogenic, lead to long term fluctuations in ecosystem structure and functioning. The frequency, type, size, timing, and intensity of a disturbance determines its impact and could eventually lead to land-use change (Chapin et al., 2005). In general, the impact of humans' interference, for example in the form of agricultural activities, is much larger than natural events (Foster et al., 2003). One of the least sensitive compartments of an ecosystem to land-use change is the mineral soil horizons (Dawoe, Isaac, & Quashie-Sam, 2009; Laclau, Ranger, Nzila, Bouillet, & Deleporte, 2003; Marques & Ranger, 1997). However, all organic components, above- and below- ground, including soil organic matter and living organisms, seem to be highly influenced by past land-use (Bellemare, Motzkin, & Foster, 2002; Jangid et al., 2011; Perring et al., 2016). Accordingly, legacies related to previous land-use are demonstrated for an array of ecosystem properties, including nutrient cycling, carbon storage, microbial community and heterotrophic respiration (Dupouey, Dambrine, Laffite, & Moares, 2002; Freschet, Ostlund, Kichenin, & Wardle, 2014; Kallenbach & Stuart Grandy, 2015). Hence, land-use legacies might be overruled if current disturbances are strong enough, ultimately leading to novel ecosystems (Hobbs et al., 2006).

Agroforestry systems can be derived from contrasting ecosystems. The cocoa agroforestry systems (cAFS) from Central Cameroon are for instance set up either on forest or savannah land (Jagoret, Michel-Dounias, Snoeck, Ngnogu , & Mal zieux, 2012b). The conversion of a tropical forest into an agricultural suitable environment is mainly achieved by slash-and-burn technics, which are very similar all over the world (Achard et al., 2002; Nepstad et al., 1999; Palm, Vosti, Sanchez, & Ericksen, 2005). The impact of the conversion of a tropical forest into a cocoa plantation is highly linked to farmers' background and culture. Either a forest gets entirely cleared and a monoculture plantation will be established or, as in most cases in Central Cameroon, a farmer will maintain several species of interest (Jagoret et al., 2012b). Those species provide the shade especially needed in the first years after establishment but are also kept for food production and as income diversification. Besides the conversion of tropical rainforests, tropical grasslands are frequently utilized for agricultural purposes. Over the last century half of the tropical grasslands and savannahs had been converted to agricultural land (UNDP, 2003). In Central Cameroon savannahs are mainly dominated by the highly resistant *Imperata cylindrica* (MacDonald, 2004). Annual intentional vegetation fires are used to clear land for cattle keeping, agriculture and hunting practices (J. X. Kugbe, Mathias, Desta, Denich, & Vlek, 2012). Yet, afforestation or reforestation of tropical savannah land with cAFS seems rare. The only other description of a region where cAFS were successfully established on *I. cylindrica* dominated grassland comes from a reforestation project of family farms in Indonesia (Ruf & Lan on, 2004). For the installation of a cAFS and the elimination of *I. cylindrica* Cameroonian farmers install either oil palms in dense stands or start planting annual crops prior to the establishment of cocoa, fruit and forest tree species (Jagoret et al., 2012b). Even though the regional topography and soil are diverse, full grown cAFS created after savannah (S-cAFS) seem to comprise the same multi-strata design as cAFS created after forest (F-cAFS (Jagoret, Michel-Dounias, & Mal zieux, 2011b; Saj, Durot, Mvondo Sakouma, Tayo Gamo, & Avana-Tientcheu, 2017).

The land-use change from a savannah or forest to a cAFS affects both above and belowground functions.

Farmers' management practices alter plant composition and above- and belowground biomass which in turn results in changes in litterfall, moisture availability and irradiation. Finally, together with the exportation of local production, changes in soil properties as soil fertility will occur. The effects of the conversion of forest into cAFS lead in most cases in a decrease of most of the previous mentioned ecosystem functions (Ahenkorah, Halm, Appiah, Akrofi, & Yirenkyi, 1987; Beer, Muschler, Kass, & Somarriba, 1998; Hartemink, 2005; G Schroth, Lehman, Rodrigues, Barros, & Macedo, 2001). Whereas the conversion of savannah land to agroforestry systems was shown to have a positive effect on most of the ecosystem functions (Don, Schumacher, & Freibauer, 2011; Nouvellon et al., 2012; Sugihara, Shibata, Mvondo Ze, Araki, & Funakawa, 2014). The time an ecosystem function stays visible after the land-use conversion depends on the function and the impact of the conversion. The intensity and the duration after conversion will determine if an introduced function will be embedded in the new land-use form or not.

Although most studies focus on the effects of past human activities on today's natural environment we focus in the present study on the persistence of legacies of two semi-natural ecosystems on an area impacted by human interference. Our aim was to compare cAFS' legacies inherited from two different past land-uses, savannah (S-cAFS) and forests (F-cAFS), on the long-term, using a selected number of aboveground and soil functional characteristics. We undertook this study in the district of Bokito, the only region in Cameroon that is documented for the production of cocoa for more than 80 years and where old and young S- and F-cAFS co-occur. We studied four groups of agroecosystem functional characteristics: standing biomass, cocoa production, leaf litter production and storage, and soil fertility. We tested the main hypothesis that ecosystem multifunctionality varies strongly with the cAFS past land-use, plot age and plot plant diversity. Specifically, we expected that 1) savannah conversion to cAFS would induce less changes in ecosystem function than forest conversion within the first years but larger effects after longer periods; 2) Past land-use would retain an impact on ecosystem functions on long time scales; 3) Farmer's practices maintaining high plant diversity play an important role in ecosystem multifunctionality.

2. Material and methods

2.1 Site characteristics and experimental setup

The study was carried out in the district of Bokito in the villages Bakoa and Guéfigué (4°30 latitude N and 11°10 longitude E; 7125 km²), located in a forest–savannah transition zone in Central Cameroon. Annual average rainfall ranges from 1,300 to 1,400 mm with a main dry season that lasts over three months, from mid-November to the beginning of March (Jagoret, Michel-Dounias, Snoeck, Ngnogué, & Malézieux, 2012a). Bokito's soils are dominated by slightly desaturated ferralitic soils (Elangwe, 1979). The landscape consists of hills with gentle slopes with an altitude between 400 and 550 m a.s.l and is characterized by a patchwork of forests and herbaceous savannahs dominated by the perennial species *I. cylindrica* (Jagoret et al., 2012a). The cocoa plantations in this region comprise mainly of complex agroforestry systems (cAFS) that contain many associated trees, including fruit and forest tree species (Jagoret, Michel-Dounias, & Malézieux, 2011a; Saj, Jagoret, & Todem Ngogue, 2013; Sonwa et al.,

2007). A study on the age distribution of cAFS in the region showed that around 22% of the cAFS were less than 22 years old whereas 45% were more than 45 years old (Jagoret et al., 2011a).

In July 2015, 28 cAFS plots were selected based on their age and past land-use. Plots' size was of 40 m x 60 m (2400 m²), each containing a subplot of 20 m x 40 m (800 m²). Fourteen plots of cAFS had been created after savannah (S-cAFS) and 14 after forest (F-cAFS). Ages were regularly distributed along a gradient from 8 to over 60 years. In 2015, two new plots were added per group to complete the age gradient, 0 (farmers just started the planting process of cocoa) and 2 years old. Finally, five control plots of each past land-use (savannah and secondary forest) were selected for comparison with the S- and F-cAFS.

2.2 Vegetation structure above and below ground biomass and accessible cocoa yields

In each plot, the diameter at breast height (DBH; 1.3m) and height of all perennial plant species, including cocoa, associated trees, standing dead trees, palms and bananas were measured. Plants with a DBH larger than 30 cm were inventoried in the 2400 m² plot, while plants with a DBH between 5 and 30 cm were inventoried within the 800 m² subplots. In case cocoa trees were smaller than 1.3 m, the DBH was measured under the first branch. Height of trees was measured either using a graduate stick (when lower than 7 m) or using a TruPulse 360 R Laser Rangefinder. In total, we counted 3036 cocoa trees and 670 associated individuals in the cAFS studied. In the forest- and savannah- control plots 304 and 92 perennial species were identified. Associated species were subset in two groups: 1) species that are local to African continent and 2) Exotic species introduced from other continents. Of the perennial plants, 11.6 % could not be identified at species level.

A non-destructive sampling method was used for the determination of total aboveground biomass (AGB). We used the allometric equation of Chave et al. (2005) to determine the AGB of the cocoa and associated perennial plants, the AGB of oil palms (*Elaeis guineensis*) was calculated using the simple regression model developed by Asari et al. (2013) and for bananas (*Musa sp.*) a model developed by Hairiah et al. (2001) was used exactly as in the study of Nijmeijer et al (submitted).

In savannah control plots, AGB of the herbaceous stratum was estimated at the end of the rainy season (October 2015), when the development of herbs was at an annual maximum. In each savannah plot, herbaceous vegetation was cut at ground level in ten randomly distributed 1 m² quadrants and fresh weight of each quadrant was measured. A fresh weighted subsample of each quadrant was then dried at 60 °C for 72 hours and weighed for dry matter calculation.

Five soil cores (replicates) with a diameter of 8 cm and to a depth of 10 cm were excavated on fixed points per plot (800 m²) in September 2016 to estimate fine root biomass. For each core, roots were separated from soil and washed within a time span of four days. Only the first three orders of roots were selected for further analyses (McCormack et al., 2015). Roots of cocoa were separated from the other roots based on their colour and dried apart for 72 hours at 60 °C to determine fine root biomass.

Finally, cocoa accessible production was estimated via pod counting on the field as in Saj et al (2017b).

2.3 Leaf litterfall and litter storage

A litterfall study was conducted during an entire year from the beginning of November 2015 until the end October 2016. Three 0.5 m² collectors were placed per plot and emptied every two weeks (111 collections in total during the study). The collectors were randomly placed within the 2400 m² area of each plot, and once a month their positions were changed to improve the representativeness of the plot means (12 different positions for each collector during the study; H. Schroth & Sinclair, 2003). Once collected, litter was first air-dried and sorted in four classes: cocoa leaf litter, associated species leaf litter, branches and reproductive organs. Subsamples were then dried in a stove at 60 °C for 72 hours and weighed for dry matter content calculation.

Minimum standing litter stock was measured at the end of the rainy season (October, 2016), when the decomposition started to slow down due to a lack of water. In each plot litter was collected in 4 randomly distributed 1 m² quadrants and fresh weight was measured. Litters from a 0.0625 m² (25 * 25 cm) sub-quadrant were then dried at 60 °C for 72 hours. These subsamples were sorted in four classes: cocoa leaf litter, associated species leaf litter, branches and reproductive organs, and weighed for dry matter calculation. Minimum litter stock and litterfall were not measured in the savannah control plots since annual fires impair normal restitution.

2.4 Soil samples

A composite soil sample of 0-15 cm depth was built from eight subsamples randomly distributed in each plot. Chemical composition and texture were determined by the IITA soil laboratory in Yaoundé (November 2016; www.iita.org). Soils were air-dried and ground to reach a particle size ≤ 2 mm. Particle size (three fractions) was after Bouyoucos (1951) and pH in water was determined in a 1:2.5 (w/v) soil:water suspension. To determine organic C, soils were further ground to reach a particle size ≤ 0.5 mm, in order to proceed to chromic acid digestion and spectrophotometric analysis (Heanes, 1984). Total nitrogen was determined from a wet acid digest (Buondonno, Rashad, & Coppola, 1995) and analysed by colorimetry (Anderson & Ingram, 1990). To determine mineral nitrogen, soil nitrate and ammonium were extracted in 1N KCl and determined colorimetrically using a UV-Vis spectrophotometer. Available phosphorus (P) was extracted using Bray 1 extractant and analysed using the molybdate blue procedure (Murphy & Riley, 1962). Potassium was extracted by ammonium acetate at pH 7 and analysed by flame atomic absorption spectrophotometry (David, 1960). A ring with a diameter of 5 cm was used to determine soil bulk density (Blake & Hartge, 1986) for soils to a depth of 0–5 and 10-15 cm. Soils were sieved using 2 mm sieves and weighted after being oven dried at 105 degrees for 48 hours.

2.5 Data analyses

African and exotic tree species rarefaction curves were computed to check for differences in the four land-use types. Calculation of biodiversity indices were performed only on the associated tree species. The number of individuals per species in the plots were extrapolated to number of individuals per species per hectare. Abundance and diversity data of associated trees were used to calculate the Shannon-Wiener index (Peet, 1974). Species richness was investigated via species count and rarefaction curves using

EstimateS (version 9.1.0) from Colwell (2012). Visual comparison of the rarefaction curves and their associated 95% confidence intervals was used to evaluate significant differences in species richness between habitats (Barlow et al., 2007).

Principal component analysis (PCA) was performed on the functional characteristic variables (standing biomass; accessible cocoa production; leaf litter production and storage; soil fertility; tab. 1) to determine the primary axes across the different plots. Shannon-Wiener index as well as soil clay content, bulk density and nitrate content were added as supplementary variables. Centroids were plotted based on age categories corresponding to the age distribution of the cAFS, to focus on the evolution of the functional characteristics of cAFS with different past land-uses and their matching control groups. One-way ANOVA was used to determine which age categories were significantly different according to their past land-use using the plot scores from the PCA with age categories nested within. Post-hoc pairwise comparisons between treatments were performed using Newman-Keuls test.

Based on the results of the PCA, age categories were regrouped in young cAFS (0-14 years) and older cAFS (≥ 15 years). We used one-way ANOVA to test if the studied variables of the different cAFS groups were different from their past land-use and between each other, followed by the Student-Newman-Keuls test as post-hoc. If the variance was not sufficiently homogeneous, the data were analyzed using the non-parametric Kruskal–Wallis test in combination with the Steel-Dwass-Critchlow-Fligner test as post-hoc. Furthermore, we performed multiple regressions to assess how the studied variables were depending on age, soil clay content and farmers' management. Management was in this case represented by the total associated above ground biomass and biodiversity since these are the direct result of farmers' practices (M. J. E. Arnold & Dewees, 1999; Jodha, 1995). During the analyses of soil variables, we included clay content since it alters nutrient storage ability (H. Schroth & Sinclair, 2002). For the litterfall, litter stock and cocoa accessible yield we also included the AGB of cocoa trees as an explanatory factor. A parsimonious modelling procedure was used starting with the most complex model and then removing step by step the less significant factors keeping the Akaike information criterion (AIC) always decreasing. All the statistical analyses were performed using XLSTAT (Addinsoft, XLSTAT, 2016).

3. Results

3.1 Past land-use legacies of S- and F-cAFS

The first two axes of the PCA covered 61.3 % of the variation in the sample (Figure 10). The primary axis of the PCA explained 30.9% of the variance and was related to soil fertility and most of the associated tree variables (Table 3; Figure 10). The second axis was more related to the cocoa stand and explained 30.5% of the total variance. Forest and savannah control plots were clearly separated on the first axis, with negative loadings for savannah control and positive loadings for forest control. Age classes of S- and F-cAFS were distributed on the second axis. Post-hoc comparisons showed that the S-cAFS of the 0-14 age class for the first and second axes of the PCA were not significant different from their past land-use (Figure 11). No fitting model was found for the first axis of F-cAFS. All age categories were significantly different from their past land-use on the second axis.

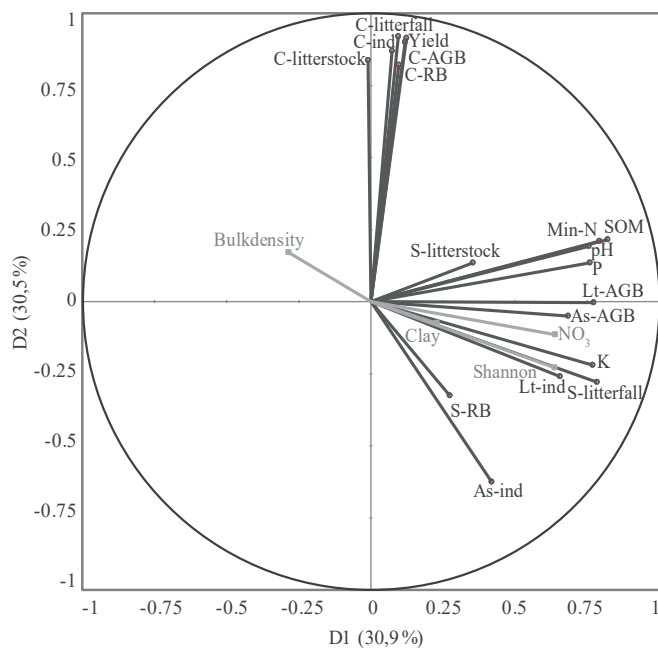


Figure 10: Vectors of the principal component analysis (PCA) after Varimax rotation represent environmental variables explained in table 1.

Table 3: Vectors of the principal component analysis (PCA) after Varimax rotation represent environmental variables explained in table 1.

