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Local farmers shape ecosystem service provisioning in West African cocoa agroforests

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Abstract 1.In many tropical areas, forests have almost undergone complete decline. In this context, agroforestry has often been acknowledged as fostering compromises between crop production, local income diversification and the preservation of forest ecosystem services. 2.Cocoa agroforestry capacity to provide ecosystem services has mainly been studied through a management intensification gradient summed up as a shade rate. This paper proposes an alternative reading grid based on different trees origins that agroforests often combine: (i) Remnants,left-alive during deforestation, (ii) Recruits that have colonized the agroforest and (iii) Planted trees. This grid has been applied to 137 cocoa fields in the south of Ivory Coast to assess the impact of farmers management on provisioning trees ecosystem services (i.e.: carbon storage, diversity, food, medicine, timber and agronomic services to cocoa trees). 3. (i) Little environmental effect was found to explain ecosystem services provisioning. (ii) However, with regard to their origins, trees provide different services: remnants stock most above-ground carbon, recruits are the most diverse and provide medicinal resources and planted trees bring food resources. (iii) According to their origin, trees belong to different species or are at different stages of maturity so that trees from different origins play a complementary role in providing ecosystem services. Our results suggest that Ivorian cocoa agrosystems are so shaped by human management of associated trees that ecosystem services are weakly linked to

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environmental variables. Two neighboring fields in similar environmental conditions will provide very different services according to farmers' management. 4. *Synthesis and applications* Preserving remnants while clearing forest is irreplaceable for large-scale climate mitigation while providing farmers with trees seedlings may have only little impact on carbon stocks. To strengthen complementarities between human-brought and human-selected trees, private companies providing trees to farmers should supply them with different valued trees from the ones they already plant or easily find in recruits. At landscape scale, policy should encourage remnants preservation to ensure that those remnants can feed the cohort of recruits with propagules thus allowing the survival of the species throughout several cycles of perennial crops.

Keywords Agroforestry · Cocoa · Farming systems · Ecosystem services · Management

Introduction

Public attention is often drawn to threats that tropical forest ecosystems encounter and to the importance of hyper-diverse irreplaceable tropical ecosystems' conservation Gibson et al. (2011); Barlow et al. (2018). Although, in some tropical areas, stakes are already beyond limiting deforestation because forests have undergone almost complete decline. Nowadays, more than 80% of 1900's forests are lost in West Africa. Smallholders agriculture was the main driver of tree cover reduction. This loss reaches 90% in East Africa Aleman et al. (2018). Commercial and smallholders agriculture accounts for 80% of global deforestation FAO (2016). Each additional forest lost accelerates fragmentation: forests fragments get smaller and their number increases Taubert et al. (2018). Post-forest landscapes are important for the conservation/restoration of present and future ecosystem services. For this reason, they are an object of close attention for environmental and aid organizations, politicians, scientists and the agricultural sector Gibbs and Salmon (2015); de Carvalho et al. (2015); Saqib et al. (2019). Seeking and accompanying local people's practices in reforestation to ensure their livelihoods and maintain or restore ecosystems' capacity to provide forests' services is at stake in post-forest tropical areas FAO (2018). Such approaches *should* not ignore political economy of deforestation Pollini (2009); Burgess et al. (2012) nor divert attention from how to reduce global demand for land-intensive export commodities Gibbs and Salmon (2015).

In this context, agroforestry has often been acknowledged as fostering promising compromises between production, local income diversification and the preservation of ecosystem services (i.e. benefits that ecosystems provide to human societies) Bene et al. (1977). Often targeted as being deforestation drivers, tropical perennial crops are also suitable for such agroforestry associations Kusters et al. (2008). For example, although cocoa cultivation has widely contributed to deforestation in West Africa Oswald (2005), it raises hopes for a better conciliation between trees and agriculture in post-forest landscapes Tscharntke et al. (2011); Vaast and Somarriba (2014). Wild cocoa (*Theobroma cacao*) is an understorey Amazonian specie: it tolerates shade and it could be suited for agroforestry systems.

Ecosystem services these agroforests provide are commonly studied through a management intensification gradient Beer et al. (1997); Steffan-Dewenter et al. (2007); Babin et al. (2009); Tscharntke et al. (2011); Blaser et al. (2018) summed up as a shade rate decreasing along a process of forest trees' cover reduction. Recently, 30–40% shade cover has been identified as being an acceptable trade-off between cocoa production and provisioning of several ecosystem services (i.e. species richness of plants and animals and aboveground carbon (C)) Steffan-Dewenter et al. (2007); Blaser et al. (2018). However, particularly in anthropogenic and specialized agroforestry systems, different shade cover rates would be poorly linked to biodiversity, for example orange trees/cocoa association in Cameroon or leguminous trees/cocoa in Central America. Despite consistent results, shade cover is thus an acute proxy for only few ecosystem services: mainly (i) carbon stocks and (ii) cocoa yields that are logically linked to shade cover. Provisioning of other ecosystem services, such as medicine or agronomic services, may be more dependent on the real nature of associated trees Bos et al. (2007), itself depending on introduction and management strategies by farmers. Agroforestry systems often combine at least three different types of trees: (i) Remnants that were left-alive, *i.e.* saved, during deforestation, (ii) Recruits that have naturally colonized the established agroforest and that have been selected by farmers (iii) Planted trees that farmers intentionally bring to the agroforest Ordonez et al. (2014). As they are the direct outcome of management choices, these three cohorts of trees may constitute a powerful reading grid to analyze the importance of farmers' management choices on the ecosystem services provision in cocoa agroforests.

The south Ivory Coast is a typical post-forest region and producer of first-world cocoa where light agroforestry systems are the most represented in cocoa orchards. As the willingness of a majority of farmers to introduce trees in their fields has been recently highlighted Smith Dumont et al. (2014); Sanial and Ruf (2018), this paper aims to understand the impact of tree introduction management on agroforests' capacities to deliver ecosystem services (carbon, diversity, food, timber, medicine and agronomic support to cacao trees). More specifically, we asked the following questions: (i) what is the magnitude of the effect of the local environmental factors alone, *i.e.* without any management, on ecosystem services provisioning? (ii) What is the relative role of each cohort in provisioning the selected ecosystem services? (iii) For a given ecosystem service, do the cohorts play a complementary role in optimizing the service provisioning? This in-depth analysis builds an understanding of the farmers' rationale behind the wide diversity of cocoa agroforestry systems. This understanding is precious, as cocoa farmers are mainly smallholders and cocoa production is organized at their level. Any policy aiming to enhance ecosystem services provisioning would thus have to deal with farmer's management practices and preferences.

Material and methods

Study area

Data were collected in Ivory Coast between January 2015 and April 2018 on four regions: Akoupé (20 fields), Divo (49 fields), Guéyo (19 fields) and Meagui (49 fields) located along a climatic (from 1200 to 1500 mm annual rainfall), forest vegetation (from semi-deciduous to evergreen forest) and historical (from the old cocoa zone of the East to 1970s' pioneer fronts of the West) gradient (Fig. 1).

