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Co-benefits and trade-offs of agroforestry for climate change mitigation and other sustainability goals in West Africa

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ABSTRACT

Agroforestry is a land management practice where trees are grown around or among crops or pastureland. This integration of agriculture and forestry is frequently seen as an option that can secure food security and co-deliver a range of environmental benefits. However, quantitative studies simultaneously integrating multiple aspects of agroforestry are rare. Focusing on four sustainability goals, namely adaptation to climate change, biodiversity conservation, climate change mitigation and rural development, this study investigated co-benefits and adverse side-effects of shaded agroforests above cocoa, coffee, oil palm, banana and citrus plantations in tropical humid West Africa. Time series of remote sensing land cover datasets were used to quantify and map recent land cover transitions in the region, and a field study in 25 agroforestry plots in Togo provided biomass carbon measurements in over 3000 trees, in addition to local farmers interviews. Estimates of theoretical agroforestry expansion and associated carbon sequestration potential in the region were compared to regional emissions from fossil fuels and deforestation. We found that about 1.6 Mha of losses in evergreen forests occurred between 1992 and 2015 (corresponding to 17% of the forest area originally present in 1992), while agricultural areas increased by 2.4 Mha (+5% relative to 1992). On average, trees in the studied agroforestry plots store 83.7 ± 7.0 t C/ha. We found synergies between rural development and adaptation benefits, no clear relationship between biodiversity and carbon storage, and a trade-off between high carbon stocks and crop yields. This trade-off can be minimized with an optimal management of agroforestry by using a mix of tree species that store medium carbon stocks and can enhance yields, soil fertility and climate resilience. In general, plant functional diversity, i.e. a balanced mix of shade trees, fruit trees, palms and bananas, emerged as a key feature of successful agroforestry systems. Besides, agroforestry trees co-products are reported as an additional, diversified source of income for local farmers. A large-scale deployment of agroforestry over seven countries in West Africa can sequester up to 135 Mt CO_2/year over two decades, corresponding to about 166% of the carbon emissions from fossil fuels and deforestation in the region. Overall, agroforestry practices in tropical humid West Africa offer multiple-win solutions that are relevant to address major local and global environmental challenges. Increasing cooperation among local farmer communities, national authorities, and international organizations are instrumental to overcome the barriers for a future expansion of agroforestry systems in the region.

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1. Introduction

Today, 49% of the world's land surface is under agricultural or pastoral use (IPCC, 2019). In developing countries, low-input, traditional agriculture has sustained livelihoods for many decades (Altieri and Nicholls, 2017), but it is now posing serious threats to human welfare and ecosystems in the doom of demographic boom and climate change. In Africa, yields of maize and rice have been stagnating for years, triggering concerns about food and income security (Garrity et al., 2010; Ray et al., 2012). Consequently, livelihoods can only be maintained through cropland expansion at the expense of natural land, threatening biodiversity and exacerbating climate change, which is in turn predicted to negatively affect crop production (Babiker et al., 2018; Lobell et al., 2011; Zhao et al., 2017).

At global scale, climate change will affect food security by decreasing both food availability and accessibility (FAO, 2018). In particular, tropical rainfed agriculture is vulnerable to heat and water stress and will suffer from reduced growing seasons (Beddington et al., 2012; FAO, 2018). Climate change also exacerbates occurrence and severity of extreme climatic events, which destabilize food prices (Beddington et al., 2012). Combined with poverty, food prices volatility hampers food accessibility, which is the major cause for the undernourishment (Chappell and LaValle, 2011; FAO, 2018; Foley et al., 2011). Mitigation and adaptation goals must be pursued jointly: if no mitigation action is taken in the agricultural sector, increased food production will significantly strengthen climate change, whereas yields are predicted to shrink in vulnerable areas unless adaptation actions are undertaken – adaptation being increasingly jeopardized as climate change effects are stronger (Beddington et al., 2012).

In West Africa, the Upper Guinean Forests, stretching across Guinea, Sierra Leone, Liberia, Côte d'Ivoire, Ghana, Togo and Benin, store 5.8 Gt of carbon, sustain livelihoods of up to 92.5 million people, provide regulating ecosystem services and host a particularly rich biodiversity, from the chimpanzee (*Pan troglodytes*) in Liberia to the Ukamia reed frog (*Hyperolius torrentis*) in Ghana (IUCN, 2015; Junker et al., 2015; Mayaux et al., 2013; Norris et al., 2010). The Upper Guinean Forests have undergone extremely rapid deforestation rates since colonial period (Gornitz, 1985) and both national estimates and remote sensing studies show that deforestation is still ongoing (Achard et al., 2014; Hansen et al., 2013; ITTO, 2011; Mayaux et al., 2013). The main driver is the expansion of commercial crops, especially cocoa and oil palm (Asubonteng et al., 2018; Barima et al., 2016; Koglo et al., 2019). Since forest soils are usually more fertile, it is common for farmers to establish commercial crops on forest land (Barima et al., 2016). As young plantations' productivity is high but declines after a few decades (Tscharntke et al., 2011), new plantations are progressively established at the forest frontier (Tutu Benefoh et al., 2018). State economic incentives favoring commercial crops and poor enforcement of protected areas indirectly stimulate this land transition pattern (Barima et al., 2016; Koglo et al., 2019).