Variable	Explanation	D1 (r ²)	D2 (r ²)
Biomass			
C-ind	Cocoa individuals	0.005	0.757
Lt-ind	Large trees (>30cm) nr individuals	0.429	0.067
As-ind	Other associated plants nr individuals	0.175	0.390
C-AGB	Cocoa aboveground biomass (t ha ⁻¹)	0.014	0.810
Lt-AGB	Large trees (>30cm) aboveground biomass (t ha ⁻¹)	0.596	0.000
As-AGB	Other associated perennial plants aboveground biomass (t ha ⁻¹)	0.466	0.003
C-RB	Root biomass cocoa (t ha ⁻¹)	0.009	0.674
S-RB	Root biomass total associated perennial plants (t ha ⁻¹)	0.075	0.107
Production			
Yield	Potential fresh yield (kg ha ⁻¹)	0.015	0.836
Leaf litter production and storage			
C_litterstock	Minimum litterstock - cocoa leaves (t ha ⁻¹)	0.000	0.702
C_litterfall	Total annual litterfall - cocoa leaves (t ha ⁻¹)	0.009	0.845
S_litterstock	Minimum litterstock - total associated perennial plants leaves (t ha ⁻¹)	0.124	0.018
S_litterfall	Total annual litterfall - total associated perennial plants leaves (t ha ⁻¹)	0.612	0.078
Soil fertility			
pH	pH water	0.569	0.037
P	Phosphor (‰)	0.575	0.018
SOM	Organic carbon content (%)	0.671	0.046
Min-N	Mineral nitrogen (%)	0.625	0.044
K	Potassium (cmol kg ⁻¹)	0.591	0.048
Supplementary data			
Shannon	Shannon index	0.475	0.062
NO ₃	Initial nitrate level in fresh soils	0.542	0.017
Clay	Clay content (%)	0.093	0.010
Bulkdensity	Bulk density with coarse material (kg ha ⁻¹)	0.157	0.057

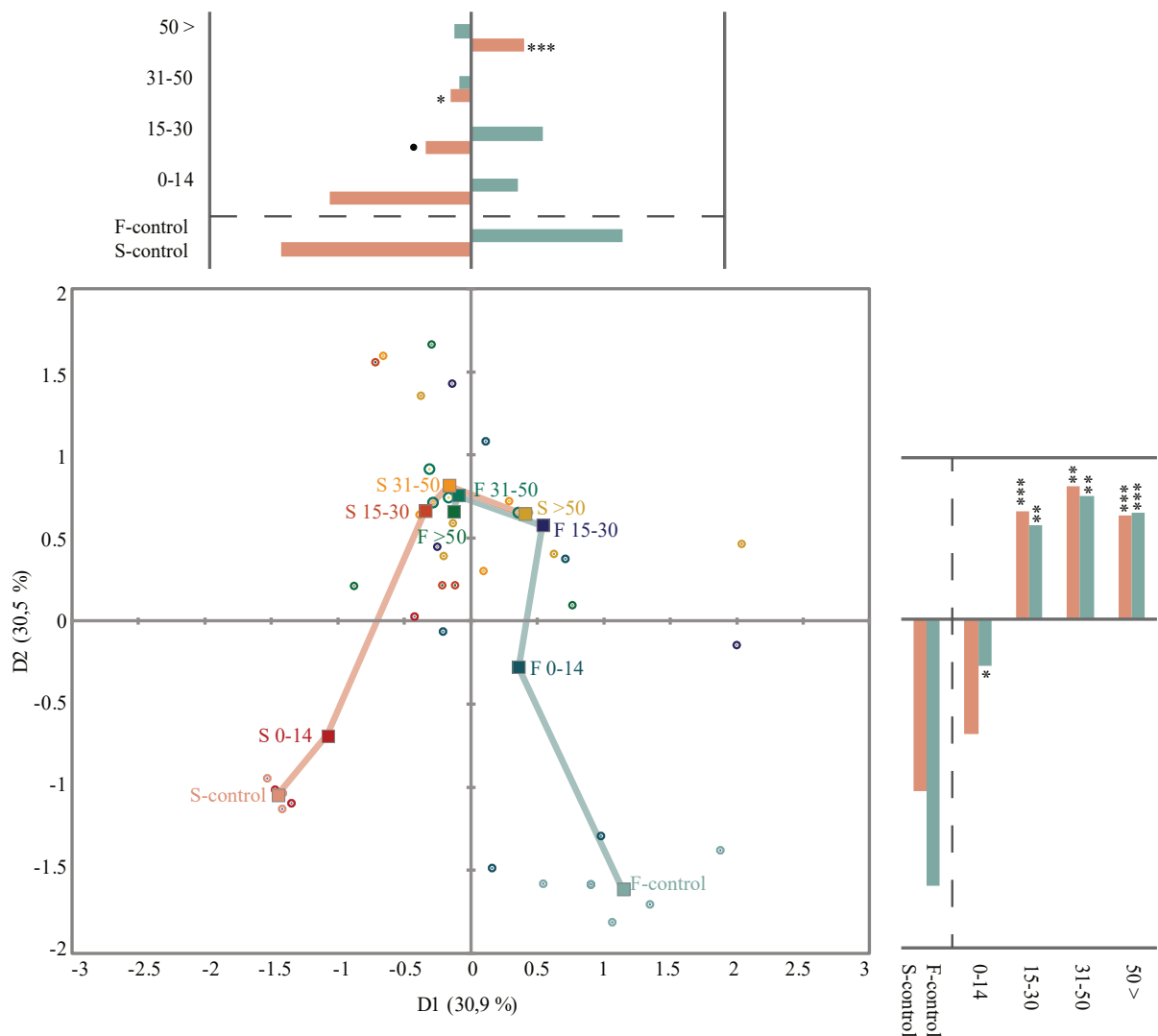


Figure 11: Biplot of the PCA, axes D1 and D2 explain together 61,3%. The used variables represent the ecosystem functions studied: standing biomass, cocoa achievable yield, leaf litter production and storage and, soil fertility and is conducted on 31 cAFS plots as well as 5 forest and 4 savannah control plots. Each cAFS age class and the control groups are represented by a different colour, and all plots are displayed (small circles), together with their corresponding centroid (squares). Lines represent the virtual temporal trajectories based on the past land-uses and the different age classes. Bar plots show for both axes the age classes of the S- and F-cAFS and their significant difference to their past land-use.

3.2 Past land-use and age effects on above- and below- ground variables studied

Aboveground biomass (AGB) differed significantly among the land-use types with the forest control recording the highest value and savannah control group the lowest (Figure 12a). Both F-cAFS and S-cAFS of $15 \geq$ years exhibited similar AGB while S-cAFS of 0-14 years were intermediate between the other cAFS and the savannah control. Total AGB of other perennial plants followed the same trajectory. AGB of large trees in cAFS fell all in the same group but were also corresponding to their past land-use. Cocoa tree biomass was significantly lower for the 0-14 age class compared to the $15 \geq$ age class cAFS. Total fine root biomass was lowest in the S-cAFS 0-14 years age class and in the savannah control

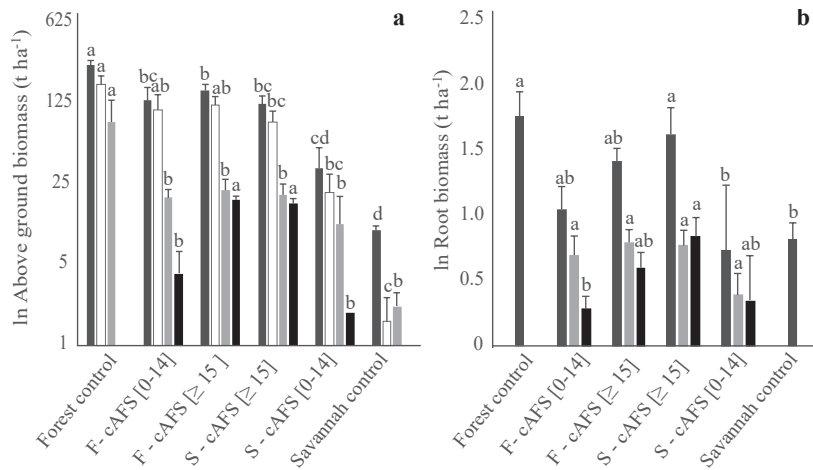


Figure 12: Past land-use legacies in standing biomass of the different age classes in the S- and F-cAFS (+ 1 SE) as revealed by univariate analyses of variance. Different letters above histograms show significant differences between categories ($P < 0.05$). Dark grey represents totals; white represents large trees > 30 cm; light grey represents other associated perennial plants; black represents cocoa.

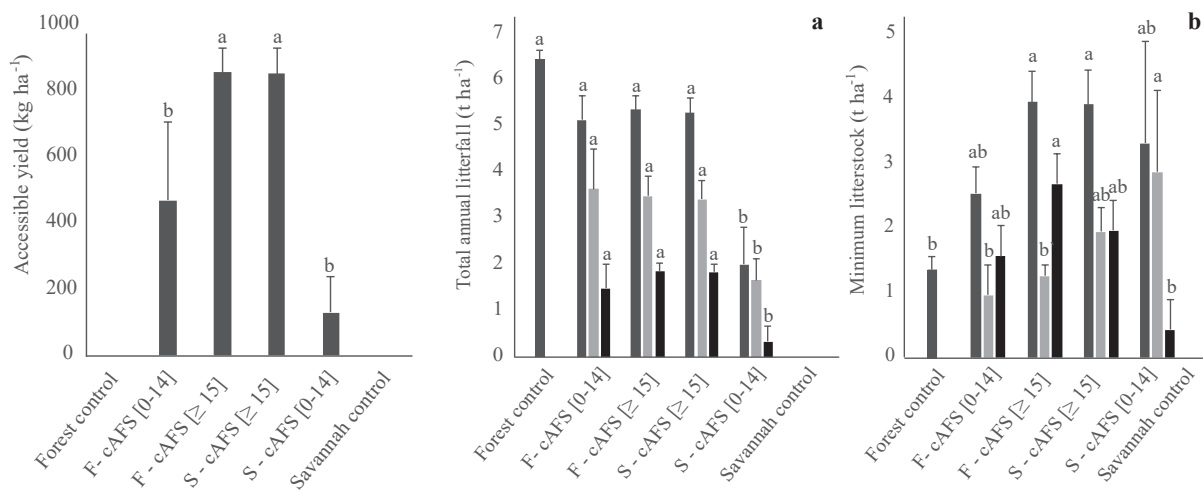


Figure 13: Past land-use legacies in cocoa accessible yield of the different age classes of the S- and F-cAFS (+ 1 SE) as revealed by univariate analyses of variance. Different letters above histograms show significant differences between categories ($P < 0.05$).

Figure 14: Past land-use legacies in leaf litter production of the different age classes in the S- and F-cAFS (+ 1 SE) as revealed by univariate analyses of variance. Different letters above histograms show significant differences between categories ($P < 0.05$). Dark grey represents totals; light grey represents total associated perennial plants; black represents cocoa.

(Figure 12b). Cocoa root biomass was significantly lower in the F-cAFS 0-14 age class. No significant differences were found between the four cAFS groups for the fine root biomass of associated trees. Cocoa accessible yield was lower in the cAFS of 0-14 years than in the older cAFS (Figure 13). Total leaf litterfall of the cocoa and the associated species, was the lowest in S-cAFS of 0-14 (Figure 14a). No significant differences were found between the other groups. Total minimum leaf litter stock was the lowest in the forest control group (Figure 14b).

Several parameters of soil fertility in the upper soil layer were lower in the savannah control and the S-cAFS (0-14) compared to the other systems (Figure 15a-i ; $p < 0.05$). Soil organic matter content

was lowest in the 0-14 age class of S-cAFS followed by the savannah control (Figure 15a). Mineral N content was significantly lower in both the savannah control and the S-cAFS age class 0-14 (Figure 15b). Nitrate content was lowest in the savannah control and the 0-14 age class of S-cAFS and highest in forest control and 0-14 F-cAFS (Figure 15e). We found no significant differences for the P, K and clay contents (Figure 15c,d and g). The pH was lowest in the savannah control and the 0-14 age class S-cAFS was in between the savannah control and the other systems (Figure 15f). Soil bulk density (including coarse material) was significantly lower in the forest control and the young F-cAFS class in the 0-5 cm depth (Figure 15h). No significant differences were found for the fine fraction of the soil bulk density of 0-15 cm (Figure 15i).

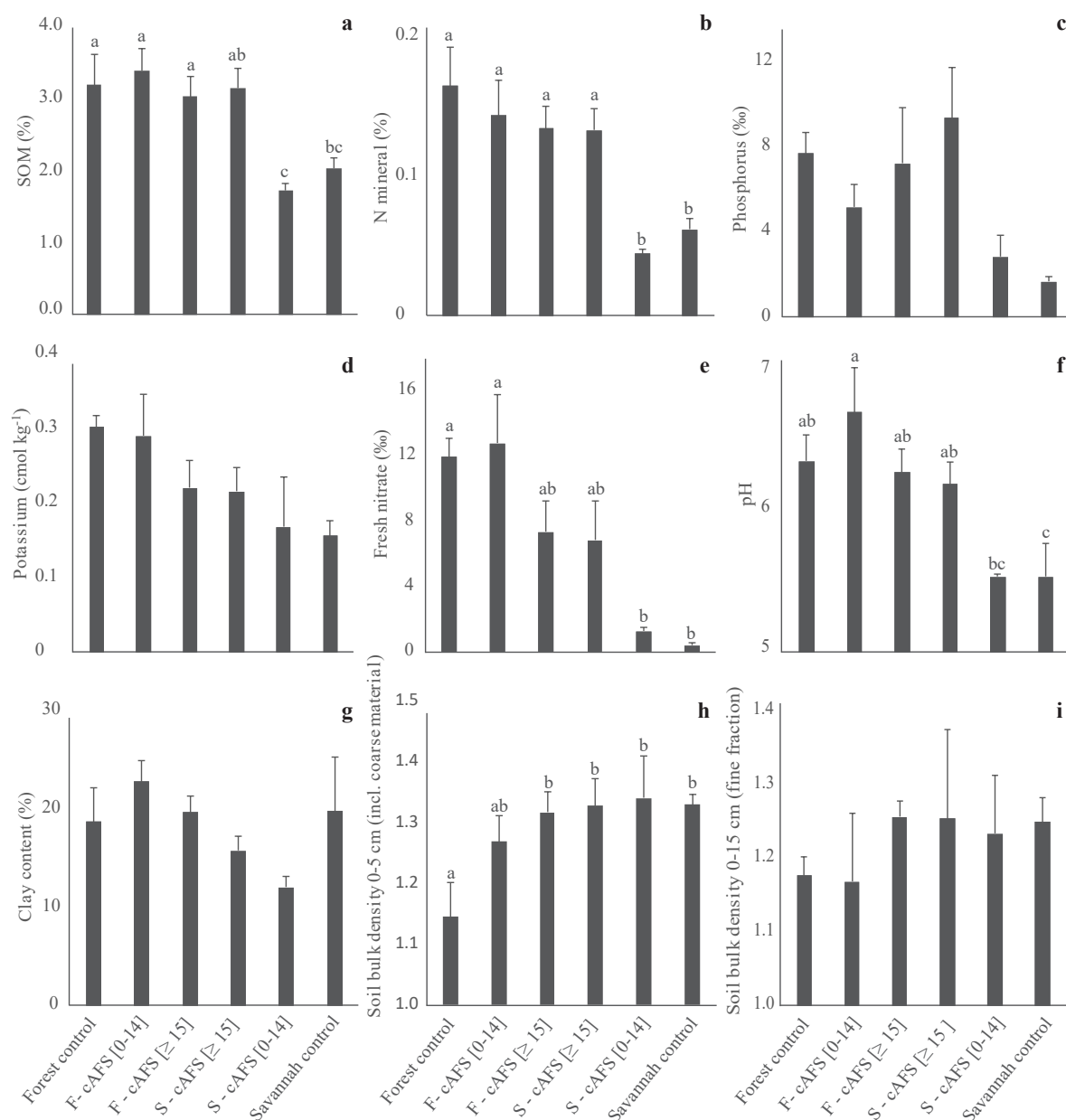


Figure 15: Past land-use legacies in soil fertility parameters of the different age classes in the S- and F-cAFS (+ 1 SE) as revealed by univariate analyses of variance. Different letters above histograms show significant differences between categories ($P < 0.05$).