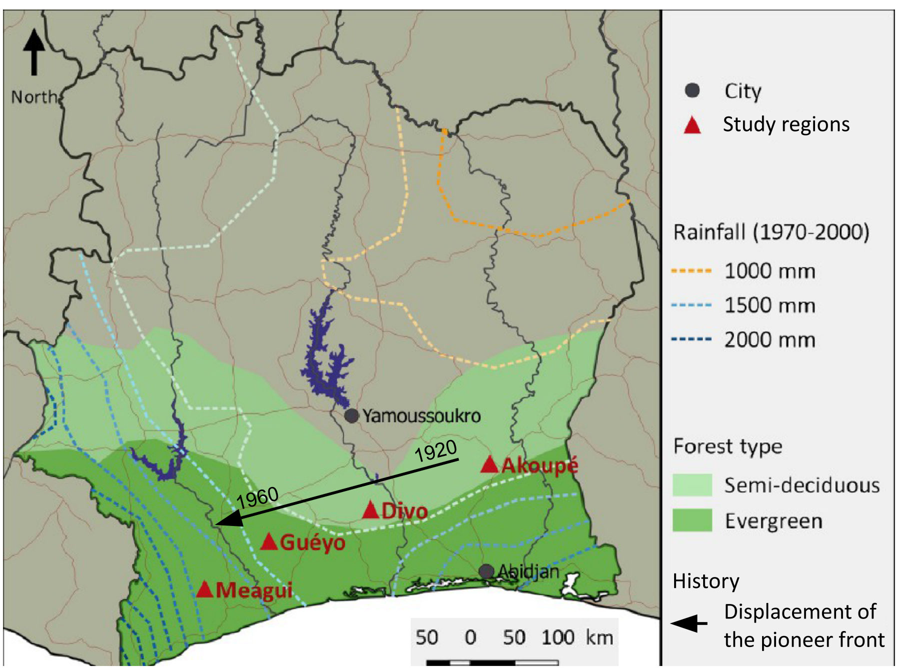

Fig. 1 Location of the study regions along a climatic, forest vegetation and historical gradient

Table 1 Local, landscape and historical environmental variables recorded for the 137 sampled cocoa fields

Category	Variable	Source	Unit	Range
Local	Altitude	GPS	Meters	66–203
	Slope	GPS	%	0.01–10.5
	Soil Carbon	Soil sampling	$g.100g^{-1}$	1.19–1.85
	Soil N	Soil sampling	$g.100g^{-1}$	0.10–0.17
	pH	Soil sampling		5.5–6.75
	Average annual temperature	WorldClim	^{o}C	25.6–26.5
	Precipitation (dryest trimester)	WorldClim	Millimeters	75–139
Landscape	Forest	GPS, Google Earth	% area	0–49
	Marshes	GPS, Google Earth	% area	0–96
	Other perennial crops	GPS, Google Earth	% area	0–38
	Forested fallow	GPS, Google Earth	% area	0-60
	Cocoa	GPS, Google Earth	% area	0.5–95
	Urban	GPS, Google Earth	% of land	0–15
	Annual crops	GPS, Google Earth	% of land	0–33
History	Previous land use	Farmers interviews	Category	–
	Field age	Farmers interviews	years	1–64
	Forest logging	Farmers interviews	Category Logging (1) or not (0)	–

Paradoxically, the old cocoa zone has the youngest plot (10–20 years old) as farmers have already planted two or three times cocoa on the same field and the West has the oldest fields: farmers started planting cocoa in the 1970s'. In each region, fields were located in one to three neighboring villages.

Data collection

Ethnobotanic inventories were established in 137 sampled cocoa fields covering 210 hectares in total. Single field areas ranged between 1 and 2 hectares. Every associated tree that farmers didn't have the intention to fall during next field's weeding was inventoried. Botanical names, introduction mode (*i.e.* cohorts' belonging) and uses were recorded. Species characteristics have been found in Ake Assi (2011) flora (Raunkiaer biological types) and PROTA4U online database (specie habitat; more details in Supplementary material). Diameters at Breast Height (DBH) and heights were measured on a subset of 40 fields. A large set of associated local (7), landscape (7) and historical (3) variables were simultaneously recorded (see Table 1). Each sampled field was GPS mapped to measure its area, average altitude and slope. Fields' history (age, previous land use, timber logging) was recorded during farmers' interviews. Fields' surroundings land use (in a 300m radius) was collected with a GPS field map to accurately discriminate cocoa agroforests, secondary forests and secondary fallows. GPS way-points were then drawn into polygons on Google Earth images. Soil data at local scale were extracted from CNRA

Table 2 Description of the studied cocoa agroforestry systems: age and density of the cocoa plantation and values of the ecosystem services

Variables	Units	Median	[5%;95%]
Cocoa Fields			
Age	years	29	[7;50]
Density	cocoa $trees.ha^{-1}$	30	[4;98]
Ecosystem Services			
Carbon (other trees)	$MgC.ha^{-1}$	8,2	[0.8;30]
Shannon α diversity		2,22	[1.05;2.99]
Food use	$trees.ha^{-1}$	14	[1;57]
Agronomic use	$trees.ha^{-1}$	20	[0;41]
Medicinal use	$trees.ha^{-1}$	2,5	[0;22]
Timber use	$trees.ha^{-1}$	1	[0;10]

database (2015) and local climate data was extracted from Worldclim database Fick and Hijmans (2017) at field scale with a 2.5 minutes resolution (Table 2).

Quantifying ecosystem services

Carbon

DBH and Height measurements were used to estimate the tree Above-Ground Biomass (AGB) using the BIOMASS package Rejou-Mechain (2018). AGB values were then converted into carbon using the 0.48 conversion factor value according to IPCC (2013).

Diversity

We used two measures of diversity α and β, both estimated at order q=1, *i.e.* Shannon diversity Marcon et al. (2014). α diversity was calculated for each field and for each cohort in each field. β diversity was calculated between pairs of cohorts at field scale to assess the cohort complementarity Marcon et al. (2012). All calculations were made using the Entropart package Marcon and Hérault (2015).

Use values

Use values were calculated on four main uses: food, timber, medicine and agronomic services to cocoa trees (fertility, shade, water availability, etc...). Based on farmers declarations and for each use, every tree was coded 0 if the farmer and his household did not use it and 1 if the tree was actually used. Then, for each use, the use value was the number of trees.$ha^{-}1$ coded 1. These values were calculated by cohort and by field. β diversity was also calculated between pairs of cohorts at field scale to assess cohort complementarity in furnishing a given service.

Data analysis

Effect of environmental factors on service provisioning

The ability of the recorded environmental factors to predict the 6 evaluated ecosystem services was assessed under a normal linear modeling framework. For each ecosystem service, the best model was selected using a stepwise selection procedure based on the Akaike Information Criterion. Variance partitioning Legendre and Legendre (2012) was then applied to the final models to decipher the relative importance of historical, landscape and local environment variables in shaping the values of the selected ecosystem services.