As an inexpensive practice for sustainable intensification of agriculture, agroforestry, or the management of trees on farm, has been advocated for decades (Garrity et al., 2010; Mbow et al., 2014b; Waldron et al., 2017). Conservation or establishment of a tree canopy above shade-tolerant crops usually brings many benefits: soil carbon enrichment, biological nitrogen fixation, tighter nutrient and water cycle, favorable microclimate, pest outbreak prevention, yield of valuable tree products, habitat for biodiversity, higher resilience to climate variability and ultimately carbon sequestration (Johns, 1999; Jose, 2009; Kumar, 2016; Lin, 2007; Méndez et al., 2010; Nair et al., 2009; Pumariño et al., 2015; Souza et al., 2012; Tscharntke et al., 2011).

Despite the large agroforestry carbon sequestration potential (CSP), relatively few studies investigated possible trade-offs using field data. Furthermore, studies on West African shaded agroforests mostly focus on CSP and tree biodiversity (Asase and Tetteh, 2016; Dawoe et al., 2016), while local policy-makers usually prioritize rural development and adaptation goals (Mbow et al., 2014b). This paper uses a combination of approaches based on satellite retrievals, field measurements, and interviews with local farmers to quantitatively assess co-benefits and trade-offs of shaded agroforests for multiple sustainability goals that are relevant for the West African tropical humid region: adaptation to climate change, biodiversity conservation, climate change mitigation and rural development.

To characterize patterns and trends of land-use changes at regional level, differences in high-resolution (300 m) maps of land cover between 1992 and 2015 were analyzed. Recent land-use transitions were quantified, mapped and synthetized in clusters. Field measurement are gathered from 25 plots cultivated with cocoa, coffee, oil palm, banana or citrus under a shade tree canopy established by farmers with support from a local non-governmental organization, Association pour la Promotion des arbres fertilitaires, de l'agroforesterie et de la foresterie (APAF), in Togo tropical humid region. Carbon stocks in the agroforestry trees were computed and information on farm biodiversity, adaptation potential and rural development was obtained from direct interviews with local farmers. Finally, this information was used to estimate potentials for a scale-up of shaded agroforests' CSP in this region.

2. Methods

2.1. Satellite data acquisition and processing

The Climate Change Initiative (CCI) project of the European Space Agency (ESA) provides annual maps of Land Cover (LC) from 1992 to 2015, at a 300 m resolution (Defourny et al., 2017). Land cover is described by 37 classes compatible with the

United Nations Land Cover Classification System (UN-LCCS) (Liu et al., 2018). Land cover change is detected at 1 km scale after two years of consecutive change and remapped at 300 m scale to build annual maps (Defourny et al., 2017). This dataset is well suited for quantification and mapping of land-use changes (Li et al., 2018).

Data can be downloaded as a matrix of land cover classes. Each entry represents a square of 300 m by 300 m, i.e. an area of 0.9 ha. A rectangle map ranging from longitude −14.4918°−2.7086° and latitude 4.3334°−11.0688° (Fig. 1) represents our study area, and the corresponding data were downloaded and analyzed. The 37 land cover classes of the UN-LCCS were aggregated into the 9 generic IPCC land-cover classes according to a correspondence table (Defourny et al., 2017). The 9 IPCC classes are: agriculture, forest, grassland, wetland, settlement, shrubland, sparse vegetation, bare area and water. To more accurately describe the land-use transitions, the forest class was further disaggregated into evergreen (CCI-LC class 50), deciduous open (CCI-LC class 62) and forest non otherwise specified. Agricultural land in the South can be mainly associated to cropland, while it is better described by a mosaic of pasturelands and croplands in the North. Shrublands here refer to savannahs. Recent land-use changes are estimated by computing the difference between 1992 and 2015 land cover maps.