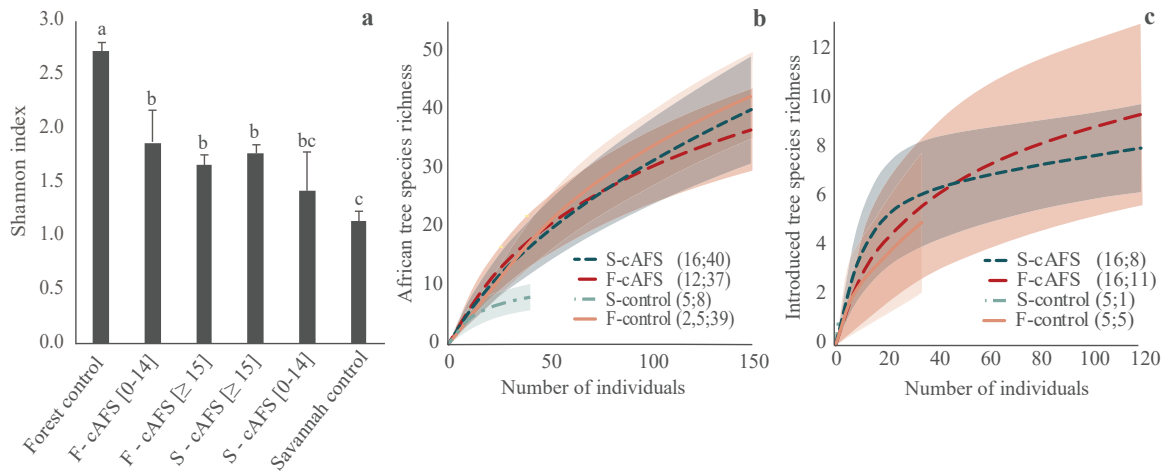


Figure 16: Shannon-Wiener index and rarefaction curves for the associated perennial plant species identified in the four different land-use groups. (a) past land-use legacies for the Shannon-Wiener index of the different age classes in the S- and F-cAFS (+ 1 SE) as revealed by univariate analyses of variance. Different letters above histograms show significant differences between categories ($P < 0.05$). (b) Perennial plant species local to the African continent (c) Exotic perennial plant species from other continents. The 95% intervals (shaded regions) were obtained by a bootstrap method based on 100 replications. The numbers within the brackets next to the system type corresponds to the number of plots needed (first number) to reach the sample size and the species richness (second number) obtained for the studied sample size.

3.3 Perennial plant diversity

Mean Shannon–Wiener diversity index values differed significantly among the land-use types with the forest and savannah control plots recording the highest and the lowest values respectively (Figure 16a). Rarefaction curves were not extrapolated, instead minimum number of individuals found for each researched group were compared (Figure 16). Patterns for forest control, S- and F-cAFS were found to be very similar for the African tree species whereas numbers of individuals and species diversity were both much lower in savannah control (Figure 16b). The abundance of individuals of associated perennial plants was very different when comparing cAFS (S-cAFS: 136 ind. ha⁻¹ F-cAFS: 234 ind. ha⁻¹) with mean forest control perennial plant density (614 ind. ha⁻¹) and savannah control (115 ind. ha⁻¹; Figure 16b). The sampling effort needed to get comparable tree species diversity in cAFS as in forest control is therefore much more important for cAFS than for forest control. Besides, the number of exotic species in the cAFS was much lower compared to African species and almost the same amount of exotic species were found in the forest controls (Figure 16c). Only the savannah controls exhibited at most one exotic species.

3.4 Multiple linear regressions

The model that best fitted patterns in AGB when considering the age and the Shannon-Wiener index was the age for S-cAFS and Shannon-Wiener index for F-cAFS (Table 4a). Between 12 and 85% of the variation of the variables that describe the biomass sequestration were explained for S-cAFS, whereas it was between 6 and 38% for F-cAFS. The difference between the two systems was mainly due to the

Table 4: Vectors of the principal component analysis (PCA) after Varimax rotation represent environmental variables explained in table 1.

a

Functional characteristic	Previous land-use	Model R ²	F	Age	Shannon	AGB cocoa trees	AGB other associated perennial plants	Clay
AGB cocoa	S	0.73	18.93	***				
	F	0.38	8.53	*				
AGB Large trees	S	0.39	9.59	**				
	F	0.08	1.29					
Other associated perennial plants AGB	S	0.16	2.78	.				
	F	0.24	4.31	.				
Total AGB	S	0.54	8.37	**				
	F	0.12	1.88					
Root biomass cocoa	S	0.47	6.29	**				
	F	0.38	8.73	*				
Root biomass other perennial plants	S	0.12	2.13					
	F	0.06	0.87					
SOM	S	0.85	24.71	***				
	F	0.17	2.82					

b

Functional characteristic	Previous land-use	Model R ²	F	Age	Shannon	AGB cocoa trees	AGB other associated perennial plants
Cocoa accessible yield	S	0.88	50.86	***			
	F	0.56	8.33	**			

c

Functional characteristic	Previous land-use	Model R ²	F	Age	Shannon	AGB other associated perennial plants	AGB cocoa ¹ / litterfall associated species ² / Litterfall cocoa ³
Litterfall species	S	0.42	11.02	**			
	F	0.26	5.01	*			
Litterfall cocoa ¹	S	0.74	19.83	***			
	F	0.62	10.49	**			
Litter stock species ²	S	0.13	2.28				
	F	0.31	6.25	*			
Litter stock cocoa ³	S	0.83	21.27	***			
	F	0.75	19.21	***			

d

Functional characteristic	Previous land-use	Model R ²	F	Age	Shannon	AGB other associated perennial plants	Clay
pH	S	0.65	27.96	***			
	F	0.29	5.66	*			
SOM	S	0.85	24.71	***			
	F	0.17	2.82				
Mineral N	S	0.74	12.51	***			
	F	0.35	3.44	.			
Phosphorus	S	0.24	4.77				
	F	0.10	1.52				
Potassium	S	0.47	6.25	*			
	F	0.38	2.42	.			
NO3 fresh	S	0.61	11.00	***			
	F	0.27	5.24	*			

much stronger partial correlations between age and the explained variables of S-cAFS whereas F-cAFS exhibited much weaker partial correlations with age or do not show this relation at all (Table 4). The best fitted model of S-cAFS cocoa AGB included both explanatory variables, with age as the strongest partial contributor. In F-cAFS 38% of the variability was explained by the F-cAFS age. The AGB of other associated perennial plants in S- and F-cAFS were marginally positively related ($p < 0.10$) to the Shannon-Wiener index. Variability of total AGB in S-cAFS was explained by both age and Shannon-Wiener index, with age as the strongest partial contributor. For cocoa root biomass, cocoa AGB was the most related partial parameter both for S- and F-cAFS. In addition, S-cAFS cocoa fine root biomass was negatively related to the age of the cAFS.

The best fitted model for yield explained 88% of the variability of S-cAFS and 56% of F-cAFS (Table 4b). Partial correlations showed that yield was more closely related to AGB of cocoa trees than to the AGB of associated trees for both system types. Associated AGB influenced the model in opposite directions, positive for S-cAFS and negative for F-cAFS. Even though, this result was not significant for S-cAFS and only marginally significant for F-cAFS, it was included in both systems.

The leaf litterfall of associated species in S-cAFS was positively related to Shannon-Wiener index whereas total associated perennial plant AGB was the best explanatory variable for F-cAFS. The model of leaf litterfall of cocoa trees was best explained by AGB of cocoa but partial negative contributions were observed from associated perennial plant species. Models did not well explain the leaf litter stock of the associated tree species, but a positive trend was found with the litterfall of the associated tree species. The best fitted models for litter stock of cocoa leaves were strong, they explained 83% of the variability in S-cAFS and 75% in F-cAFS. Strongest partial positive contributor to both models was the leaf litterfall of cocoa. Opposite results were found for the total associated AGB, where total associated AGB contributed positively to the model for S-cAFS and negatively for F-cAFS. For S-cAFS, age also contributed positively to the model.

The results of the regressions showed that, besides P, most of soils' minerals responded positively to clay content (Table 4c). The best fitted model for SOM for S-cAFS included age, clay content and total associated perennial plants AGB. On the contrary (Table 4a). The best regression model for mineral N of S-cAFS included age, clay content and total associated AGB. All variables contributed positively but age was the strongest contributor to the model. For F-cAFS, only a marginally significant model could be sorted including Shannon-Wiener index and clay content. Fresh soil nitrate of both c-AFS was positively related to total associated AGB. The leaf litterfall of cocoa for both c-AFS were positively explained by AGB of cocoa and negatively with associated AGB. The best model for soil available P of S-cAFS included only the Shannon-Wiener index. For F-cAFS no significant model could be sorted. Potassium in soils of S-cAFS was partially positively correlated to Shannon-Wiener index and clay content. In total 47% of the variability of potassium was explained for S-cAFS. For F-cAFS the model that best fitted the potassium of was found to be marginally significant and included age, clay content and the total associated perennial plants AGB. The pH of both land-uses was most related to age. For S-cAFS this was stronger and positive, while it was weaker and negative for F-cAFS.

4. Discussion

4.1 Past-land-use legacies in today's ecosystem functions

This study shows that the previous land-use types alter cAFS ecosystem functions on the long term and that these alterations fade partly with time. S- and F-cAFS display comparable levels of ecosystem functions after a certain age, as previously suggested in other studies from the same region (Jagoret et al., 2012a; Saj, Durot, et al., 2017). Legacies of aboveground structures and soil fertility characteristics were visible for ca. 15 years in S-cAFS. Contrastingly, F-cAFS showed direct changes for the above ground structures. The slash and burn techniques used prior to the installation of F-cAFS represent the major cause of the rapid decrease of above- and belowground biomass and species richness (Palm et al., 2005). For S-cAFS, biomass accumulation and species recruitment occur along with seedling appearance and tree growth over decades. Nevertheless, S-cAFS reached in ca. 15 years equivalent levels of biomass and species richness as F-cAFS.

The cocoa accessible yields in S-cAFS did not seem impaired by their past land-use and confirms that, despite a priori unfavourable conditions, well managed afforestation is achievable using cocoa (Jagoret et al., 2012a). The trajectories of accessible yields were comparable for both systems and reached similar levels for the ≥ 15 age class. Leaf litterfall and its subsequent decomposition are considered to be effective in the improvement and conservation of soil quality and, as such, play an important role in the regulation of nutrient cycling (de Carvalho, Vasconcelos, Kato, Capela, & Castellani, 2014; Vitousek & Sanford, 1986). The temperature and moisture levels in forests with a closed canopy generally favour decomposition of litter and could explain the lower minimum litter stocks of the forest control plots compared to the more open canopy of cAFS (Prescott, 2002; Steffan-Dewenter et al., 2007). The probably drier and warmer conditions in young S-cAFS, that are still lacking a closed canopy and produce significantly less litter, could also explain the higher litter stock in young S-cAFS. We may hypothesize that while young S-cAFS benefited less from the nutrients released by litter decomposition than older S-cAFS or F-cAFS, the lower competition for light they encountered actually authorized a better cocoa productivity (Blaser, Oppong, Yeboah, & Six, 2017). This would explain the comparable yields obtained in young S and F-cAFS. Besides, as cAFS mature and the cocoa stand developed, the poor quality of cocoa leaf litter and its subsequent lower decomposition rate may account for the higher litter stocks noticed in the older S- and F-cAFS (Dawoe et al., 2009).

The SOM as one of the most important reserve of nutrients for plants did not, contrastingly to other studies (Götz Schroth, D'Angelo, Teixeira, Haag, & Lieberei, 2002; Snoeck, Abolo, & Jagoret, 2010; Yang, Huang, Pan, Tang, & Han, 2004) decrease in the top layer of the F-cAFS after conversion. This could either be due to the preservation of significant amounts of litterfall even after conversion to F-cAFS and/or by the disturbed forest control plots that were found in our research region. The overall lower nutrient contents in the upper layer of savannah plots might be explained by the tillage and annual burnings of savannah which are known to lead to extensive nutrient losses (J. X. Kugbe et al., 2012). The effect of low SOM in the savannah was maintained for over a decade after conversion (Jagoret et al., 2012a; Lal & Bruce, 1999). However, the increase of SOM in older S-cAFS shows that the systems were able to build-up SOM over time and increase their soil fertility. The nitrogen characteristics studied

showed limited availability of N to plants in the savannah controls and young S-cAFS. The inhibition of soil-nitrification by inhibitors released by roots of *I. cylindrica*, that are still present in young S-cAFS could be an explanation (Subbarao et al., 2009). Even though, other soil fertility characteristics did not show significant differences based on their previous land-use and age class, the observed patterns were in line with what is found in literature. Available P in the savannah control and the young S-cAFS could have been influenced by the soils' clay content but could also be linked to their lower pH (H. Schroth & Sinclair, 2002; Six, Conant, Paul, & Paustian, 2002; Yemefack, Rossiter, & Njomgang, 2005). The decreasing trajectory exhibited by K in the soils of F-cAFS after conversion may be linked to the high the acknowledged absorption of K by cocoa trees and its exportation with cocoa-beans harvest (van Vliet & Giller, 2017). Furthermore, the production of cocoa has been linked to the acidification of the soil (Hartemink, 2005; Snoeck et al., 2010). However, our study did not show significant pH changes after the conversion of forest to F-cAFS and also other studies revealed contrasting results (Dawoe et al., 2009; Isaac & Kimaro, 2008). The composition and abundance of associated trees and their diverse litter restitution to the soil could account for those contrasting results (Finzi, Canham, & Van Breemen, 1998). Likewise, this could partly explain the higher pH of S-cAFS ≥ 15 age class compared to the young S-cAFS and the savannah control. As in other studies we found significant compaction of the 0-5 cm soil due to forest conversion to F-c-AFS as an effect of human passages (Dawoe, Quashie-Sam, & Oppong, 2014; Don et al., 2011; Yang et al., 2004). For this same reason afforestation of savannah did not lead to a decrease of the soil bulk density that was expected as a result of the increase of SOM, due to the negative correlation between SOM and the soil bulk density (Federer, Turcotte, & Smith, 1993).

Overall, all the cAFS, be these set up on savannah or on forest land, exhibited legacies on most of the ecosystem functions studied. These legacies differed in magnitude and lasted from a few years to several decades. Past land-use legacies were found more intense and persistent in S-cAFS for the above- and below- ground functions without having a negative impact on the accessible yields. Interestingly, most of the soil fertility parameters of F-cAFS, inherited from the forest, were not significantly impacted by the land-use change.

4.2 Farmer's practices maintaining high plant diversity play an important role in ecosystem multifunctionality.

Even though agroforestry systems might not preserve as many species as primary forests, cAFS can contribute to the preservation or the introduction of many tree species (De Beenhouwer, Aerts, & Honnay, 2013; Saj, Durot, et al., 2017). The amount of species (African and exotic) found in the studied cAFS fell within the same range of a meta-analysis of biodiversity in coffee and cocoa AFS in South America (Somarriba et al., 2013) but was much higher compared to a study in Ghana, where only 18 forest species were reported (Asase & Tetteh, 2010). Interestingly, S-cAFS exhibited almost as much African tree as F-cAFS (40 vs. 42) - showing that farmers are actively introducing/preserving or transferring seedlings of these species into their S-cAFS. Such a result underlines the fact that local species are at least valued as much as exotic ones in these systems. Nevertheless, the density of local tree species was lower in S-cAFS than in F-cAFS since the area (sampling effort) needed to reach at the same amount of local tree species was larger for S-cAFS. The studied cAFS contained 8 to 11 exotic species, which were

in most cases introduced for food production.

Furthermore, our study confirms the crucial role of tree biodiversity in Central Cameroonian cAFS and its support to the ecosystem functions studied. Within the four functions we selected, the Shannon-Wiener index was regularly positively correlated to several biomass and soil fertility parameters. This was especially true for S-cAFS. Such a result shows that successful installation of cocoa on savannah land would be closely related to the management of the plots' tree diversity (Jagoret et al., 2012a). This could also underline the positive role of tree diversity in the acknowledged sustainability of Cameroonian cAFS, be these set-up after forest or savannah (Saj, Durot, et al., 2017). Several studies mention positive relations between biodiversity and pest control (G Schroth, Krauss, Gasparotto, Aguilar, & Vohland, 2000), herbivory suppression (Bisseleua, Missoup, & Vidal, 2009) or edge effect from local forest patches (van Bodegom & Price, 2015). The rather high biodiversity and abundance of associated trees in a cAFS may also improve nutrient cycling thanks to increased litterfall with different leaf litter traits (Prescott, 2002; van Bodegom & Price, 2015). A major trade-off could be the limitation of cocoa yield due to competition with associated trees. Yet, studies from Saj et al., (2017 a, b) mention that for many of the farmers in Central Cameroon such trade-offs may be balanced by the complementary incomes and/or the support to food security and diet diversity coming from associated trees by-products.