The relative role of cohorts in service provisioning

To assess the role of each cohort in provisioning each ecosystem service, we regressed the values of the ecosystem service of interest of a targeted cohort against the summed values for the non-targeted cohorts. In doing so, we were able (i) to rank the cohorts in terms of ecosystem services provisioning and (ii) to test for positive, negative or absent links between the values of a targeted cohort and the two others. In other words, we were able to see if, when a given service is high in a given field for a given cohort, this service is high, low or averaged for the other cohorts in this field.

Cohort complementarities in provisioning services

To evaluate the complementarity of the 3 cohorts in storing carbon, we computed the ratio between the carbon stocked by each individual tree over the maximum carbon stock recorded for the species it belongs to. We used this ratio as a proxy of tree maturity and then compared the distribution of tree maturity between cohorts.

To evaluate the complementarity of the 3 cohorts in the total diversity of the field, we computed the taxonomic β diversity between all pairs of cohorts for each field. We then compared the distribution of taxonomic beta diversity between the 3 possible pairs of cohorts.

To evaluate the complementarity of the 3 cohorts in shaping the use values, we calculated, for each field, the beta diversity of the 4 use values (food, agronomic, medicinal, timber) between pairs of cohorts. For instance, the beta diversity of two cohorts having respectively use values of (10, 10, 0, 0) and (0,0,10,10) respectively is 2 while for use values of (5, 5, 5, 5) and (5, 5, 5, 5) respectively, beta diversity is 1. We then compared the distribution of use values' beta diversity between the 3 possible pairs of cohorts.

Results

In the 137 fields sampled, 6747 trees belonging to 45 different families, 129 genders and 213 species were recorded. Among these trees, 500 are remnants (7.4%), 2472 are recruits (36.6%) and 3771 have been planted (56%). Among the non-exotic forest species (*n* = 185), less than 12% have a strict evergreen forest habitat. 41% can be found in semi-deciduous forest and 32% in dry forests. 30% of all forest species are typical secondary forest species (Tables 3 and 4 in Supplementary material).

Median tree density is 30 trees.ha^{-1}, it varies between 0 and 232. Aboveground C stocked by associated trees also differs a lot from one field to another and ranges between almost no carbon stock to nearly 50 MgC.ha^{-1} with a median of 8.2 MgC.ha^{-1}. Regarding use values, an average field gathered 14 food trees, 2.5 medicinal trees, 0.6 timber trees and farmers expect from 5 trees to support cocoa production (bring soil fertility, shade, maintain soil humidity during dry periods, host ants to struggle against cocoa pests...) but with high variability between fields.

Effects of environmental factors

All together, environmental variables alone explained between 0.02% (timber) and 28% (diversity) of the service provisioning. The local physical environment gather the main group of predictors (Fig. 2). The main environmental variables retained include altitude, average temperature and soil properties. Any historical variable is retained only once (field age for medicinal service). For diversity service, two landscape variables are retained: the proportion of land occupied by cocoa and by other perennial crops (Table 5 in Supplementary material for detailed results). Use values are less linked to environmental variables than α diversity or carbon.

Cohorts and service provisioning

For each service, one cohort stands out for its overwhelming contribution (Fig. 3). Remnants stock the most carbon (Fig. 3A). Even if 35% of fields have known past logging, remnants still stock 54% of the total carbon on average while recruits and planted trees stock 28% and 18% respectively.

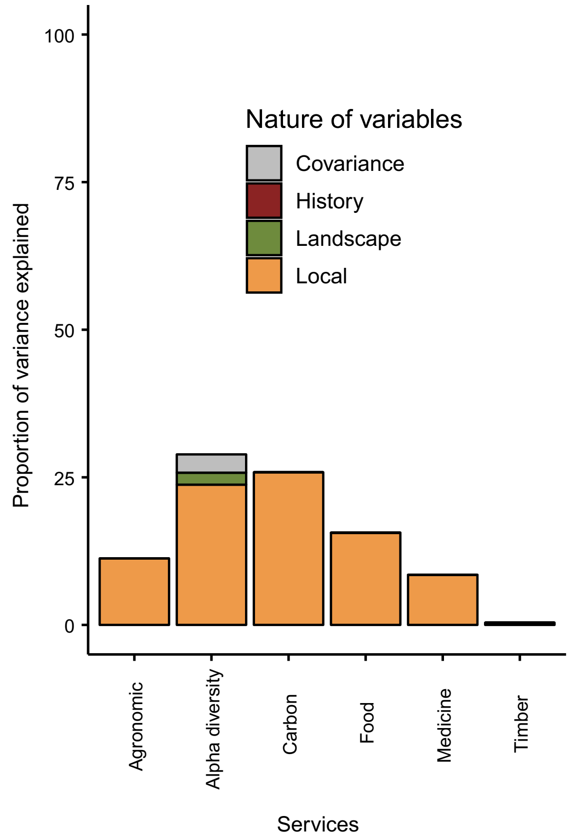

Fig. 2 Proportion of the variance in ecosystem services provisioning explained by local, landscape and history variables

Recruits belong to 173 different species and are the most diverse cohort (remnants present 77 different species and planted ones, 76) (Fig. 3B). On average, they are almost twice more diverse than planted trees and over 3 times more diverse than remnants. Farmers expect that they deliver agronomic services to cocoa trees (Fig. 3D) and are also the main providers of medicinal products (Fig. 3E).

Planted trees have a clear specific function. They are the main providers of food (Fig. 3C). There is a quartet of planted food trees found in almost all cocoa fields: Mango (*Mangifera indica*, *n* = 407), Orange (*Citrus sinensis*, *n* = 907), Avocado (*Persea americana*, *n* = 638) and Kola tree (*Cola nidita*, *n* = 725). These four species represent almost 40% of all inventoried trees.

Finally, farmers find timber wood in recruits and to a lesser extent in remnants (Fig. 3F).

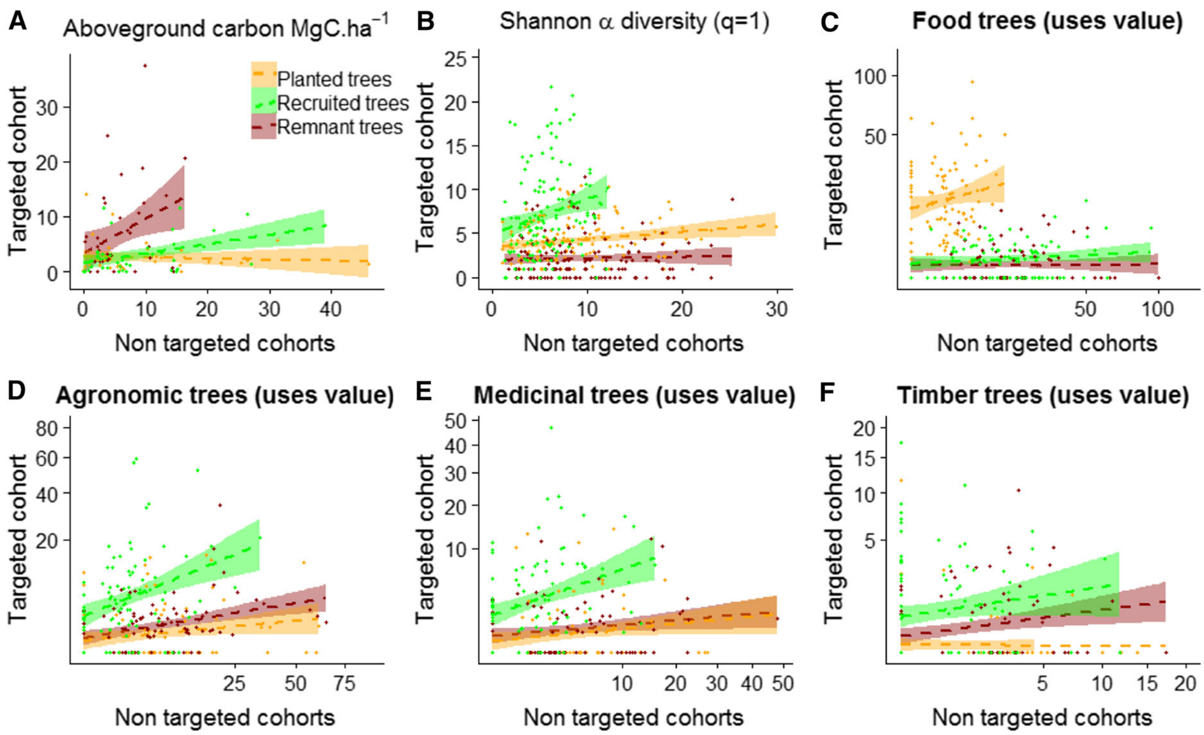

Fig. 3 The importance of tree cohorts to understand service provisioning in cocoa field. The observed values (dots) of a targeted cohort are regressed (dashed lines) against the summed values of the non-targeted cohorts with 95% confidence intervals reported in shaded areas

Complementarities between cohorts in service provisioning

In 96% of fields at least two different cohorts are present and all the 3 cohorts are found in more than 65% of fields.

For carbon provisioning, each cohort brings trees with different stages of maturity (Fig. 4A). Remnants are the most mature (the median ratio of the carbon stocked by each individual tree over the maximum carbon stock recorded for the species it belongs to is 0.45), planted trees are mostly less mature (median ratio of 0.16) and recruits are the least mature (median ratio of 0.05).

For diversity, when each cohort is present, it is complementary to others (Fig. 4B). Planted trees are characterized by 26 species not found in other cohorts and recruits bring 86 original species. These two groups are the most complementary. Remnants bring 14 original species and are highly complementary to planted trees (median β diversity of 1.9). Remnants and recruits are, in comparison with other pairs, less complementary. Nevertheless, the β diversity is, on average 1.8 (Table 7 of the ten most frequent species present in each cohort in Supplementary material). Given that almost 60% of all species in our dataset are present in only one cohort, each cohort brought an original contribution to the agroforestry system. Recruits comprise a lot of shrubs (37%) with some having a pioneer strategy (16%) (Table 6 in Supplementary material). Their habitat is mostly dense humid forests and 42% of these species are secondary forest species (Table 6 in Supplementary material). Remnants are tall tree species without any pioneer species nor any species of secondary forests. Their habitat is dense humid forests. Finally, specific planted species are exotic species, savanna food species quoted beforehand and also medicinal species whose seeds where brought by migrant farmers from their region of origin such as *Nauclea pobeguinii*, *Acacia nilotica*, *Annona senegalensis*, *Detarium senegalense* and *Cassia sieberiana*. Therefore, 42% of specific planted species have a dry forest habitat (Table 6 in Supplementary material).

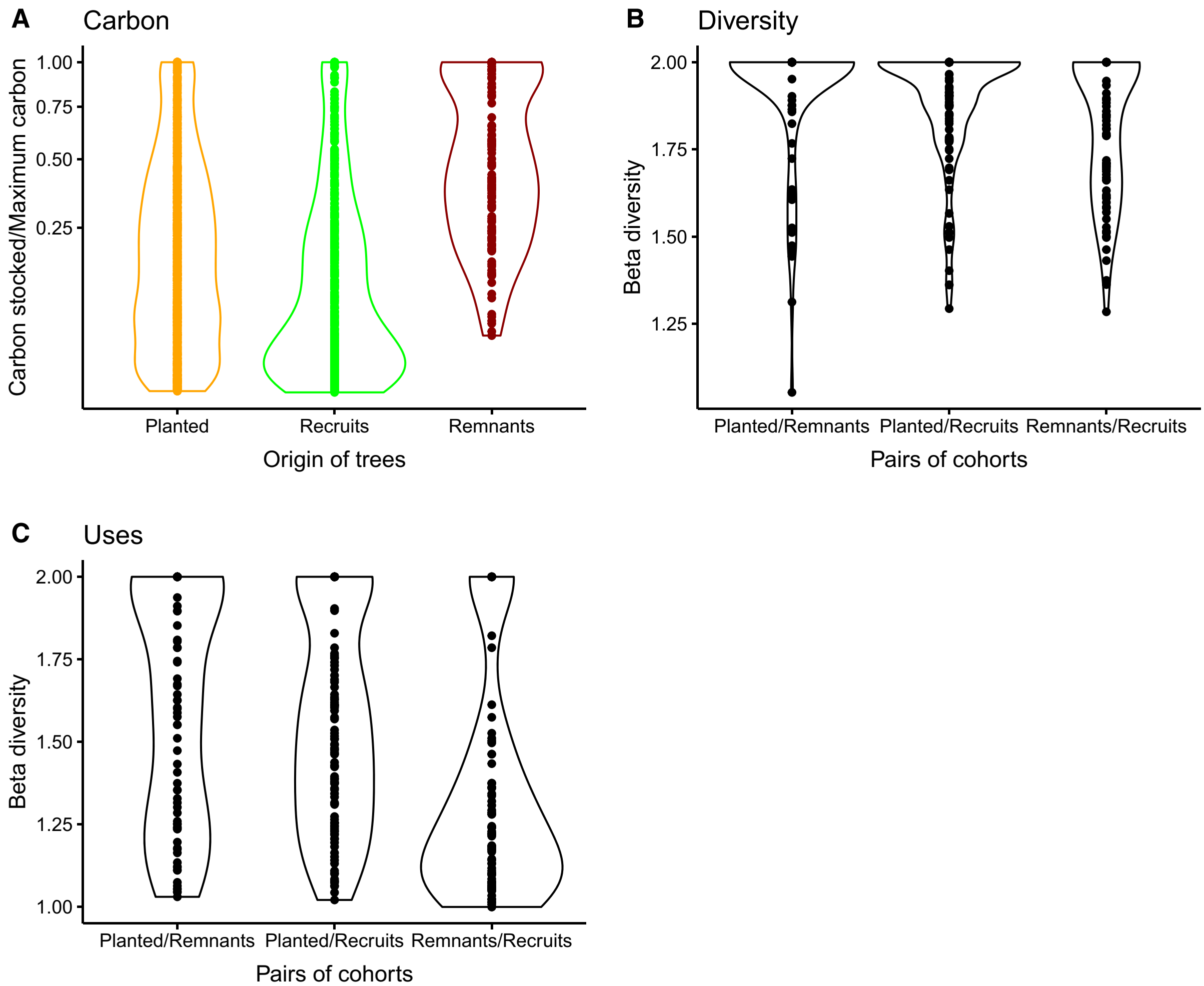

Fig. 4 Testing for cohort complementarities in service provisioning (**A** Dot density of Carbon stocked over maximum carbon for each cohort. **B** Dot density of β diversity between pairs of cohorts. **C** Dot density of use values' β diversity between pairs of cohorts.)