4.3 Interactions between cAFS ecosystem functions

Within the multiple linear regression models performed, more of the data of S-cAFS was explained compared to the F-cAFS. This could be partly explained by the more gradual changes occurring in S-cAFS, like the systems' biomass accumulation, compared the biggest changes in F-cAFS which happen prior to the installation of the cocoa trees. Furthermore, the variability of many of the parameters of F-cAFS was found to be substantial during the entire length of the chronosequence studied. Such an observation underlines the complexity of those systems and the perpetual adaptation of management practices of farmers during cAFS lifespan that may be induced by the variable pedoclimatic conditions encountered (Jagoret et al., 2017; Saj, Jagoret, et al., 2017). Likewise, synergies between ecosystem functions in cAFS were clearer for S-cAFS than for F-cAFS. While the AGB of associated perennial plants was unsurprisingly found to positively contribute to associated species litterfall, it also significantly and positively contributed to many of the S-cAFS soil fertility parameters studied. Increased nutrient cycling by increasing litter input and more elaborated rooting systems of trees compared to savannah herbs could be pointed out. As well as the absence of annual fires, which can lead to 50 to 99% of nutrient losses from the combusted vegetation and which interfere with the natural nutrient cycling (J. Kugbe, Fosu, & Vlek, 2015).

Contrasting trends were observed between the accessible yield and the AGB of associated perennial plants of S- and F-cAFS. A positive input for S-cAFS and a negative trend for the F-cAFS, but also the negative contribution of the associated perennial biomass on cocoa leaf litter production for both cAFS, could point out the fine balance between yield and interspecific competition and the subsequent optimum of associated biomass next to cocoa production.

5. Conclusion

Our study shows that the timespan and intensity a past land-use legacy stays visible after conversion highly depend on the nature of this past land-use and on the strategy of farmers. The high impact of the land-use change from savannah to S-cAFS were fading after 14 years while significant changes occurred in the ecosystem functions biomass, litterfall and -stock and soil fertility. The abrupt forest to F-cAFS conversion made that most functions, except for soil fertility, changed rapidly. Contrasting with the forest to F-cAFS conversion, most of the ecosystem functions in S-cAFS shifted in a way that led to great similarities between S- and F-cAFS after 15 years of management. A stronger focus on the young (0-14 years) and medium aged (15-30 years) cAFS could give greater insight of the temporal frame of functional changes and their embedment in S- and F-cAFS. Despite great dissimilarities at the time of cAFS installation, previous land-use adapted management strategies for the quantity and diversity of associated trees seemed to lead to equivalent results, making sustainable cocoa production possible for over 80 years. The partly negative relation of the AGB of perennial plants with cocoa related variables could indicate that the balance between cocoa and associated trees still could be optimized.

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CHAPTER 3



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"Harvest"

Preparing for submission

Seasonal litter dynamics in complex cocoa agroforestry systems in Central Cameroon – the effect of past land-use and contribution of associated species.

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Abstract

Litterfall biomass and its decomposition constitute a major component of nutrient cycling in unfertilized cocoa agroforestry systems (cAFS). In Central Cameroon cAFS are either set up after forest (F-cAFS) or after savannah (S-cAFS) which may influence litterfall dynamics and decomposition of litter in the system. Litterfall dynamics and decomposition of cocoa and associated species leaf litter were studied using 80 years chronosequences. Secondary forests in the same area were included as reference. Our study shows that annual litterfall of cAFS in Central Cameroon is relatively high compared to other regions in the world but does not reach the same levels as the forest control plots. Litterfall of S-cAFS reached in 15 years, i.e. at full productivity, similar levels as other cAFS showing the ability of S-cAFS to reach similar productivity levels as F-cAFS. During decomposition, weight loss of the low-quality litter of cocoa was lower compared to associated species leaf litter. Yet, non-additive effects couldn't be demonstrated for litter mixtures of cocoa and associated tree species. Unexpected leaf litterfall peaks of cocoa could be related to an unusual long drought period and endorses the vulnerability of cocoa to predicted climate change. Overall, afforestation of savannah with cAFS shows to create similar cycles of litterfall and decomposition after 15 years as F-cAFS. Furthermore, cAFS showed a great ability of recycling litter back into the cAFS, especially due to the high input of associated species leaf litter.

Keywords: Cocoa agroforestry; Litterfall dynamics; decomposition;

1. Introduction

Complex cocoa agroforestry systems (cAFS) can display both socio-economic and ecological advantages compared to monoculture systems (Jezeer et al., 2017; Mortimer et al., 2017). Associated species in cAFS help diversify production of smallholder cocoa producers (Jagoret et al., 2014) and have a general positive effect on soil quality by amplifying root development as well as diversifying and increasing litter production (Schroth et al., 2001). The last is of special interest for tropical ecosystems whose soils are highly weathered and often nutrient poor, making litter one of the main resource of nutrient return to the soil (Lian and Zhang, 1998; Martius et al., 2004). In Central Cameroon, cAFS are both set up on forest and on savannah land. For the conversion of forest into cAFS a part of the trees is conserved - maintaining a part of the original litterfall and nutrient cycling (Snoeck et al., 2010). For savannah, the planting and upkeep of associated trees is needed to slowly build up a forest-like nutrient cycling (Jagoret et al., 2012). According to Hartemink (2005), litterfall variations in cAFS are the result of different combinations of precipitation dynamics and level, age and associated tree species density. As a result total litterfall in cAFS was found to be ranging from 5 to 21 t dry matter (DM) ha⁻¹ yr⁻¹, consisting of cocoa leaves for 50% (Hartemink, 2005). The only study performed on litterfall dynamics in Cameroon stated a total litterfall of 9 t DM ha⁻¹ yr⁻¹ under light shaded cAFS (Boyer, 1972). In many cases cAFS' leaf litterfall dynamics were positively correlated to the local drought period (Boyer, 1972; Costa et al., 2016; Dawoe et al., 2009) albeit Fassbender et al., (1991) did not find such a link for the cocoa leaf litterfall in Costa Rica.

The amount of nutrients that get transferred back into the soil depend on the quantity of litter and its nutrient content but also on the decomposition rate (Dawoe et al., 2009). Decomposition of litter varies with several biotic and abiotic factors as microclimate, decomposer communities, soil nutrient content, vegetation type and subsequent litter quality (Bakker et al., 2011; Cornwell et al., 2008; Freschet et al., 2012; Loranger et al., 2002). For years temperature and humidity have been seen as predominant regulators of decomposition due to their strong regulating effect on the decomposers' activity (Bradford et al., 2016; Moorhead et al., 1999; Wall et al., 2008). García-Palacios et al., (2016), observed soil moisture as a stronger regulator of decomposition compared to temperature variability. However, leaf quality has shown to have an even stronger effect on the leaf litter decomposition (Cornwell et al., 2008). Finerty et al., (2016) showed that decomposition was better explained by the functional diversity and the common weighted mean (CWM) of litter traits than the species origin. Also other studies found the CWM and the mass ratio hypothesis as good predictors of decomposition (Bílá et al., 2014; Quested et al., 2007). Functional diversity of litter, on the other hand, could lead to non-additive effects of leaf litter decomposition by either moderating or increasing leaf litter decomposition (Cuchietti et al., 2014; García-Palacios et al., 2017; Gartner and Cardon, 2004; Makkonen et al., 2013). Scherer-Lorenzen, (2008) and Cuchietti et al. (2014), found an overall positive effect of functional diversity of litter on the decomposition rate. Notably, land-use change leads in general to changes of the litter quality and quantity and asks for adaptation of the decomposer community. Jangid et al., (2011), showed that legacies of the microbial community were visible even 17 years after conversion which could be a constraint for decomposition after land-use change.

Cocoa has been pointed out as a species with a low leaf litter quality, due to its high concentrations in

lignin and polyphenols, that decreases its decomposability (Dawoe et al., 2009; Muoghalu and Odiwe, 2011). One study found that cocoa leaves decomposed better in cAFS compared to monoculture systems (Ofori-Frimpong et al., 1998), but others stated cocoa leaves to decompose faster in monoculture systems (Boyer, 1972; Isaac et al., 2007). Reasons for these differences in weight losses are unclear. However, in those studies cocoa leaves in cAFS were not decomposed without interaction with associated species leaf litter to be able to check if differences were field related or could be linked to non-additive effects. Furthermore, interaction of decomposition and the plots' microclimate were missing, which should be taken into account when comparing cAFS and monoculture systems.

The aim of this study was to compare the litterfall and leaf litter decomposition of cAFS with different preceding land-uses (forest and savannah) and to test in situ non-additive effects in decomposition of cocoa and associated species leaf litter mixtures. Therefore, we hypothesized that litterfall quantities as well as the share of cocoa leaf litter it comprises would depend on cAFS' past land-use but would be similar for full grown cAFS (≥ 15 years). We further expected litterfall dynamics to be negatively related to rainfall. Finally, we hypothesized that if associated species in cAFS increase the functional diversity of the litter, mass loss of the cocoa leaf litter could increase due to non-additive effects independent of the microclimate.

2. Methods

2.1 Site characteristics

The study area was located in a forest–savannah transition zone of Central Cameroon, in the villages Bakoa and Guéfigué in the district of Bokito (4°30' N and 11°10' E). Annual average rainfall ranges from 1,300 to 1,400 mm with a main dry season that lasts over three months, from mid-November to the beginning of March (Jagoret et al., 2012). Soils are dominated by slightly desaturated ferralitic soils (Elangwe, 1979). The landscape is characterized by a patchwork of forests and herbaceous savannahs dominated by the perennial species *Imperata cylindrica* located on hills with gentle slopes with altitudes ranging from 400 and 550 m a.s.l (Jagoret et al., 2012). Cocoa plantations in this region comprise mainly of complex agroforestry systems (cAFS) of different ages (Jagoret et al., 2011; Saj et al., 2013; Sonwa et al., 2007). In those cAFS main upper canopy tree species comprise of *Ceiba pentandra*, *Milicia excelsa*, *Guibourtia tessmannii*, *Albizia adianthifolia*. Farmers also introduce many fruit trees such as butterfruit (*Dacryodes edulis*), oil palm (*Elaeis guineensis*), mango (*Mangifera indica*) and orange (*Citrus sinensis*).

In July 2015, 32 cAFS plots were selected based on their age and past land-use. Sixteen plots of cAFS had been created after savannah (S-cAFS) and 16 after forest (F-cAFS). Plot' size was of 40 m x 60 m (2400 m²), each containing a subplot of 20 m x 40 m (800 m²; see below). Ages were regularly distributed along a gradient from 0 (farmers just started the planting process of cocoa) to over 60 years. Based on earlier findings (Nijmeijer et al., submitted), plots were divided into two age categories, cAFS from 0-14 years and 15 years and older. Finally, five control plots of secondary forest were selected as controls.

2.2 Plots' microclimate

Temperature and rainfall data were collected once a day in a climate station located within Bakoa during the entire period of the study (October 2015 – December 2016). Humidity and temperature registering chips (Ibutton® – Maxim integrated) were installed from July until December 2016 on ground level where leaf decomposition takes place. Due to a limited number of chips, the IButtons® could only be installed in 23 of the plots.

2.3 Litterfall

At the end of October 2015 three round litter traps with a surface of 0.5 m² were installed for one year in each studied cAFS and forest control plots (Muller-landau and Wright, 2010). Litter traps consisted of round PVC tubes with a piece of 1 mm nylon mesh screen of around 50 cm depth preventing litter to get blown out of the traps. Each trap was installed randomly within the plot, 50 cm above the ground to prevent rainwater of splattering into the traps. The position of each trap was changed every month to improve the representativeness of the plot (12 different positions for each collector during the study). Once collected, the litter was air-dried for a week and sorted into four litterfall categories: a) cocoa and b) associated species leaves including petioles and rachis, as well as c) non-woody tendrils, fine wood and d) reproductive parts including flowers, fruits, seeds and their supporting structures or pedicels. Subsamples were then dried at 60 °C for 72 hours and weighed for dry matter content calculation.

2.4 Leaf litter decomposition

Litterbags of 10 x 10 cm with a mesh size of 0.5 mm were prepared according to Cornelissen (1996) and Pérez-Harguindeguy et al. (2013). This mesh size permits the entry of micro- and meso- fauna, while it excludes some of the macrofauna from the decomposition process. For each plot, 24 bags were prepared containing 1 g (airdry weight) of leaf litter including either cocoa leaves (n=8), associated species leaves (n=8) or a mixture of both (n=8). The litter mixtures were based on the ratio of associated species and cocoa leaf litterfall during the first three months of collection (Nov. 2015 – Jan. 2016). Litterfall of cocoa trees from the youngest (age ≤ 2 years) four S- and F-cAFS was negligible and no litter mixtures or cocoa leaf litter decomposition study was performed in those plots. To obtain homogeneous litter mixtures, leaves were cut in pieces of 1 to 3 cm² and mixed elaborately. To estimate litter water content, subsamples were then dried at 60 °C for 72 hours. Bags were installed five meters out of each corner of the 800 m² plot on the ground in May 2016. The first half of bags were then collected after 2 months (July 2016), the second half after 7 months (December 2016) at the end of the rainy season when decomposition slows down (Valentini et al., 2009).

2.5 Data analyses

Leaf litterfall patterns of cocoa and associated species were examined individually and using share of cocoa leaf litterfall on total leaf litterfall. Prior to the analysis of variance, data were checked to comply with the ANOVA test requirements. To test for the effects of litterfall components (cocoa leaves, associated species leaves, branches, reproductive organs), land-use system (cAFS post forest, cAFS posy

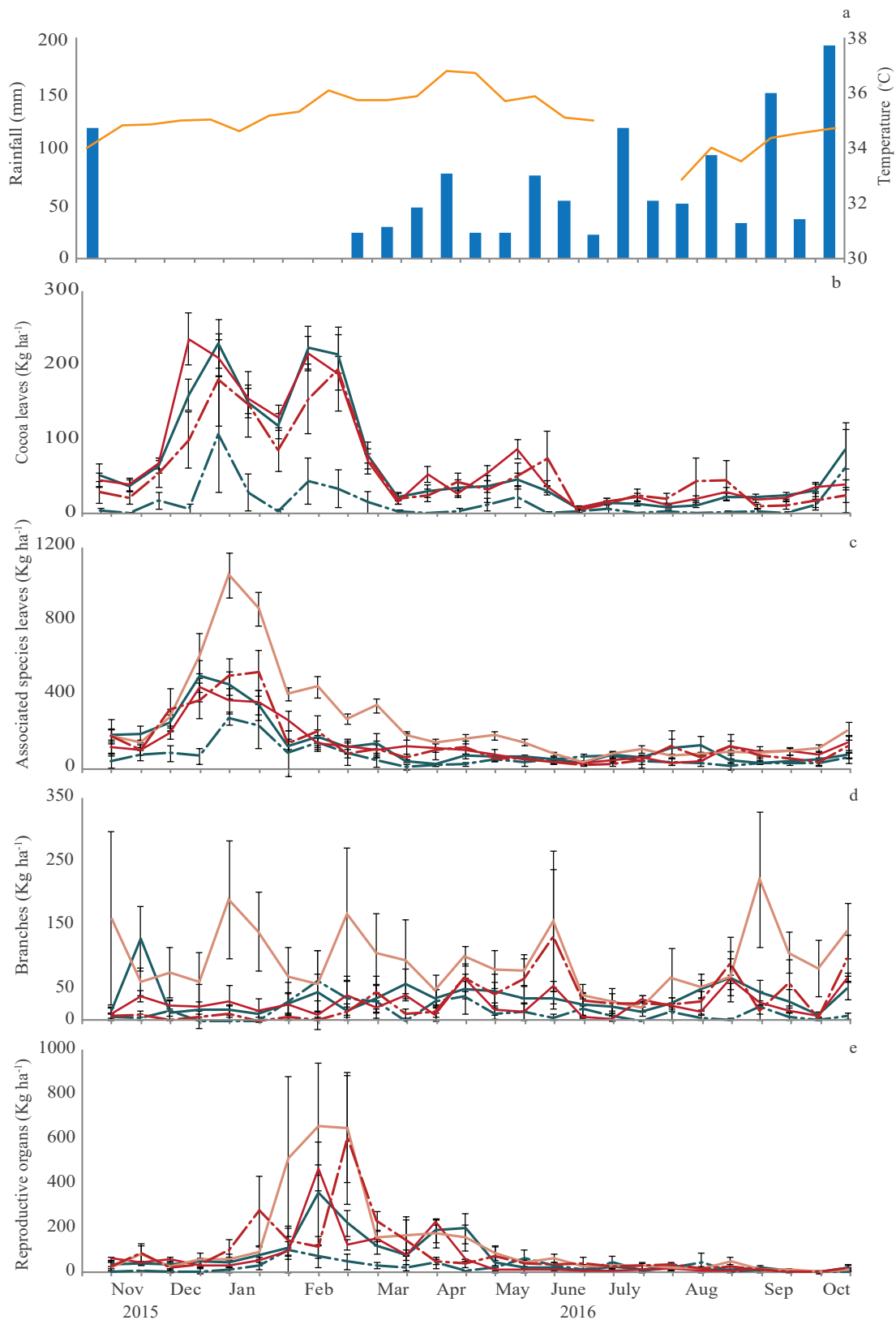


Figure 17: Fortnight rain- and litter-fall dynamics 2015-2016 (mean SE): (a) rainfall, (b) cocoa leaf litterfall, (c) associated perennial plant species leaf litterfall, (d) branches litterfall, and (e) reproductive organs litterfall. Pink: forest control; dark blue: S-cAFS; red: F-cAFS. Dashed lines represent cAFS of 0-14 years old and solid lines represent cAFS ≥ 15 years old.

savannah and forest control) and season (dry vs. rainy) on total litterfall per season, we performed a one-way ANOVA with repetitions per plot as nested data. Mean fortnight litterfall per season, decomposition of leaf litter and humidity data were also analysed using one-way ANOVA. ANOVAs were followed by the Tukey's HSD test for post-hoc comparisons. Statistical significance was set at $p < 0.05$. Data analyses were performed using XLSTAT (Addinsoft, XLSTAT, 2016).