For use values, remnants and recruits are the most similar (Fig. 4C) with a median β diversity of 1.22. When complementarity is high between uses, it is thus due to planted trees. Yet, even if all levels of complementarity are possible between planted trees and other cohorts, the median β diversity is high (1.6 between remnants and planted trees and 1.5 between recruits and planted trees). Even if 67% of fields present at least 3 of the 4 main declared uses, this multifunctionality is not necessarily provided by cohorts' complementarity. Low complementarity is marked in fields where farmers chose specialization towards one single use (22% of fields): either only one cohort is present or different cohorts are present but provide the same use.

Discussion

Our results suggest that Ivorian cocoa agrosystems are so shaped by human management of associated trees (clearing forest, planting trees, selecting recruit, logging) that ecosystem services are weakly linked to environmental variables. In other words, two neighboring fields in similar environmental conditions will provide very different services according to farmers' management approach and whether they have chosen to associate trees to cocoa or not. Socio-economic variables influencing farmers' decisions about trees association (market access, farmers' knowledge about trees, risks mitigation strategy, local governance, non-forest tree products (NFTP) commercial opportunities) are thus more determinant than environmental variables to predict the values of ecosystem services. This "black box" of farmers' decisions is investigated by social sciences. For example, the latter show that land scarcity or risk aversion are determining factors for agroforestry adoption Gyau et al. (2015); Meijer et al. (2015). Recent works in remote sensing have also attempted to integrate large-scale mapping of fine socio-economic data Watmough et al. (2016) in order to upscale small scale results. However, even fine remote sensing could not totally replace fieldwork and data enabling the understanding of farmers' decisions. This understanding is central to predict the values of ecosystem services in cocoa fields at every scale.

Cohorts provide different ecosystem services

Remnants play a major role in carbon storage. Large trees are already known for their significant storage contribution Saj et al. (2013); Andreotti et al. (2018); Bastin et al. (2018). The median values (6.2 MgC.ha^{-1}) have to be compared to carbon stocks of evergreen (144 MgC.ha^{-1}) and semi-deciduous (88 MgC.ha^{-1}) forests in Ivory Coast FAO (2017). Considering that cocoa trees store about 19 MgC.ha^{-1}N'Gbala et al. (2017), the carbon content of the agroforest represents, on average, one fifth of that stocked in the anterior forest. As remnants come from the former old-growth forest, one could expect that their timber would be of interest for farmers. However, this cohort presents a low timber use value (Fig. 3F), meaning that the farmers' intention is not to harvest these trees even if 56% of remnants are listed as commercial species according to Dupuy (1998) list and hold thus a potential in terms of future timber provisioning. If farmers' interest in timber was to increase due to better market conditions and secured tenure rights, farmers could value these remnants as timber trees. However, forest logging by industry often happened without farmers' consent and without any compensation Ruf and Bini (2010). This discourages farmers to introduce timber trees Sanial (2018). Improving tree tenure security could partly fill the gap between potential uses for timber (1262 trees from all cohorts belong to commercial species) and farmers actual declared intentions (464 trees).

Recruits are the most diverse. The range of species offered by recruit is remarkably wider than (i) what is locally available for plantation in cooperative or farmers nurseries (fruit trees, common timber trees, exotic leguminous species) and (ii) what is saved by farmers at the time of clear-cutting. This high diversity may also be an indirect consequence of the uses these trees are selected for: agronomy and medicine. For instance, species that provide good shade (*Terminalia superba*, *Milicia excelsa*, *Terminalia ivorensis*) are different from those used to cure Malaria (*Morinda lucida*, *Alstonia boonei*, *Monodora myristica*). Globally, 48% of recruits are expected to support cocoa production (Fig. 3 plot D). This confirms the importance of agronomic service in the choice of the trees to be preserved by West African farmers Smith Dumont et al. (2014). Even if 81% of fields have at least one agronomic service tree.ha^{-1} in our dataset, the median value is only 5.6 trees.ha^{-1} and this confirms that there is no large-scale re-adoption of high-density traditional agroforestry systems in this country Ruf (2011). Indeed, many farmers seem to seek the optimal balance between limiting dry period impact, enhancing their fields' longevity and getting rid of what they perceive as dis-services from traditional tree-rich agroforests (rodents, black pod) Ruf (2011). In their view, agronomic services are not expected from dense and complex agroforests but from finely selected and well-known recruits. Recruits also bring medicinal resources (Fig. 3E). In our data set, malaria is the main target of these medicinal trees with *Morinda lucida* (n = 223) being the most used (Table 7 in Supplementary material). Its properties are known by both local people and migrant farmers as it grows everywhere from evergreen to Guinean dry forests PROTA4U (2018). In Ivory Coast, where allopathic medicine and drugs are available and consumed in most rural areas, this finding, although already documented by botanists Herzog (1994); Vroh et al. (2015); Adou Yao et al. (2016), confirms that allopathic and traditional medicines still coexist in West African countries Diallo et al. (2006).

Planted trees play an important role in providing food (Fig. 3C) with two distinct strategies: planting food trees (i) when farmers planted cocoa trees or (ii) when former monoculture cocoa fields aged Sanial and Ruf (2018). In the latter case, dying cocoa trees leave open spaces where farmers introduce fruit trees.

In doing so, (i) they keep trunks of cocoa trees from being directly exposed to sunlight, (ii) they alleviate the decrease of cocoa revenues and (iii) they allow the introduction of new cocoa seedlings under the shade of these fruit trees. In fields close to urban market opportunities, these trees may give birth to local, informal and specialized fruit value chains as shown by orange trees in Cameroon Dury and Temple (1999). Elsewhere, food trees are a domestic resource with some local fruit forest trees (*Ricinodendron heudelotii* (n = 84), *Irvingia gabonensis* (n = 7)) coexisting with non-indigeneous species such as Tamarind (*Tamarindus indica*, n = 13), Néré (*Parkia biglobosa*, n = 15) or Baobab (*Adansonia digitata*, n = 9) brought by migrant farmers. Planted trees are mainly introduced by direct seed sowing but some farmers experiment with other strategies, for example taking cuttings, preparing trees seedlings in nurseries or grafting. Sometimes certified cooperatives provide farmers with forest or exotic leguminous seedlings and future transformation of the composition of planted trees may be expected with the development of massive environmental certification standards (UTZ, Rainforest Alliance). However, such initiatives represent for the time only 131 trees of the whole dataset (1.9% of all trees and 3.5% of planted trees). This may be due to (i) the low interest of farmers for trees they might not know or not value, (ii) high mortality rates of seedlings not adapted to the local environment combined with (iii) strong uncertainties on premium benefits Ruf et al. (2013); Sanial and Ruf (2018).

Advantages of diversifying trees' origins

Regarding carbon stocks, each cohort is characterized by a specific maturity level (Fig. 4A), which makes their contribution to the present and future carbon stocks highly complementary. Long term, recruits could take over remnants in carbon stocking N'Guessan et al. (2019). However, given that after one cycle of cocoa (30–50 years) farmers usually grow other perennial crops, this long-term substitution may be challenged in future by oil palm or rubber tree monocultures where associated trees are not usually kept. In other words, trees introduced nowadays might not be remnant trees tomorrow. If this rotation from cocoa to another perennial crop is not changed, the impact of planting new trees may be very little at short-term as compared to encouraging tree preservation at the clearing step. Overcoming this constraint would require halting the classical boom and bust cycles of cocoa leading to the continuous conquest of forest frontiers Ruf (1995) and finding sustainable ways to maintain cocoa fields (and companion trees) in the long-term. The cocoa sector is facing a global challenge to meet growing demand by increasing or maintaining cocoa production without expanding the area under cocoa Vaast and Somarriba (2014). As several authors show, some farmers have already engaged in this transition Smith Dumont et al. (2014); Gyau et al. (2015); Sanial (2015) and adopt rehabilitation practices Jagoret et al. (2017) that could ensure longevity to associated trees and therefore the renewal of carbon stocks.

Regarding species diversity, the overall system diversity is maximised by the coexistence of the 3 cohorts (Fig. 4B). Therefore, our results nuance the hypothesis that farmers will tend to associate trees with an overwhelming presence of low diversity food and commercial trees that will lead to the disappearance of complex agroforests Ruf (2011). Indeed, the predominance of planted trees with a dietary function does not imply low overall diversity of this cohort and the species it brings in the system are original and complementary to the species brought by other cohorts. Moreover, the species brought and planted by migrant farmers enrich the overall diversity. The presence of these dry forest species in the South of Ivory Coast might be of high interest for further research, *i.e* adaptation of these species in different environmental conditions, relative importance of these human-introduced and functionally-different species in future ecosystem trajectories Hérault and Piponiot (2018), behaviour of the enriched system to future climate changes Aguirre-Gutiérrez et al. (2019).

Regarding uses, the rather even distribution of β diversity on uses for planted/remnants and planted/recruits cohorts illustrates the high variety of agroforests' profiles in the studied fields. When beta diversity is high, farmers usually complement the tree species (i) found at the clearing step and (ii) selected in recruits with well-chosen planted trees to get the range of uses they wish. Cohorts' specialization in providing one or several specific uses (Fig. 3) does not mean that they do not participate at all in providing other uses. (i) Food trees, predominantly provided by planted trees, may be found in the recruits. For example, *Irvingia gabonensis* and *Garcinia kola* can't be planted by farmers as they have not been widely domesticated. Indeed, *Garcinia kola* dormancy lasts several months and is rarely available in local nurseries. (ii) Agronomic services, predominantly provided by recruits may sometimes be expected from planted trees. *Gliricidia sepium* is an exotic leguminous tree. (iii) Medicinal trees predominantly provided by recruits may also be planted. Local population has raised medicinal knowledge on exotic species, like *Psidium guayava* or *Mangifera indica*, introduced in West Africa centuries ago. These agronomic and medicinal planted trees are exotic species that farmers can't find in the recruits.

Synthesis and applications

The overriding role of human management on ecosystem services provisioning, the importance of specific cohorts in each service provisioning and the existence of complementarities between cohorts should be taken into consideration to set future policies on environmental services for both local population, global climate mitigation and diversity preservation.

First, in order to enhance timber use potential and favour contractualisation between timber industry and cocoa farmers, securing trees outside forests' tenure through national policy (land and tree rights) and local arrangements' framing (added-value sharing) would provide economic diversification for farmers and timber provision for the industrial sector. If this value chain was to be developed, attention should be given either to preserving remnants from being logged down or to renewing trees. For farmers, a real and strong economic interest to invest in timber might be a sufficient incentive to grant this renewal.

Second, to strengthen complementarities between human-brought (planted) and human-selected (recruits + remnants) trees, private companies providing trees to farmers according to their sustainability commitments could provide them with valued trees different from the ones they already plant or easily find in recruits. By doing so, attention would be given to diversifying the pool of species present in cocoa fields. Providing what farmers can already find in the recruit or what they already plant would merely be a way to increase tree densities in fields. The agroforestry standard watched by certification (i.e. UTZ 2015 standard) is often the sole tree density variable but (i) this might not be optimal to maximize the studied ecosystem services and (ii) this does not recognize the diversity of management type made by local farmers (preserving trees during deforestation, selecting naturally recruits and planting additional trees). These management practices should be recognized, acknowledged and correctly valued by certification programs.

Third, carbon stocks are nowadays almost entirely linked to management choices made at the clearing step. This result questions the efficiency of carbon compensation policies rewarding farmers in function of the carbon stock. Indeed, such reward is an indirect way of acknowledging past (sometimes decades ago) clearing practices. It may lead to a paradoxical policy rewarding some forms of "better" deforestation for carbon storage sake. As preserving remnants while clearing forest is irreplaceable at short and medium terms for large-scale climate mitigation and as aging cocoa fields are currently replaced by rubber and palm monocultures, any policy for carbon sequestration should then be larger than a sector policy on cocoa production. At landscape scale, policy should encourage remnants preservation to ensure carbon stock permanence. Those trees could even feed the cohort of recruits with propagules thus allowing the survival of the species throughout several cycles of perennial crops.

To conclude, reading agroforestry systems through the origins of trees provides an understanding of their capacity to provide ecosystem services that includes farmers management and decisions. Recent works on cocoa agroforestry look for management strategies ensuring trade-offs between ecosystem services Andreotti et al. (2018). The reading grid we propose provides a complementary management indicator to the ones already taken into account in previous studies (i.e. shade rate, cocoa trees density, forest trees density, etc ...).