3. Results

3.1 Rainfall, temperature and humidity

Total amount of rainfall during the 12 months of the litterfall study was 1208 mm (Figure 17a). No rainfall was recorded between the beginning of November and the end of February – signaling 4 months of complete dryness. The mean maximum day temperature was fluctuating between 33 and 36 °C. The mean minimum temperature was 21 °C.

Between July 2016 and December 2016, the daily humidity ranged from 57 to 100% with a mean of 85% for S- and 86% for F-cAFS (Figure 18). Highest mean daily humidity was found in the forest control plots with a mean of 95% (Figure 18). No significant interactions of past land-use and humidity was found on decomposition of associated species leaf litter bags for all cAFS (data not shown).

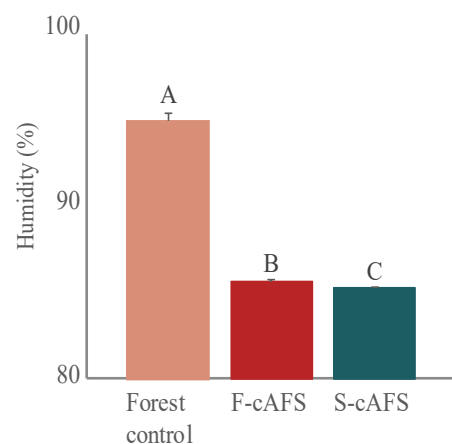


Figure 18: Mean humidity at soil level from July 2016 to December 2016. Pink: forest control; dark blue: S-cAFS; red: F-cAFS.

3.2 Litterfall production, composition and seasonal dynamics

Fortnight litterfall of the different studied litter components followed, except for branches, similar patterns among the different land-uses (Figure 17b-e). Litterfall was varying from fortnight to fortnight with peak leaf (cocoa and associated species) litterfall observed during the dry season (Figure 17b-c). Total litterfall during both the dry and the rainy seasons was highest in the forest controls (Table 5). Significant lower litterfall was observed S-cAFS of 0-14 years during the rainy season. From the total leaf litterfall, on average 30% came from cocoa for the F-cAFS and the S-cAFS ≥ 15 years (Figure 19). With peaks where cocoa leaves make up for more than 70% of the total leaf litterfall in February and May/June 2016.

3.3 Litterfall composition during the dry and rainy seasons

Total litterfall during the dry and the rainy season was highest in the forest control plots (Table 5). Significant lower litterfall was observed S-cAFS of 0-14 years during the rainy season but not during the dry season (Table 5). Associated species leaf litterfall, which made up around 50% of the total litterfall, showed similar results as total litterfall (Table 5). Except for S-cAFS of 0-14 years old, cAFS and forest control total branch fall was significantly lower compared to the leaf- and reproductive organs- litterfall during the dry season (Table 5). Mean 2-weeks litterfall composition differed significantly among the

Table 5: Total litterfall (t DM ha⁻¹ yr⁻¹) during the dry and the rainy seasons (mean ± 1 SE). Significant differences (p<0.05) between the different land-uses are indicated by different superscripts after SE. Significant differences (p<0.05) between the different litter groups are indicated by different capital letters after SE. ● marginal significant difference (p<0.1). ***: significant effect at p<0.001

Dry season	Cocoa leaves	Associated species leaves	Branches	Reproductive organs	Total
Forest control		4.07±0.18 ^{a A}	0.82±0.22 ^{a C}	2.12±0.57 ^{a● B}	7.02 ±0.72 ^a
F-cAFS 0-14	0.93±0.23 ^{ab BC}	2.23±0.32 ^{b A}	0.05±0.01 ^{b C}	1.36±0.51 ^{ab AB}	4.57 ±0.58 ^b
F-cAFS ≥15	1.19±0.09 ^{a B}	2.13±0.26 ^{b A}	0.27±0.06 ^{b C}	0.92±0.30 ^{b BC}	4.52 ±0.45 ^b
S-cAFS ≥15	1.23±0.09 ^{a B}	1.97±0.20 ^{b A}	0.20±0.03 ^{b C}	0.88±0.25 ^{b B}	4.30 ±0.34 ^b
S-cAFS 0-14	0.24±0.14 ^{b B}	1.53±0.50 ^{b A}	0.18±0.10 ^{b B}	0.29±0.15 ^{b B}	2.23 ±0.74 ^b
Rainy season	Cocoa leaves	Associated species leaves	Branches	Reproductive organs	Total
Forest control		2.35 ±0.17 ^{a A}	1.65 ±0.32 ^{a AB}	1.03 ±0.17 ^{n B}	5.03 ±0.50 ^a
F-cAFS 0-14	0.55 ±0.15 ^{a B}	1.36 ±0.31 ^{b A}	0.78 ±0.18 ^{b AB}	0.79 ±0.13 ^{n AB}	3.47 ±0.43 ^b
F-cAFS ≥15	0.56 ±0.06 ^{a B}	1.26 ±0.15 ^{b A}	0.64 ±0.10 ^{b B}	0.81 ±0.12 ^{n B}	3.27 ±0.24 ^b
S-cAFS ≥15	0.59 ±0.06 ^{a B}	1.40 ±0.19 ^{b A}	0.49 ±0.08 ^{b B}	0.64 ±0.14 ^{n B}	3.12 ±0.25 ^b
S-cAFS 0-14	0.13 ±0.09 ^{b B}	0.80 ±0.23 ^{b A}	0.27 ±0.12 ^{b B}	0.37 ±0.11 ^{n B}	1.57 ±0.39 ^c
Dry vs. Rainy	<i>F</i> =47.05***	<i>F</i> = 25.45 ***	<i>F</i> = 24.86 ***		<i>F</i> = 17.89 ***

Table 6: Mean litterfall per fortnight during the dry (kg DM ha⁻¹) and rainy seasons (mean ± 1 SE). Significant differences (p<0.05) between the different land-uses are indicated by different superscripts after SE. Significant differences (p<0.05) between the different litter groups are indicated by different capital letters after SE. ***: significant effect at p<0.001

Dry season	Cocoa leaves	Associated species leaves	Branches	Reproductive parts	Total
Forest control		508±32 ^{b A}	102±11 ^{b C}	264±47 ^{b B}	876±58 ^a
F-cAFS 0-14	117±12 ^{b B}	280±32 ^{a A}	6±11 ^{a C}	171±47 ^{ab B}	576±58 ^b
F-cAFS ≥15	149±8 ^{b B}	267±21 ^{a A}	34±7 ^{a C}	115±32 ^{ab B}	566±39 ^b
S-cAFS ≥15	154±7 ^{b A}	248±20 ^{a A}	25±7 ^{a C}	111±29 ^{a B}	539±36 ^b
S-cAFS 0-14	29±15 ^{a B}	191±41 ^{a A}	22±14 ^{a B}	35±61 ^{a B}	278±75 ^c
Rainy season	Cocoa leaves	Associated species leaves	Branches	Reproductive parts	Total
Forest control		131 ±9 ^{b A}	92 ±7 ^{b B}	58 ±9 ^{a B}	282 ±16 ^a
F-cAFS 0-14	31 ±3 ^{b B}	77 ±9 ^{a A}	44 ±7 ^{a B}	44 ±9 ^{a B}	197 ±16 ^b
F-cAFS ≥15	31 ±2 ^{b B}	71 ±6 ^{a A}	36 ±5 ^{a B}	46 ±6 ^{a B}	185 ±10 ^b
S-cAFS ≥15	33 ±1 ^{b B}	80 ±5 ^{a A}	27 ±4 ^{a B}	36 ±5 ^{a B}	178 ±10 ^b
S-cAFS 0-14	7 ±3 ^{a B}	45 ±12 ^{a A}	15 ±9 ^{a B}	21 ±12 ^{a B}	90 ±20 ^c
Dry vs. Rainy	<i>F</i> =593.01***	<i>F</i> = 450.24***		<i>F</i> = 51.82***	<i>F</i> = 513.81***

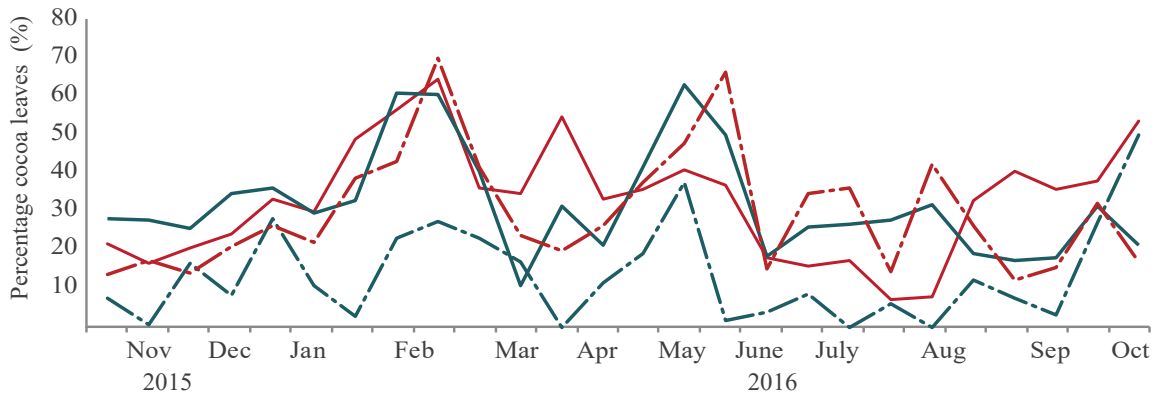


Figure 19: Fortnight dynamics of the share of cocoa leaves within the total leaf litterfall biomass 2015-2016. Dark blue: S-cAFS; red: F-cAFS. Dashed lines represent cAFS of 0-14 years old and solid lines represent cAFS ≥ 15 years old.

four litter components studied (cocoa leaf litter, associated species leaf litter, branches and reproductive parts) with mean fortnight leaf litterfall of the associated species being the largest for all cAFS and forest control during the wet and dry season (Table 6). During the dry season litterfall of branches was significantly lower compared to the other litter components, except for S-cAFS 0-14 years old (Table 6). Mean 2-weeks seasonal litterfall production differed significantly between the dry and the rainy seasons with significantly higher litterfall during the dry season (Table 6). Mean litterfall of branches and associated species leaves was higher in the forest plots compared to the cAFS, both during the dry and wet seasons (Table 6).

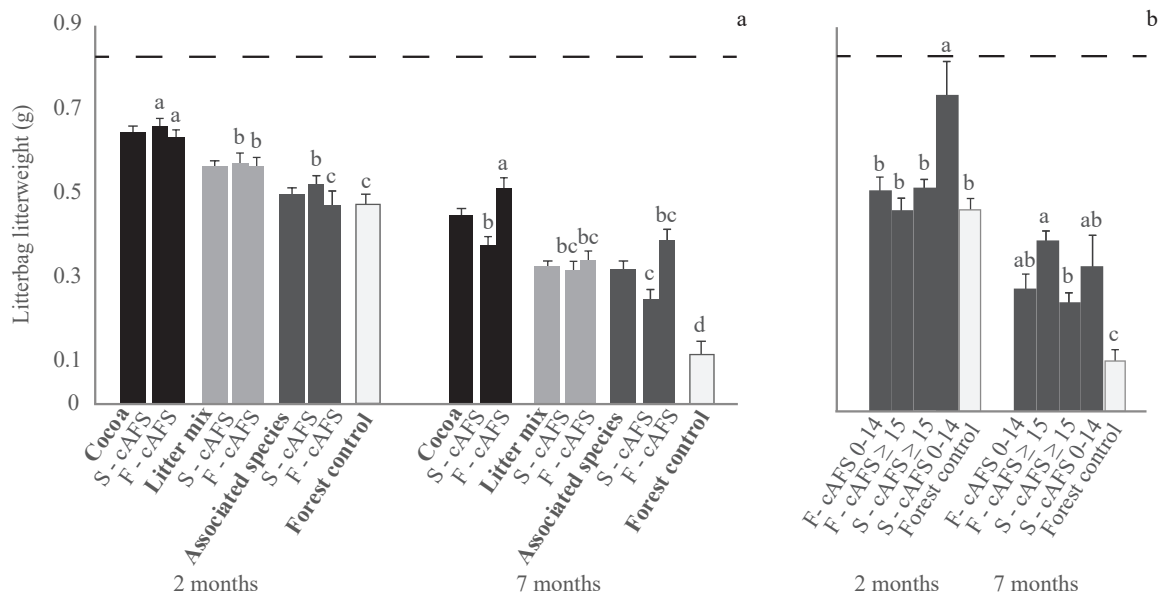


Figure 20: Leaf litter decomposition from May 2016 to December 2016 (mean ± 1 SE) with the initial weight shown as dashed line. (a) Mean weight of the three types of litterbags in cAFS and forest control plots after two and seven months in the soil: black: cocoa leaves alone; dark grey: associated species leaves alone; light grey: leaf litter mix; white: forest control leaves. (b) Mean weight of associated species leaf litter two and seven months after installation for all age classes of S- and F-cAFS and forest control. Different letters above histograms show significant differences in remained weight after decomposition ($P < 0.05$).

3.4 Decomposition

Two months after the installation of the litterbags, we found a significant lower weight loss for the bags containing solely cocoa leaves compared to those containing leaf litter mixtures or solely associated species (Figure 20a). No significant differences were observed between the weights of the bags containing the mixtures and those with associated species and between the latter and the bags from the forest controls (Figure 20a).

After seven months, bags containing solely cocoa leaves showed significantly lower weight loss compared to those containing leaf litter mixtures or solely associated species. No difference was observed between the weight loss of the litter mixtures and associated species leaves in cAFS. Significant more weight loss was observed for bags from the forest control plots.

When treating results for S- and F-cAFS ≥ 15 years separately weight loss of solely cocoa leaves, litter mixtures and solely associated species leaves outcomes are less clear, especially for the second collect 7 months after installation (Figure 20a). For the first collect the solely associated species weight loss in F-cAFS was significantly higher compared to the weight loss of associated species in S-cAFS and as the litter mixtures and the solely cocoa leaves in S- and F-cAFS. Seven months after installation the relative high weight loss of solely cocoa leaves in S-cAFS and the relative low weight loss of associated species leaf litter in F-cAFS ≥ 15 years were unexpected (Figure 20a).

Comparing the weight losses of solely associated species leaves including cAFS of 0-14 years old, revealed significant less weight loss of solely associated species leaves in S-cAFS 0-14 years compared to the S-cAFS ≥ 15 years, all F-cAFS and forest control two months after installation (Figure 20b). Seven months after installation no significant differences in weight loss of associated species leaves in S- and F-cAFS 0-14 years were observed.

4. Discussion

4.1 Litterfall

In unfertilized cAFS, litter production is one of the most important contributor to nutrient cycling within the system. A great number of studies demonstrated that litterfall in cAFS is highly variable and can range from 1.6 to 8.6 t DM ha⁻¹ yr⁻¹ (Abou Rajab et al., 2016; Costa et al., 2016; Dawoe, 2009; Hartemink, 2005; Pérez-Flores et al., 2017; Triadiati et al., 2011) with an amount as high as 21.2 t DM ha⁻¹ yr⁻¹ observed in Venezuela (Aranguren et al., 1982). Such a variability is multifactorial and likely depends on the density, biomass and species functional characteristics (eg. growth, leaf life span) of the trees cAFS comprise. In our study, total litterfall in S- and F-cAFS ≥ 15 years (full grown productive systems) were, with respectively 7.4 and 8.0 t DM ha⁻¹ yr⁻¹, consistent with the data from literature. Furthermore, the only study mentioning cAFS litterfall in Cameroon we found registered similar production levels of 6.0 and 8.5 t DM ha⁻¹ yr⁻¹ in light shaded cAFS (Boyer, 1972). Finally, the total litterfalls of full grown cAFS (≥ 15 years) were similar to litterfall rates found in tropical evergreen- and rain- forests (Isaac et al., 2005; Vitousek and Sanford, 1986; Zhang et al., 2014). The share of cocoa leaf litter, with 1.8 and 1.7 t DM ha⁻¹ yr⁻¹ for S- and F-cAFS ≥ 15 years, was higher compared to the one found by Abou Rajab et al. (2016) in Brazil, but was lower compared to another study by Addicott

(1978) where cocoa litter ranged from 3.9 to 7.6 t DM ha⁻¹ yr⁻¹.