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Author contributions Elsa Sanial, François Ruf, Michel Mietton, Dominique Louppe and Bruno Hérault conceived the ideas and designed methodology. Elsa Sanial collected the data. Elsa Sanial and Bruno Hérault analysed the data and led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

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References

Adou Yao C, Kpangui KB, Vroh BTA, Ouattara D (2016) Pratiques culturales, valeurs d'usage et perception des paysans des espèces compagnes du cacaoyer dans des agroforêts traditionnelles au centre de la Côte d'Ivoire. Revue d'ethnoécologie 9:2–17

Aguirre-Gutiérrez J, Oliveras I, Rifai S, Fauset S, Adu-Bredu S, Affum-Baffoe K, Baker TR, Feldpausch TR, Gvozdevaite A, Hubau W, Kraft NJB, Lewis SL, Moore S, Niinemets Ü, Peprah T, Phillips OL, Ziemińska K, Enquist B, Malhi Y (2019) Drier tropical forests are susceptible to functional changes in response to a long-term drought. Ecol Lett 22(5):855–865

Aké Assi L (2001) Flore de la Côte-d'Ivoire : catalogue systématique, biogéographie et écologie, I et II. Mémoires de botanique systématique. Conservatoire et Jardin Botanique ville de Genève, Genève, boissiera edition

Aleman JC, Jarzyna MA, Staver AC (2018) Forest extent and deforestation in tropical Africa since 1900. Nat Ecol Evol 2(1):26–33

Andreotti F, Mao Z, Jagoret P, Speelman E, Gary C, Saj S (2018) Exploring management strategies to enhance the provision of ecosystem services in complex smallholder agroforestry systems. Ecol Indic 94:257–265

Babin R, Ten Hoopen G, Cilas C, Enjalric F, Lumaret J-P (2009) Impact of shade on the spatial distribution of Sahlbergella singularis in traditional cocoa agroforests. Agric For Entomol 12(1):69–79

Barlow J, Franca F, Gardner TA, Hicks CC, Lennox GD, Berenguer E, Castello L, Economo EP, Ferreira J, Guénard B, Gontijo Leal C, Isaac V, Lees AC, Parr CL, Wilson SK, Young PJ, Graham NAJ (2018) The future of hyperdiverse tropical ecosystems. Nature 559(7715):517–526

Bastin JF, Rutishauser E, Kellner JR, Saatchi S, Pélissier R, Hérault B, Slik F, Bogaert J, De Cannière C, Marshall AR, Poulsen J, Alvarez-Loyayza P, Andrade A, Angbonga-Basia A, Araujo-Murakami A, Arroyo L, Ayyappan N, de Azevedo CP, Banki O, Barbier N, Barroso JG, Beeckman H, Bitariho R, Boeckx P, Boehning-Gaese K, Brandão H, Brearley FQ, Hockemba Breuer Ndoundou M, Brienen R, Camargo JLC, Campos-Arceiz A, Cassart B, Chave J, Chazdon R, Chuyong G, Clark DB, Clark CJ, Condit R, Honorio Coronado EN, Davidar P, de Haulleville T, Descroix L, Doucet JL, Dourdain A, Droissart V, Duncan T, Silva Espejo J, Espinosa S, Farwig N, Fayolle A, Feldpausch TR, Ferraz A, Fletcher C, Gajapersad K, Gillet JF, do Amaral IL, Gonmadje C, Grogan J, Harris D, Herzog SK, Homeier J, Hubau W, Hubbell SP, Hufkens K, Hurtado J, Kamdem NG, Kearsley E, Kenfack D, Kessler M, Labrière N, Laumonier Y, Laurance S, Laurance WF, Lewis SL, Libalah MB, Ligot G, Lloyd J, Lovejoy TE, Malhi Y, Marimon BS, Marimon Junior BH, Martin EH, Matius P, Meyer V, Mendoza Bautista C, Monteagudo-Mendoza A, Mtui A, Neill D, Parada Gutierrez GA, Pardo G, Parren M, Parthasarathy N, Phillips OL, Pitman NC, Ploton P, Ponette Q, Ramesh BR, Razafimahaimodison JC, Réjou-Méchain M, Rolim SG, Saltos HR, Rossi LMB, Spironello WR, Rovero F, Saner P, Sasaki D, Schulze M, Silveira M, Singh J, Sist P, Sonke B, Soto JD, de Souza CR, Stropp J, Sullivan MJ, Swanepoel B, ter Steege H, Terborgh J, Texier N, Toma T, Valencia R, Valenzuela L, Ferreira LV, Valverde FC, Van Andel TR, Vasque R, Verbeeck H, Vivek P, Vleminckx J, Vos VA, Wagner FH, Warsudi PP, Wortel V, Zagt RJ, Zebaze D (2018) Pan-tropical prediction of forest structure from the largest trees. Global Ecol Biogeogr 27 (11):1366–1383

Beer J, Muschler R, Kass D, Somarriba E (1997) Shade management in coffee and cacao plantations. Agrofor Syst 38(1–3):139–164

Bene J, Beall H, Cote A (1977) Trees, food and people: land management in the tropics. Technical report, CRDI, Ottawa (Canada)

Blaser WJ, Oppong J, Hart SP, Landolt J, Yeboah E, Six J (2018) Climate-smart sustainable agriculture in low-to-intermediate shade agroforests. Nat Sustain 1(5):234–239

Bos M, Steffan-Dewenter I, Tscharntke T (2007) Shade tree management affects fruit abortion, insect pests and pathogens of cacao. Agric Ecosyst Ant Environ 120:201–205

Burgess R, Hansen M, Olken BA, Potapov P, Sieber S (2012) The political economy of deforestation in the tropics. Q J Econ 127(4):1707–1754

de Carvalho CM, Silveira S, La Rovere EL, Iwama AY (2015) Deforested and degraded land available for the expansion of palm oil for biodiesel in the state of Para in the Brazilian Amazon. Renew Sustain Energy Rev 44:867–876

Diallo D, Graz B, Falquet J, Traoré AK, Giani S, Mounkoro PP, Berthé A, Sacko M, Diakité C (2006) Malaria treatment in remote areas of Mali: use of modern and traditional medicines, patient outcome. Trans R Soc Trop Med Hyg 100(6):515–520

Dupuy B (1998) Bases pour une sylviculture en forêt dense tropicale humide africaine. Technical report, FORAFRI-CIRAD, Montpellier

Dury S, Temple L (1999) Diversification of peri-urban small farms toward fruit production in Yaoundé (Cameroon). Consequences for the development process and research. Planetary Garden, pp. 531–535

FAO (2016) State of the world's forests Forests and agriculture: land-use challenges and opportunities. Technical report, FAO, Rome

FAO (2018) The state of the world's forests Required pathways to sustainable development. Technical Report CC BY-NC-SA 3.0 IGO, FAO, Rome

FAO R (2017) Données forestières de base pour la REDD+ en Côte d'Ivoire. Inventaire de la biomasse forestière pour l'estimation des facteurs d'émission. Technical report, Organisation des Nations Unies pour l'alimentation et l'agriculture et Secrétariat exécutif permanent REDD +, Abidjan

Fick S, Hijmans R (2017) Worldclim 2: new 1 km spatial resolution climate surfaces for global land areas. Int J Climatol 37(12):4302–4315

Gibbs HK, Salmon JM (2015) Mapping the world's degraded lands. Appl Geogr 57:12–21

Gibson L, Ming Lee T, Koh LP, Brook BW, Gardner TA, Barlow J, Peres CA, Bradshaw CJA, Laurance WF, Lovejoy TE, Navjot SS (2011) Primary forest are irreplaceable for sustaining tropical biodiversity. Nature 478:378–381

Gyau A, Smoot K, Diby L, Kouamé C (2015) Drivers of tree presence and densities: the case of cocoa agroforestry systems in the Soubré region of Republic of Côte d'Ivoire. Agrofor Syst 89:149–161