Total litterfall was the highest during the dry season. This seasonality was the greatest for the leaf litterfall and slightly less clear for the reproductive parts. The lack of seasonality in branch fall could be more related to physical climatic factors such as wind and rain and therefore less linked to the dry season (Dawoe et al., 2009). Seasonality in associated species and cocoa leaf litterfall in cAFS is also observed in Cameroon by Boyer (1972) and in several other countries as Ghana (Dawoe et al., 2009), Nigeria (Muoghalu and Odiwe, 2011) and Mexico (Costa et al., 2016). Yet, not all studies found a strong seasonality in litterfall (Fassbender et al., 1991; Pérez-Flores et al., 2017). The absence of a distinguishable dry season, such as in the Atlantic rainforest, may constitute a first reason for such discrepancies. In these regions leaf senescence and abscission takes place concomitantly with the appearance of new leaves (Moraes et al., 1999). In regions with an extended dry season, as in our study area, reduced humidity and lower night temperatures have been linked to the stimulation of abscisic acid synthesis in plant foliage which, in turn, stimulates leaf senescence (Addicott, 1978). Secondly, the life cycle of tropical tree leaves could be linked to the absence of a strong seasonality in litterfall. Cocoa leaf abscission for example, has been shown to take place between 11 and 12 months after flushing (Boyer, 1970). This could also explain the peak of cocoa litterfall that is observed at the end of June (Figure 17 b). Yet, this cannot explain the secondary cocoa leaf litterfall peak halfway in February. Interestingly, this secondary peak matched with a peak in abscission of reproductive organs. For several tropical tree species, as for example the kapok tree *Ceiba pentandra*, floral production is linked to leaf senescence as a resource separating strategy (Singh and Kushwaha, 2006). Yet, peak floral production of cocoa occurs especially during the rainy season in correspondence with leaf flushing and such a phenomenon is therefore unlikely to explain this cocoa leaf litterfall secondary peak (Boyer, 1970; Frimpong-Anin, 2014; Lachenaud, 1991). Alternatively, the 3.5/4 months dryness observed during the study could point out the vulnerability of cocoa to long periods of drought - especially those extending over 3 months with less than 100 mm precipitation (Wood and Lass, 2001) - which could force increased leaf shedding (Hartemink, 2005). Local statements by farmers in the researched region confirmed this interpretation by linking the high cocoa leaf senescence and partial die-back of cocoa trees to increased drought during the dry season 2015-2016. One could hypothesise that local climate was influenced by the El Niño event during the studied period that causes slightly increased droughts during the dry season in Central Africa (Balas et al., 2007). Since climate data from the region are rare, we compared our data with the data that were available over the period 2006-2016 (6 years in total; data not shown). This showed that in all other registered years at least some rainfall occurred during the dry season whereas during our study no rainfall was measured for over four months. This augmented leaf litterfall as a consequence of a prolonged drought, could be a sign that local cocoa production is in danger (Schroth et al., 2016). Associated shade trees are able to reduce the effect of increases in temperature and prolonged dry period but could also lead to competition for water (Schroth et al., 2016).

Contrasting with our findings for young F-cAFS (0-14 years), other studies found significant increases in litterfall during the first 15 to 25 years after installation of F-cAFS (Dawoe et al., 2009; Isaac et al., 2005; Ofori-Frimpong et al., 1998). For S-cAFS total litterfall increased from young S-cAFS to full grown S-cAFS. Litterfall of reproductive organs during the dry season, and of reproductive organs and

branches during the rainy season, of F-cAFS of 0-14 years were relatively higher compared to older cAFS ≥ 15 years. This could be an indication that a high number of forest trees was preserved at the time of F-cAFS installation resulting in similar total litterfall mass. Even though comparisons are not straightforward, the number of associated forest shade trees in these studies was varying between 15 and 35 trees ha⁻¹ (Dawoe et al., 2009; Ofori-Frimpong et al., 1998), where as we found a mean 35 trees ha⁻¹ with a diameter > 30 cm in all F-cAFS (Nijmeijer et al unpublished). For very young S-cAFS litterfall is minimal in the beginning and needs to be entirely built up by the management of farmers, who decide the tree species composition by planting and preserving a certain number of associated species. Therefore, S-cAFS appearance change a lot during the first 14 years after planting which is underlined by the high variability within the 'S-cAFS 0-14 years' litterfall notably according to the strategy set up by the farmers (Jagoret et al., 2012).

In our study, the relative contribution of cocoa leaf litter in total associated species leaf litterfall was variable during the year. Over the whole studied period, leaf litterfall of associated species (*ca.* 70%) was higher compared to leaf litterfall of cocoa trees (*ca.* 30%). Most studies, on the contrary, do find that the leaf litterfall of cocoa to be more important (Boyer, 1972; Costa et al., 2016; Dawoe et al., 2009; Fontes et al., 2014). This could point out the particular importance of shade trees in our systems in young as well as in full grown cAFS. Such a result may be due to the peculiar selection farmers operate on trees (Saj et al., 2017) and/or the increased appearance of deciduous tree species in drier surroundings (Aranguren et al., 1982; Hartemink, 2005). The latter hypothesis is backed up by the relatively higher litterfall in the forest controls compared to tropical forests with higher rainfall regimes (Vitousek and Sanford, 1986; Zhang et al., 2014). Even though, total litterfall of cAFS was much higher than for example litterfall in cAFS in Mexico, it did not arrive to the same level as total litterfall in the forest control. Therefore, it is not certain if levels of litterfall and subsequent nutrient restitution to the system were sufficiently high to sustain cAFS growth and production as was argued by Isaac et al. (2005). However, this study compares their litterfall data with litterfall data from literature and not with litterfall levels from forests in the same region. The lower litterfall in cAFS was probably the result of the lower tree -biomass and different tree composition of cAFS compared to forest control plots (Nijmeijer et al., submitted; Saj et al., 2013).

4.2 Leaf litter decomposition

This study confirmed the relative slow decomposition of cocoa leaves with weight losses that were around 30% lower than that of leaf litter of associated species. Yet, litterbags may alter decomposition due to the exclusion of litter macrofauna (arthropods, millipedes, termites and earthworms), the modification of local micro climate or the hindering from soil contact (Hanlon and Anderson, 1980; De Freitas Santos, 2011). Therefore, we checked minimum and maximum leaf litter stocks data from a study of Nijmeijer et al. (submitted) executed in the same cAFS. First, these data confirmed the percentage found during the litterfall study, with cocoa leaves making up between 25 and 30% of the leaf litter stock after the dry period when the leaf litter stock is at its maximum in S- and F-cAFS. Simultaneously, this demonstrated the slow decomposition of cocoa leaves, by showing relative accumulation of cocoa leaves, with cocoa leaves making up to 60% of the minimum leaf litter stock after the rainy season.

Interestingly, decomposition of the cocoa-associated species leaf litter mixture was higher in cAFS compared to the decomposition of cocoa leaves alone. Nevertheless, we could not confirm positive nor negative non-additive decomposition rates (Cuchietti et al., 2014) since variation in weight loss was too high and differences could be explained just by added effects. This could indicate that cocoa leaf litter does not show synergistic decomposition rates and total decomposition might be calculated using the average of each component species (Finerty et al., 2016). Furthermore, weight loss of litter in the forest control plots was greater seven months after installation compared to the associated species leaf decomposition in S- and F-cAFS. This could either be due to the difference in species composition and the subsequent litter qualities or this could indicate differences in microclimate or the soil decomposer communities (Bakker et al., 2011; Cornwell et al., 2008; Freschet et al., 2012). However, with high levels of humidity (89 – 98%) and a difference of 10% between cAFS and forest control plots the differences in associated species leaf litter decomposition is unlikely to be explained by differences in soil humidity only. Yet, humidity and the decomposition study were only carried out during the rainy season and larger differences in humidity might be observed during the dry season. Instead, differences in decomposition could also be due to differences in leaf litter quality as a consequence of differences in tree stands between forest and cAFS (Saj et al., 2017). The high number of evergreen fruit trees in cAFS, whose leaves are in general thought to have a lower quality in terms of nutrients compared to deciduous trees, could be one explanation (Yuanyuan Huang et al., 2017). Though, the contribution of litter of low quality to soil carbon storage was found to be relatively high in cAFS, even when associated species with trees shedding high quality litter (Schroth et al., 2002). Wartenberg et al. (2017), did not find any positive effect of associated tree species on soil fertility in cAFS compared to monoculture and would rather suggest the preservation of primary or secondary forest parts alongside monoculture cocoa plantations. However, the cAFS studied were only *ca.* 13 years old and the buildup of soil fertility in cAFS might be slower in cAFS compared to secondary forest seen the low quality of cocoa leaf litter. A study to 25 year old cAFS on soil fertility and mycorrhizal fungi did not find significant differences between these cAFS and secondary forest whereas young cAFS (1-4 years old) showed a significant lower mycorrhizal diversity and spore density (Snoeck et al., 2010). For total ecosystem functioning of cAFS, it is of high importance that a farmer preserves sufficient tree individuals that shed high quality litter and that are beneficial for the cAFS fertility (Jagoret et al., 2014). However a good equilibrium should be found between good quantities of high quality leaves from associated trees and the competition for light (Saj et al 2017), water and nutrients (Schroth et al., 2001).

5. Conclusion

The cAFS in Central Cameroon created after savannah, reached within 15 years equivalent annual litterfall production as cAFS created after forest. Albeit being relatively high cAFS litterfall did not reach the same levels as local secondary forests. Furthermore, litterfall was found to depend on the season, leaf litter- and reproductive organs- fall, being highest during the dry season. Cocoa trees vulnerability to drought was underlined by the second leaf litterfall peak during the dry season. The low quality of cocoa leaves was likely to explain the lower decomposition cocoa leaf litter compared to that of associated trees. Nevertheless, no beneficial non-additive effects of associated species leaves on the cocoa leaf

decomposition could be revealed. In the light of climate change, cAFS in the forest-savannah transition zone are of special risk since local rainfall dynamics and quantity records are already sub-optimal for cocoa growth. This makes the presence of associated shade trees even more important for this shade-tolerant species. Overall, it is suggested to increase efforts to optimize the composition of the associated tree stand by eliminating species that are competing for water during the dry season and increase the fertility of the system by adding tree species with a high litter quality.

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6. References

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DISCUSSION



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"Thank you!"

This PhD thesis provides new insights about the ecosystem functions and services of cAFS with different past land-uses (savannah: S-cAFS and forest: F-cAFS). Firstly, the effect of the past-land use and its' history is discussed. Secondly, the role of perennial plants biodiversity in cAFS is positioned in a social and economic perspective. Its role in ecosystem multifunctionality is also highlighted. Finally, the future of cAFS with respect to climate change and its potential role in climate mitigation is debated.

From legacies to novel ecosystem and the history of past land-use

Savannah and tropical forests differ highly in aboveground structure due to the different plant forms that they comprise (tree versus grass). Therefore, it is not surprising that in our study, biodiversity of perennial plants, and the aboveground- and fine root- biomass, were significantly lower in the savannah plots compared to the forest plots. As hypothesized, soil fertility parameters of the savannah plots were significantly different from those in forest (Oliveras and Malhi, 2016) - with lower nutrient concentrations and a higher bulk density for the first 15 cm of soil in the savannah plots (chapter 2). Yet, not all studies found soil fertility in the upper soil layers of savannah to be lower as that of forest land. For example, in a study in Central Africa no remarkable differences were observed between soil parameters from the top soils of savannah and forest in a savannah-forest transition zone, except for a higher soil bulk density in savannah (Sugihara et al., 2014). Though, management of those savannahs seem similar to our study site, with annual fires and agricultural practices.

Even though afforestation of savannah with cAFS is reputed uneasy to achieve and seems rare (Gockowski et al., 2004), the practice has been used for over 60 years in Bokito (Jagoret et al., 2011). We found that changes due to the conversion of savannah resulted in legacies of the savannah ecosystem in S-cAFS during the first years after conversion. Yet, after *ca.* 15 years the conversion leads into novel ecosystems that could not, with the parameters we used, anymore be related to its past land-use, savannah (Hobbs et al., 2006; Six et al., 2014). The afforestation of savannah with cAFS had a positive effect on most of the studied ecosystem functions resulting eventually in similar levels for soil and above-ground functions as F-cAFS. Our study showed that around 75 years were needed for S-cAFS to reach similar aboveground carbon levels compared to F-cAFS (chapter 1). Fine root biomass of S-cAFS ≥ 15 years was slightly higher compared to F-cAFS ≥ 15 years, which could mean that investment in roots is higher in the slightly nutrients poorer S-cAFS. Average total litterfall and litterfall dynamics during the studied year were similar for S- and F-cAFS after 15 years old (chapter 2). Contrasting with F-cAFS, S-cAFS cannot rely during installation on a "forest rent" that provides, at least during the first years, nutrients for a productive cAFS (Dawoe et al., 2009). Despite the contrast between forest and savannah, S-cAFS' soil fertility and above- and below- ground biomasses were found to be increasing during this period. This increase could be related to the elimination of the annual fires and occasional agriculture, as well as the increased flux and decomposition of litter restituting nutrients to the upper soil layers (Prescott, 2002). However, such phenomenon does not explain the overall increased fertility. Several studies suggest that newly installed perennial plant species could take advantage from a change in N availability as past savannah vegetation putatively tended to immobilize N (Laclau et al., 2005; Subbarao et al., 2009). Furthermore, deeper soil layers of savannahs might be less depleted in nutrients. In such a case, trees

could function as a nutrient pump, taking up nutrients from deeper soil layers and distributing this to other parts of the plants that will return to the upper soil in the form of litter (Bond, 2010; Oliveras and Malhi, 2016). In this case, instead of an overall low soil fertility, only the upper soil layers of savannahs are depleted in soil nutrients. Annual cropping systems set up in those savannah areas could be a reason for this (Schroth et al., 2001). But also, annual fires, to support hunting and land clearance for these agricultural practices, could constitute a cause for the depletion in top soil nutrients (Kugbe et al., 2015, 2012). Since annual savannah burnings constitute a common practice that is overall positively perceived, it is meant to last (Kugbe et al., 2012). So, even though afforestation is a widely adopted technique in Bokito, place for further implementation will be limited. Yet, afforestation with cAFS could be promoted in other regions lacking this knowledge since tropical forest-savannah transition zones are widely spread (Oliveras and Malhi, 2016).

Besides, spatial heterogeneity in fertility due to variations of the topography and the land-use, the long-term history of the area could have an impact on today's ecosystem functioning. The annual burnings raise questions around the age and history of savannahs in the region. Fires for a savannah in a steady state will occur, but are not necessary to maintain a savannah. Though, in an area as Bokito where annual rainfall is far above 650 mm (the threshold for savannah-forest transitions), savannahs are not in a steady state and natural reforestation or afforestation will occur in case annual burnings stop (Staver et al., 2011). Furthermore, forest remnants are often located on the top of hills where water should be less available than in valleys. This tends to support the fact that valleys could naturally support forest growing (Oliveras and Malhi, 2016). To study such a hypothesis, boundaries and age of the savannah could be tested using methods for δ^{13} and ^{14}C in soil profiles (Furley, 2010; Jackson et al., 2002). The outcome of such a study might reveal "reforestation" a more adequate term for the land-use change from savannah to S-cAFS than "afforestation".

In addition to the unknown pedoclimatic history of the local savannahs, pieces of pottery were found in several cAFS. Some of these pieces of pottery were dated between 900 and 500 years BC (de Saulieu in Freycon, 2017) and could be an indication for ancient human settlements. Human communities are known to alter local resource availability and legacies of settlements have shown to last over a long period (Freschet et al., 2014; Lehmann et al., 2003; Perring et al., 2016), meaning that still, today ecosystem functioning and soil fertility could be influenced. Some of the variability of the soil fertility parameters might be explained by those settlements and we would therefore recommend an archeological study on their geographical distribution. Overall, the past of our two chosen past land-uses could shed some more light on today's ecosystem functioning, the fertility status and heterogeneity of the area by identifying the age of the savannahs and indicating the locations of ancient settlements.

Associated tree diversity in cAFS

Despite the great differences between the ecosystem functions of the two past land-uses studied here, farmers do manage to create, after *ca.* 15 years, S-cAFS that are not distinguishable from F-cAFS. In this process, the selection of perennial plants that are planted or preserved and further maintained in a field is of great importance and, in our systems, resulted in similar levels of species richness and diversity

both in S- and F-cAFS. The similarities are underlined by the comparable number of African tree species found in S- and F-cAFS. Furthermore, multiple statistical regressions showed that perennial plant species diversity was more than once positively linked to parts of the ecosystem multifunctionality such as biomass in cAFS and several soil fertility parameters. The link between biodiversity and ecosystem multifunctionality has also been highlighted in other studies where it has been related to functions such as carbon sequestration (Saj et al., 2013), pest control (Schroth et al., 2000), herbivory suppression (Bisseleua et al., 2009) or edge effect from local forest patches (van Bodegom and Price, 2015).