Hérault B, Piponiot C (2018) Key drivers of ecosystem recovery after disturbance in a neotropical forest. For Ecosyst 5(1):2

Herzog F (1994) Multipurpose shade trees in coffee and cocoa plantations in Côte d'Ivoire. Agrofor Syst 27:259–267

Jagoret P, Snoeck D, Bouambi E, Todem Ngnogue H, Nyassé S, Saj S (2017) Rehabilitation practices that shape cocoa agroforestry systems in central Cameroon: key management strategies for long-term exploitation. Agrofor Syst 92(5):1185–1199

Kusters K, Ruiz Perez M, De Foresta H, Dietz T, Ros-Tonen M, Belcher B, Manalu P, Nawir A, Wollenberg E (2008) Will agroforests vanish? the case of Damar agroforests in Indonesia. Hum Ecol 36:357–370

Legendre P, Legendre LF (2012) Numerical ecology, vol 24. Elsevier, London

Marcon E, Hérault B (2015) entropart: an R package to measure and partition diversity. J Stat Softw 67(1):1–26

Marcon E, Hérault B, Baraloto C, Lang G (2012) The decomposition of Shannon's entropy and a confidence interval for beta diversity. Oikos 121(4):516–522

Marcon E, Scotti I, Hérault B, Rossi V, Lang G (2014) Generalization of the partitioning of shannon diversity. PloS one 9(3):e90289

Meijer S, Catacutan D, Ajayi O, Sileshi G, Nieuwenhuis M (2015) The role of knowledge, attitudes and perceptions in the uptake of agricultural and agroforestry innovations among smallholder farmers in sub-Saharan Africa. Int J Agric Sustain 13(1):40–54

N'Gbala FN, Martinez Guéi A, Tondoh JE (2017) Carbon stocks in selected tree plantations, as compared with semi-deciduous forests in centre-west Côte d'Ivoire. Agric Ecosyst Environ 239:30–37

N'Guessan AE, N'dja JK, Yao ON, Amani BH, Gouli RG, Piponiot C, Zo-Bi IC, Hérault B (2019) Drivers of biomass recovery in a secondary forested landscape of West Africa. For Ecol Manag 433:325–331

Ordonez J, Luedeling E, Kindt R, Tata H, Jamnadass R, Van Noordwijk M (2014) Constraints and opportunities for tree diversity management along the forest transition curve to achieve multifonctional agriculture. Curr Opinion Environ Sustain 6:54–60

Oswald J (2005) Dynamique des formations agroforestières en Côte d'Ivoire (des années 1980 aux années 2000). Université des Sciences et Technologies de Lille, Lille, Thèse de doctorat en géographie

Pollini J (2009) Agroforestry and the search for alternatives to slash-and-burn cultivation: from technological optimism to a political economy of deforestation. Agric Ecosyst Environ 133:48–60

PROTA4U (2018) PROTA4u

Rejou-Mechain M, Tanguy A, Piponiot C, Chave J, Hérault B (2018) BIOMASS Estimating aboveground biomass and its uncertainty in tropical forests

Ruf F (1995) Booms et crises du cacao: les vertiges de l'or brun. KARTHALA, karthala editions edition

Ruf F (2011) The Myth of complex cocoa agroforests: the case of Ghana. Hum Ecol 39:373–388. https://doi.org/10.1007/s10745-011-9392-0

Ruf F, Bini S (2010) Are cocoa farmers ready for timber? the case of jasikan, ghana. In Technical report

Ruf F, N'dao Y, Lemeilleur S (2013) Certification du cacao, stratégie à hauts risques. Inter-réseaux Développement rural, page 7

Saj S, Jagoret P, Todem Ngogue H (2013) Carbon storage and density dynamics of associated trees in three contrasting Theobroma cacao agroforests of Central Cameroon. Agrofor Syst 87(6):1309–1320

Sanial E (2015) A la recherche de l'ombre: analyse du retour des arbres associés dans les plantations de cacao ivoiriennes. Mémoire de master 2, Université Lyon 3, Lyon

Sanial E (2018) L'appropriation de l'arbre, un nouveau front pour la cacaoculture ivoirienne ? Contraintes techniques, environnementales et foncières. Cahiers agricultures, 27

Sanial E, Ruf F (2018) Is kola the enemy of cocoa? Critical analysis of agroforestry recommendations made to ivorian cocoa farmers. Human Ecology (first online), page 12

Saqib M, Akhtar J, Abbas G, Murtaza G (2019) Enhancing food security and climate change resilience in degraded land areas by resilient crops and agroforestry. In Climate change-resilient agriculture and agroforestry, pp. 283–297. Springer

Smith Dumont E, Gnahoua G, Ohouo L, Sinclair F, Vaast P (2014) Farmers in Côte d'Ivoire value integrating tree diversity in cocoa for the provision of ecosystem services. Agrofor Syst 88(6):1047–1066

Steffan-Dewenter I, Kessler M, Barkmann J, Bos M, BUchori, D., Erasmi, S., Faust, H., Gerold, G., Glenk, K., Gradstein, R., Guhardja, E., Harteveld, M., Hertel, D., Höhn, P., Kappas, M., Köhler, S., Leuschner, C., Maertens, M., Marggraf, R., Migge-Kleian, S., Mogea, J., Pitopang, R., Schaefer, M., Schwarze, S., Sporn, S., Steingrebe, A., Tjitrosoedirdjo, S., Tjitrosoemito, S., Twele, A., Weber, R., Woltmann, L., Zeller, M., and Tscharntke, T. (2007) Tradeoffs between income, biodiversity, and ecosystem functioning during tropical rainforest conversion and agroforestry intensification. Proc Natl Acad Sci USA 104 (12):4973–4978

Taubert F, Fischer R, Groeneveld J, Lehmann S, Muller MS, Rodig E, Wiegand T, Huth A (2018) Global patterns of tropical forest fragmentation. Nature 554:519

Tscharntke T, Clough Y, Bhagwat SA, Buchori D, Faust H, Hertel D, Holscher D, Juhrbandt J, Kessler M, Perfecto I, Scherber C, Schroth G, Veldkamp E, Wanger TC (2011) Multifunctional shade-tree management in tropical agroforestry landscapes: a review. J Appl Ecol 48(3):619–629

Vaast P, Somarriba E (2014) Trade-offs between crop intensification and ecosystem services: the role of agroforestry in cocoa cultivation. Agrofor Syst 88(6):947–956

Vroh BTA, Cissé A, Adou Yao C, Kouamé D, Koffi Kouao J, Kpangui KB, Koffi Béné JC (2015) Relations entre la diversité et la biomasse aérienne des espèces arborescentes dans les agroforêts traditionnelles à base de cacaoyers: cas de la localité de Lakota (Côte d'Ivoire). Afr Crop Sci J 23(4):311–326

Watmough GR, Atkinson PM, Saikia A, Hutton CW (2016) Understanding the evidence base for poverty-environment relationships using remotely sensed satellite data: an example from Assam, India. World Dev 78:188–203