Biodiversity and conservation

Alfa diversity in cAFS is higher compared to full sun systems, but depending on the species richness and the distribution of species, cAFS diversity can be highly variable. We used the Shannon-Weaver index as it is one of the most commonly used diversity indices and therefore easy when comparing diversity results (chapter 2). For cAFS ≥ 15 years results of the Shannon Weaver were between 1.5 and 2.0, similar to results of other studies (Cerdeira et al., 2014; Hervé and Vidal, 2008) and higher than complex cAFS in the study of Wartenberg et al. (2017). On the other hand, the results were lower compared to other studies in Cameroon (Jagoret et al., 2011; Zapfack et al., 2002). Yet, these studies were conducted in the South of Cameroon closer to the Congo-basin with higher precipitation, which has been linked to higher biodiversity (Linder, 2001). While converting a forest to F-cAFS, Shannon-Weaver of our forest control plots was *ca.* 2.7, species diversity risks not only to decrease, but is also likely to change in composition altering the regions β diversity decreasing their conservation status (Deheuvels et al., 2014). Species heterogeneity between forests and cAFS was *ca.* 40% higher in the region of Bokito compared to two other regions of Cameroon (Saj et al., 2017a). This might be related to the fact that this was the only area including S-cAFS, where all species, native or exotic, are introduced and are probably less reflecting forest species composition. For S-cAFS on the other hand, the species richness and Shannon-Weaver of perennial plants increased as a result of the conversion of savannah that had a Shannon-Weaver of *ca.* 1.2 (chapter 2). The composition of perennial plants almost entirely changed with it (data not shown). The abundance of associated perennial plants is almost three times lower in cAFS compared to forests, resulting in a bigger area needed for cAFS to contain similar species diversity as natural forests. However, it is very well possible that diversity will never get as great for cAFS as for forest due to the management strategies of farmers that will specifically eliminate certain species.

Furthermore, the perennial plants community is not the only one that is negatively impacted by the conversion to cAFS. Conversion is to also have consequences for animal, bird and insect species as highlighted below. Overall, it seems that the abundance of insects and birds is not negatively impacted by the conversion forest to F-cAFS but depending on the researched group, species richness declines or alters in such a way that the evenness of the populations increases (Bos et al., 2007; Clough et al., 2009; Tschardt et al., 2008). For example, the negative effect on beetle species due to the conversion of forest into cAFS was much larger compared to that on ant species richness (Bos et al., 2007). While, cAFS are found to provide habitat for a great number of forest-dependent species, higher hunting pressure within the cAFS compared to natural forest negatively affects the actual numbers of species present (McNeely and Schroth, 2006).

Regarding conservation, both “land-sparing” and “land-sharing” strategies have been opted as valuable policies. Cocoa-AFS would be categorized as a land-sharing method, where eco-agriculture and low-input methods are adopted as an answer to the rising food demand at the least cost to biodiversity (Goulart et al., 2016). Land-sparing on the other hand proposes to spatially separate biodiversity and production, resulting in full-sun systems alongside preserved forest patches. In our region, local forest patches could be conserved by adopting afforestation of local savannahs (Niles et al., 2002; Zomer et al., 2008). Though, savannah species will probably disappear as a result of the conversion. Cocoa-AFS could also play a corridor function by connecting fragmented forest patches (Asare et al., 2014). This would provide room for both, land sparing and sharing strategies within one region, resulting in a mosaic landscape of full sun plantations, spared forest patches and cAFS as corridors in between (Mertz and Mertens, 2017).

The substitution of cAFS by tropical forest is hardly possible in terms of species richness and diversity, and total species diversity in cAFS has found to depend on nearby forests for the number of species present (Faria et al., 2006). Even though, plant species richness and Shannon-Weaver increased for S-cAFS perennial plants as a result of the land-use change, consequences for the species diversity within other kingdoms and phyla has not been studied. Furthermore, should β - and γ -diversity be considered in a mosaic landscape as Bokito.

Biodiversity and production

The role of biodiversity in cAFS multifunctionality seems very positive, nevertheless local policies are still mainly endorsing land sparing or full sun systems as main production models (Mertz and Mertens, 2017). An argument for this policy of land sparing is the supposed hampering of cocoa yield due to competition for light and resources caused by the presence of associated shade trees and the somewhat doubtful role of these same associated trees in regulating pests and diseases (Andres et al., 2016; Gidoïn et al., 2014; Schroth et al., 2000). Though, the few existing studies stating that cocoa production of cAFS is lower compared to monoculture systems were performed between 1985 and 1999 (Vaast and Somarriba, 2014). Furthermore, the production of new hybrids is still currently only tested in full sun environments, hindering comparisons with today’s potential productions levels in cAFS (Vaast and Somarriba, 2014). The mean accessible yield of *ca.* 800 kg ha⁻¹ found during our study, was lower (chapter 2) compared to potential cocoa yields of 2000 t ha⁻¹ that were obtained in on-station trials using cocoa hybrids and prescribed amounts of fertilizer and pesticides (Aneani and Ofori-Frimpong, 2013). Yet, in another study on cAFS in Central Cameroon, Saj et al. (2017b) reported maximum accessible yields of more than 2000 kg ha⁻¹. The mean accessible yield calculated from Saj et al. (2017b) were found to be close to those from our study (*ca.* 895 kg ha⁻¹). The accessible yield measured in our cAFS is the maximum possible obtainable yield of a cAFS and probably overestimates the obtained yields by 15 to 20% (Jagoret et al., 2011).

The average actual yield in Cameroon was reported to be between 180 and 600 kg ha⁻¹ depending on the cAFS age and the type of farmers (Jagoret et al., 2011; Pédelahore, 2014). Discrepancies between

accessible yields and actual yield could be due to a number of factors. Firstly, the used research method could overestimate the number of pods that reach full growth and get yielded. Secondly, management practices of farmers concerning for example the correct application of pesticides could be pointed out as a factor lowering the actual yield (Sonwa et al., 2008). Even though, the discrepancy between cAFS' actual and accessible yield, Cameroonian farmers are known to value the perennial plants associated with cocoa (Jagoret et al., 2014) and manage their abundance and diversity (Jagoret et al., 2017). The main upper canopy tree species, in terms of biomass, in our cAFS comprised of *Ceiba pentandra*, *Milicia excelsia*, *Guibourtia tessmannii*, *Albizia adianthifolia*. All four species were indicated to be useful for the growth of cocoa, and except for *C. pentandra*, all species were produced for their wood as well. Interestingly, these trees have different leaf litter shedding patterns, with the first two species being deciduous and the other two being evergreen, which will influence the overall litterfall and decomposition dynamics. Yet, almost all tree species served a role in the cAFS and some more than one (Figure 21). Only, F-cAFS, and especially those younger than 15 years old, comprised species remaining from forest that did not serve any role. In older F-cAFS those trees are probably eliminated to manage overall associated tree community in the plots to maintain competition to a suitable level (Jagoret et al., 2017).

Socio-economically, the adoption of cAFS might be more attractive for smallholder farmers compared to full sun systems. Cocoa-AFS involve less expenses during installation, since no entire land clearance and no fertilizers or irrigation are needed. Furthermore, the upkeep of full sun systems requires higher costs for fertilizers and pesticides and (hired) labour for application of these products and weeding (Jezeer et al., 2017). Even though, production of full sun systems might be higher, the costs for inputs and risks for pollution are higher (Vaast and Somarriba, 2014) and productivity of full sun systems is known to decline after 20 to 30 years. On the other hand, cAFS in Cameroon showed to remain productive for over 60 years (Saj et al., 2017b). Trade-offs between yield and diversity in cAFS may be balanced by the complementary incomes and/or the support to food security and diet diversity coming from associated

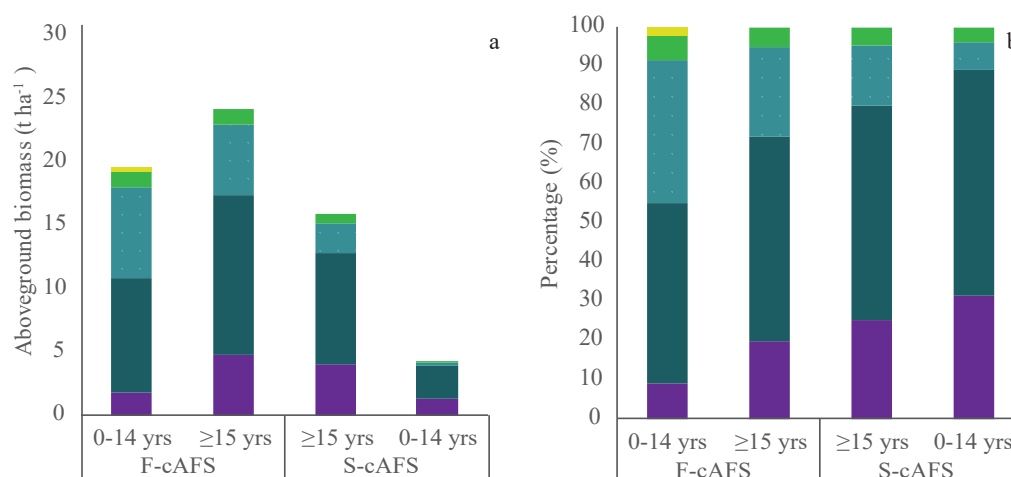


Figure 21: The use of tree species according to local farmers in S- and F-cAFS in Bokito with a) The percentage of biomass involved per type of use, and b) The total biomass involved per use (this is higher than the actual aboveground biomass since several trees have more than one use). Purple useful for food production, dark blue useful wood production, blue useful for cocoa growing, green useful for other uses (e.g. medicinal, cultural) and yellow no specific use.

trees by-products (Gockowski et al., 2004; Jezeer et al., 2017; Saj et al., 2017a, 2017b; Schneider et al., 2016; Soria et al., 1996). In Central America, secondary products consist mainly of bananas, oranges, peach palm, other fruits, and timber and were found to mainly contribute to food security (Cerda et al., 2014). Most important fruit trees in our cAFS were found to be butter-fruit (*Dacryodes edulis*), oil palm (*Elaeis guineensis*), mango (*Mangifera indica*) and orange (*Citrus sinensis*). The exact revenue farmers in Bokito obtain from these by-products is not clear and probably differs from year-to-year. Sonwa et al. (2007) found that density of fruit trees tended to decrease with distance to market facilities. For our study area, it seemed that infrastructures for marketing of these products was insufficiently developed and many of the products of these trees are used for own consumption (Alemagi et al., 2014; Ruf and Schroth, 2015). Products that could not be used for own consumption were as a consequence left within the cAFS to rot. Since governments are lacking to tackle these problems, the role of researchers and NGO's is important. They could help tackle the problems by mapping local overproduction increasing possibilities for distribution and lecturing local farmers. Economically, considering that cAFS might not deliver the highest revenues, Franzen and Borgerhoff Mulder (2007), suggests that diversification might be the most effective way of optimizing ecological, economic, and social aspects.

Biodiversity and litterfall and decomposition

Compared to full-sun systems, the rather high biodiversity and abundance of associated trees in a cAFS may exhibit improved nutrient cycling thanks to additional litterfall of leaves with varying leaf litter traits (Prescott, 2002; Scherer-Lorenzen, 2008; van Bodegom and Price, 2015). This was for example shown by the positive link between biodiversity and the litterfall of S-cAFS in our study (chapter 2). A subsequent increase in the soil fertility parameters of S-cAFS and the rather stable soil fertility parameters of F-cAFS gives support to the idea that diversity in litter has a positive effect on soil fertility of cAFS (Isaac et al., 2007; Lal, 2016; Mbow et al., 2014; Tschamtkke et al., 2011). Nevertheless, Wartenberg et al. (2017), found soil fertility of F-cAFS to decrease up to similar levels as monoculture systems. Though their Shannon-Weaver of complex cAFS was lower compared to ours. This could, as was suggested in chapter 2 for production, also be an indication that there is an optimum in the number of associated trees and their biomass. Furthermore, the exact composition of tree species and their different functional groups could be of importance in the restitution of nutrients back to the soil and its subsequent fertility. For example, the differences between functional green leaf traits from N-fixing trees or evergreen compared to deciduous trees result in differences in decomposition rate (Cornwell et al., 2008). Results of our decomposition study were not as clear as hoped even though overall associated leaf litter weight loss through decomposition was higher compared to the decomposition of cocoa leaves and the mix between cocoa and associated species leaves. However, we did not find non-additive effects of the decomposition of associated leaf litter in combination with the low-quality cocoa leaves. A trait-based approach could be used to better understand the decomposition of leaves in our cAFS since this has been pointed out to be a good predictor for measuring changes in ecosystem functioning (Cornelissen et al., 2003). For example, several green leaf traits, chemical and structural, have been linked to decomposition. Leaf quality goes from high quality leaves that are characterized by short living, nutrient rich and carbon poor concentrations that tend to decompose faster than low quality leaves

that are characterized by opposite traits (Bakker et al., 2011; Santiago, 2007). This has been described as the resource economic spectrum (RES) which is based on interspecific variation in traits from species using fast resource acquisition to species that emphasis on resource conservation (Dias et al., 2017). This variation in traits or functional diversity is in many cases positively correlated to biodiversity, though, it could be that functional diversity is lower than species richness due to internal variation and an overlap in niches between species (Song et al., 2014). Though farmers do not choose their associated species based on their functional diversity but indicate a great number as being advantageous for cocoa growth (Figure 21). Therefore, the selection may partly be “translated” into functional traits (Saj et al., 2017b). Complementary investigations on green leaves traits within the studied cAFS is currently ongoing (Agropolis funded Stradiv project, 2016-18).

Besides the production of aboveground litter, the annual production of root litter should also be taken into account (Freschet et al., 2013). In our study, at the moment of sampling, fine roots from the first 10 cm of soils of cAFS ≥ 15 years reached quantities of *ca.* 1.5 t ha⁻¹. This would be around 30% of the total annual aboveground litterfall. However, the total amount of fine roots in the soil is probably higher, since most fine roots grow up to depths of around 20 to 40 cm (Moser et al., 2010). The decomposition of fine roots is slower compared to the decomposition of aboveground leaf litter and is considered to slow down the systems’ total nutrient cycling (Freschet et al., 2013). In cAFS changes in the proportions of above- to below- ground litter could influence cAFS productivity. For example climatic stress, as a decrease in water availability, could be hypothesized to increase the proportion of the slower decomposing root fraction in a cAFS negatively influencing aboveground production.

Climate change and the future of cAFS in the savannah transition zone

Since cocoa production demands specific climatic circumstances, it is vulnerable to climate change (Vaast and Somarriba, 2014). For the future of cocoa production two main topics can be pointed out. The first topic deals with the resilience of cocoa production abilities to the predicted climate change, while comparing cAFS and full-sun systems (Schroth et al., 2016). On the other hand, several studies suggest that especially long-term growing cAFS have a function in climate mitigation by storing carbon in their biomass and soil (Gama-Rodrigues et al., 2010; Gockowski et al., 2004).

Climate change adaptation

Schroth et al. (2016), predict that part of the West-African cocoa belt will get unsuitable for the production of cocoa. According to this study, full sun systems will especially suffer from extra irradiations and droughts. The presence of shade partly buffers an increase in temperature and improves the hydrological cycle and are thus thought to support the resilience of cAFS (Ofori-Boateng and Insah, 2011; Schwendenmann et al., 2010; Tschardt et al., 2011; Vaast and Somarriba, 2014). Nevertheless, severe drought could as well negatively affect the cAFS of Bokito due to the competition for water

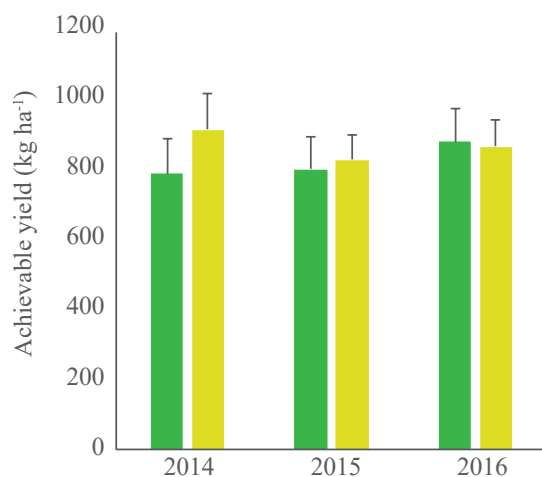


Figure 22: average yields of S- and F-cAFS ≥ 15 years for the years 2014 to 2016. Yellow indicate S-cAFS and Green indicate F-cAFS

between cocoa and associated trees. A comparison between cocoa trees under two different tree species and full sun cocoa, showed a much higher die back of cocoa trees under shade compared to the full sun system (Abdulai et al., 2017). Especially the nitrogen fixing *Albizia ferruginea* showed to have a negative effect on cocoa during the El-Niño event of 2015-2016. Therefore the use of cAFS was suggested to be reconsidered, but especially the composition and density of associated tree species with cocoa should be carefully managed (Franzen and Borgerhoff Mulder, 2007). On the other hand, associated shade trees could decrease the evapotranspiration from the soil due to their buffering effect drought resulting in a more favorable microclimate (van Vliet and Giller, 2017). Besides the duration of the dry period, soil depth, soil texture and the topographical position of a cAFS will have an influence on the soil moisture availability (van Vliet and Giller, 2017). We hypothesized that the second cocoa leaf litterfall peak we observed in our cAFS was also the result of the severe drought period endured. In our plots, some dieback was seen as well but proper observations are lacking. This reaction of cocoa to drought was, as far as we know, not shown before. Yet, increased drought has been linked to a decrease in subsequent cocoa production (Adjei-Nsiah and Kermah, 2012; Moser et al., 2010). However, we did not notice a decrease in the accessible yields of cAFS ≥ 15 years when looking at the cocoa production over the last three years (Figure 22). It is known that cocoa flowers are highly sensitive to drought (Frimpong-Anin et al., 2014), therefore we may hypothesize that the rainfall during the rainy season was sufficiently high to compensate for the negative effects of the dry period. The fact that increased drought leads to shifts in commodity cultivation was already observed during the nineties. In the forest-savannah transition zone in Ghana, a decline of the cocoa yield and the difficulty in establishing new cocoa farms as a result of frequent bushfires, changing rainfall regimes and a severe dry season forced farmers to shift in cropping system from cocoa plantations to maize based cultivation during the rainy season (Adjei-Nsiah and Kermah, 2012). However, these systems seemed to lack any shade making them more probably more vulnerable. Some suggest the installation of irrigation systems in farms to overcome the difficulties of increasing drought (Ofori-Boateng and Insah, 2011). Yet, this seems a highly unlikely practice for smallholder farmers that do not even have access to running water. A study on the response of seedlings

of several cocoa varieties found significant differences among those varieties (Ofori et al., 2015). We suggest to increase focussing on drought- and shade- tolerant cocoa varieties and especially focus on the productive period. Simultaneously, cAFS topographical position and soil depth should be included while analysing their production potential. Finally, cocoa trees under different associated trees should be followed over a longer period than usually (often less than 20 years).

Climate change mitigation

For the mitigation of climate change an accumulation of carbon needs to take place and this carbon needs to be stored over a long period. For the AGC, accumulation of carbon is especially related to trees with a DBH > 30 cm which include mainly the bigger shade trees (Chapter 1, Saj, Jagoret, & Todem Ngogue, 2013). For the SOC we did not find accumulation for F-cAFS with age, but we neither found a decrease in SOC due to the conversion of forest to F-cAFS as was observed in other studies (Schroth et al., 2002; Snoeck et al., 2010; Wartenberg et al., 2017; Yang et al., 2004). Despite the soils in our study area being very heterogenous, they showed an annual accumulation of carbon in S-cAFS for the time span investigated. Furthermore, the accumulation of SOC together with the accumulation of AGC makes S-cAFS interesting for climate mitigation programmes such as the “4 per mille” and the “Climate Smart Agriculture” initiatives. The latter is slightly controversial, especially for F-cAFS, since the initially carbon status of forests was higher. On the other hand it would be, based on our results, a great opportunity for S-cAFS. This study seems in line with other researchers that see afforestation or reforestation as an opportunity for climate mitigation and which could slow down deforestation in certain zones (Niles et al., 2002; Robert J. Zomer et al., 2008). Therefore, we think that development projects on afforestation should be promoted and especially that associated trees should be selected carefully with regard to competition for water and nutrients. The appraisal of their potential C sequestration seems further essential for the implementation of the REDD+ programme which is currently discussed in Cameroon. Some researchers suggest supporting payments from a certification or policy mechanisms (such as REDD+) will be required to keep cAFS economically viable for farmers (De Beenhouwer et al., 2016; Gockowski and Sonwa, 2011). In Ghana, for instance, the public and private sectors already claimed thinking about the implementation of insurances for farmers that adopt “climate smart” cocoa production methods but that endure negative impacts from climate change (Mckinley et al., 2014).

Conclusion

Our study showed that afforestation of savannah with cAFS (S-cAFS) represents a valuable local strategy that combines cocoa production with other perennial plants resulting in comparable levels of ecosystem multifunctionality compared to F-cAFS. A stronger focus on the young (0-14 years) and medium aged (15-30 years) cAFS could give better insight of the temporal frame of the functional changes observed and their embedment in S- and F-cAFS. Furthermore, an elaborated study on topographical placing of cAFS and on the history of human settlements in the region could help better characterizing the variability of certain soil parameters. For the entire forest-savannah transition zone of Central- and

West-Africa, studies on the existence and possibilities for development of S-cAFS are necessary for future implementations without leading to competition with other local commodities. The decades-long gathered empirical knowledge of S-cAFS by farmers could be of great value in case of implementation.

Afforestation appears as a valuable local strategy to combine cocoa production with other perennial plants and increase above- and below- ground carbon storage while avoiding deforestation. Besides their potential climate mitigation function, S-cAFS seem very compatible at the field level with both the “4 per mille” and the “Climate Smart Agriculture” initiatives. This makes further exploration of the functioning of these systems potentially very promising. Though, the vulnerability and adaptation of cAFS in the savannah-transition zone to climate change, and especially the competition for water during increased drought events, should have priority in future research. This would allow the better understanding of the environmental conditions and the structural and compositional characteristics in cAFS that would permit the maintenance of a realistic cocoa production, among other goods, while being acceptable for farmers.

SCIENTIFIC COMMUNICATIONS

CARBON CONTENT IN CACAO AFS

Afforestation of Savannah as a Carbon Storage Opportunity in Central Cameroon

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Introduction

Afforestation of savannah areas by cacao agroforestry systems (AFS) is relatively rare¹⁻⁴. Soil and climate conditions are generally considered undesirable for this type of perennial production system⁵. However, previous studies in a forest-savannah transition zone in Central Cameroon have shown that smallholder farmers were able to afforestation on savannah land by establishing cacao plantations on it^{4,6}. Compared to plantations setup after formal forests in the same region, cocoa production levels and associated tree species densities were found to be comparable on the long-term⁴. Considering the low level of carbon storage in savannah, partly due to yearly burning of these areas, afforestation with cacao plantations could be of great potential in the light of climate change mitigation due to their increased carbon storage capacity.

Methods

Field studies are conducted in Bokito in the central region of Cameroon, this area is known as a patchwork of savannah, forest, agricultural area and AFS. Savannahs in these area are yearly burnt for hunting practices and land clearance is carried out for agricultural practices. Carbon measurements were taken in cacao plantations setup on two previous land-use types (savannah and gallery forest) with an age gradient of 0 to 80 years. Results were compared with two control groups in gallery forests and savannah. Carbon content and accumulation were assessed both in cacao trees and associated tree species as well as in plantations' soil.

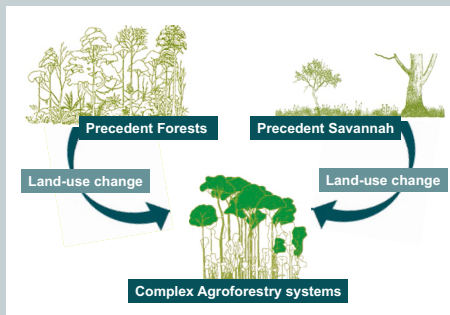
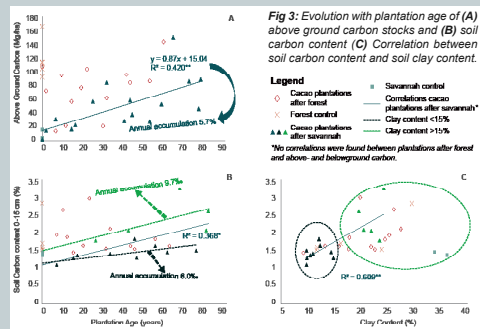


Fig. 1: What influence has converting savannah or forest to complex-cacao agroforestry systems on the long-term carbon budgets?

Results



The above ground total carbon and soil organic carbon (SOC) of the first 15 cm of savannah plantations are significant correlated with the age of the plantations (Fig. 3A,B). For the same parameters no correlations were found in forest plantations and the soil layer 15-30 cm.

Even though, a correlation between age and SOC was found an even stronger correlation was found between soil clay content and SOC content (Fig. 3C). When separating cacao plantations after savannah into two groups 1) low (<15%) and 2) high (>15%) clay content, SOC tended to increase at an annual rate of 9.7% for the plantations on soils with a high clay content and 6.0% for the plantations on soils with a low clay content (Fig. 3B).

Results

Mean total above ground carbon is around 40% lower in cacao plantations set-up after forest compared to forest control plots. Above ground carbon stocks of plantations set up after savannah have increased by 1011% compared to the measurements that have been taken on savannah (Fig. 2).

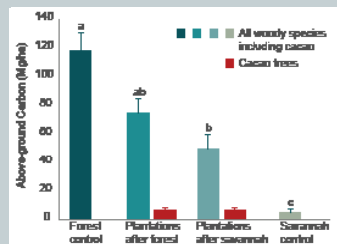


Fig. 2: Mean total above ground carbon stocks in forest- and savannah control plots, cacao plantations after forest and after savannah.

Conclusion

- Afforestation of savannah has a positive effect on the total above ground carbon with an annual accumulation of 5.7% resulting in similar carbon levels as cacao plantations after forest in \pm 60 years.
- Setting up a cacao plantation after forest decreases the mean above ground carbon stock but no significant change was shown with aging of the cacao plantations.
- Soil carbon and soil clay content of plantations set up after savannah are strongly correlated but also correlations are found between soil organic carbon and the plantations age.

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Abstract

Cocoa agroforestry systems (cAFS) in the Central Cameroonian forest-savannah transition zone can be set up after either forest or savannah. Ecosystem multifunctionality of those cAFS is partly created by the farmer who determines species richness and tree density, but is also partly inherited from the past land-use. Ecosystem functions and services were studied using chronosequences of over 80 years for cAFS created after savannah (S-cAFS) and forest (F-cAFS). The original land-uses, forest and savannah, were also studied for comparisons and to investigate the long-term legacies of several ecosystem functions and services. Vegetation structure, above- and below- ground biomass and accessible cocoa yields were estimated in each plot. For one year, a litterfall study was executed to investigate litterfall dynamics, litter stocks were measured twice within this same year, and for seven months a decomposition study was performed. In each plot, composite soil samples from 0-15 and 15-30 cm depths were analysed for nutrient and texture investigations. Finally, in each plot fine roots (first 3 root orders) from the 0-10 cm soil layer were studied.

Results showed that most land-use legacies were longer visible for S-cAFS compared to F-cAFS, but after 15 years most of the variables and services studied exhibited comparable levels for both types of cAFS. For F-cAFS, aboveground structure changed right after conversion, soil fertility parameters, on the other hand, stayed rather stable during and after the transition. For S-cAFS, above- and below-ground carbon stocks increased but also biodiversity of perennial plants, litterfall and most soil fertility parameters augmented. Annual litterfall of cAFS in Central Cameroon was relatively high compared to that of cAFS from other regions in the world but did not reach the same levels as in the forest control plots. Accessible yield appeared, with ca. 800 kg ha⁻¹, higher compared to average cocoa production levels usually cited. Even though actual yield was probably lower, production from associated food and timber trees might compensate this missed income.

A stronger focus on the young (0-14 years) and medium aged (15-30 years) cAFS could give better insight of the temporal frame of the functional changes observed and their embedment in S- and F-cAFS. Furthermore, an elaborated study on topographical placing of cAFS and on the history of human settlements in the region could help better characterizing the variability of certain soil parameters. For the entire forest-savannah transition zone of Central- and West-Africa, studies on the existence and possibilities for extension of S-cAFS are necessary for future implementations without leading to competition with other local commodities. The decades-long gathered empirical knowledge of S-cAFS farmers could be of great value in case of implementation.

Afforestation appears a valuable local strategy to combine cocoa production with other perennial plants and increase above- and belowground carbon storage while avoiding deforestation. Besides their potential climate mitigation function, S-cAFS seem very compatible at the field level with both the “4 per mille” and the “Climate Smart Agriculture” initiatives. This makes further exploration of the functioning of these systems potentially very promising. Though, the vulnerability and adaptation of cAFS in the savannah-transition zone to climate change, and especially the competition for water during increased drought events, should have priority in future research. This would allow the better understanding of the environmental conditions and the structural and compositional characteristics in cAFS that would permit the maintenance of a realistic cocoa production, among other goods, while being acceptable for farmers.

Keywords: Cocoa agroforestry; Land-use change; Ecosystem multifunctionality; Land-use legacies; Climate change

Résumé de la thèse

Les systèmes agroforestiers à base de cacaoyers (SAFc) dans la zone de transition entre la forêt et la savane du Centre Cameroun peuvent être mis en place après forêt ou après savane. La multifonctionnalité écosystémique dans ces SAFc est en partie créée par l'agriculteur qui détermine la richesse en espèces et la densité des arbres, mais est également partiellement héritée du 'précédent', savane ou forêt. Les fonctions et les services écosystémiques des SAFc ont été étudiés à l'aide de chronoséquences de plus de 80 ans pour des systèmes créés après savane (S-cAFS) et après forêt (F-cAFS). Les précédents ont également été étudiés afin de servir de témoins. La structure de la végétation, la biomasse aérienne et souterraine et les rendements accessibles en cacao ont été estimés dans chaque parcelle. Pendant un an, nous avons réalisé une étude sur la dynamique de production de litière aérienne, les stocks de litières ont été évalués deux fois durant cette année, et, pendant 7 mois, une étude de décomposition a été effectuée. Dans chaque parcelle, des échantillons composites de sols de 0 à 15 et de 15 à 30 cm de profondeur ont été prélevés pour des analyse physico-chimique. Enfin, dans chaque parcelle, les racines fines de la couche de 0 à 10 cm du sol ont été étudiées.

Nos résultats montrent que la plupart des influences issues du précédent restent visibles plus longtemps dans les S-cAFS par rapport aux F-cAFS. Après 15 ans cependant, les niveaux des variables et services étudiés sont pour la plupart comparables pour les deux types de SAFc. Pour les F-SAFc, la structure aérienne change juste après la conversion tandis que les paramètres de fertilité du sol semblent rester stables pendant et après la transition. Pour les S-SAFc, les stocks de carbone aériens et souterrains augmentent avec le temps, tout comme la biodiversité des plantes associées, la production de litière aérienne et les paramètres de fertilité du sol. Le rendement accessible apparaît, avec environ 800 kg ha⁻¹, élevé par rapport aux niveaux moyens de production de cacao généralement reportés. Même si le rendement final est probablement plus faible, la production des aliments associés et des arbres à bois peut vraisemblablement compenser ce revenu.

Une attention accrue accordée aux SAFc jeunes (0-14 ans) et d'âge moyen (15-30 ans) permettrait par ailleurs de mieux renseigner sur les trajectoires des changements écosystémiques qui s'y déroulent après conversion. De plus, des études topographiques et archéologiques pourraient aider à expliciter certaines des variabilités observées au niveau des sols. Pour toutes les zones de transition forêt-savane de l'Afrique Centrale et de l'Ouest, des études sur l'existence et sur les possibilités de création de S-SAFc seraient nécessaires avant toute mise en place afin notamment d'éviter la concurrence avec d'autres produits locaux.

L'afforestation apparaît comme une stratégie locale précieuse qui permet de combiner la production de cacao avec celle d'autres plantes pérennes. Elle permet également l'augmentation des stocks de carbone aérien et souterrain tout en évitant la déforestation. Outre leur fonction potentielle d'atténuation du changement climatique, les S-SAFc semblent compatibles sur le terrain avec les initiatives du «4 pour mille» et d'«Agriculture Climato-Intelligente» ce qui rend l'exploration de leur fonctionnement potentiellement très prometteuse. Cependant, la vulnérabilité et l'adaptation des SAFc dans la zone de transition forêt-savane face au changement climatique, et en particulier face à la compétition pour l'eau lors de sécheresses accrues, devraient être prioritairement étudiées dans les recherches futures. Cela permettrait une meilleure compréhension des conditions environnementales et des caractéristiques structurelles et compositionnelles des SAFc qui permettraient de maintenir une production réaliste de cacao, parmi d'autres biens, tout en étant acceptable pour les agriculteurs.

Mots de clés: Agroforestiers à base de cacaoyers; Afforestation; Caractéristiques écosystémiques; Changement climatique