2.2. Field study site

The field study took place in the Plateau region in South-Western Togo. This region has a tropical Guinean climate characterized by a dry season from November to January, a small rainy season from February to April and a big rainy season from May to October. The closest weather station, Atakpamé, has a mean annual precipitation of 1364 mm and mean annual temperatures between 21 °C and 31 °C. Soils are clayey vertisols with a deep arable layer, some being degraded by erosion and continuous monoculture without fertilizers. Togolese agriculture is characterized by the predominance of smallholder rainfed farms with a low level of inputs. Cocoa and coffee cultivation are incentivized by the government, but poor management practices and dwindling prices often result in low monetary returns for the farmers. Togo is world's 15th cocoa producer, but 56% of global production is concentrated in neighboring Côte d'Ivoire and Ghana (FAOSTAT, 2017). There is no primary forest in Togo, and Plateau region's hilly landscapes are characterized by mosaics of settlements, herbaceous crops, perennial crops, fallows and new growth secondary forest.

For the sake of consistency and accuracy, only one form of agroforestry, *shaded agroforests*, was studied. Shaded agroforests can be described as multistrata systems where a perennial crop (small tree, shrub, palm or stem, usually less than 3 m high) is grown under a canopy of trees (10−40 m high) preserved from natural vegetation or introduced on field. *Multistrata* refers to the different vegetation layers: cash crops (cocoa, coffee), companion crops (oil palm, banana), herbaceous crops (taro), lianas (yam) and trees (Fig. 1d). Each plot was thus characterized by a main crop which was primarily grown by the farmer, and by an agroforestry component including trees and companion crops. Herbaceous plants and lianas were excluded from the analysis.

The field study was conducted in November and December 2018 in the agroforestry fields established by a local NGO, APAF, in two different zones, Kpalimé and Badou. Agroforestry practices were introduced between 2000 and 2004 on old cocoa or coffee plantations in cooperation with the farmers owning the plots. Before APAF intervention, plots had little shade, coming mainly from fruit trees (banana, oil palm, orange, kola nut) or trees that naturally grew on the field (ficus, kapok). APAF promoted the establishment of multistrata structures using trees with additional co-benefits: timber trees (African mahogany, iroko, wawa) and nitrogen-fixing trees (*Albizia spp.*). Using both seedlings provided by APAF and their usual plantlets,

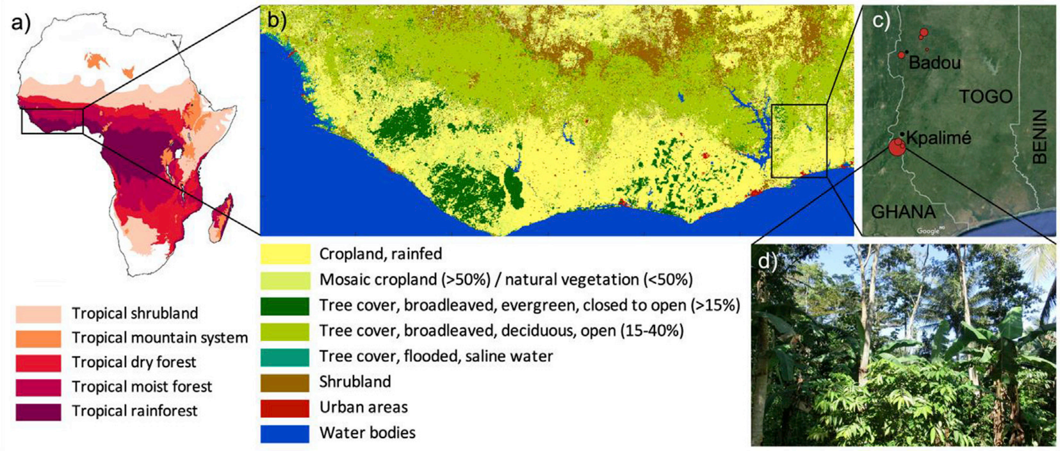

Fig. 1. Localization of the area of interest. **a** Global Ecological Zones over Africa, modified from FAO (2012); our study area mainly includes tropical moist forest and tropical rainforest, which in this paper is generically referred to as *tropical humid West Africa*. **b** CCI-LC dataset for the study area, in year 2015, with the major land cover types. **c** Google Earth satellite view of the plots for the field measurements; the size of the dot is proportional to the number of the plots sampled in that location (the smallest dot indicates 1 plot, the largest 10 plots). **d** Structure of a shaded agroforestry plot: cocoa trees under a diverse canopy of banana stems, palms and shade trees (own picture).

farmers established combinations of species that vary in each plot, with a tree density higher than usual fields (150 trees per hectare on average, excluding banana and oil palm).

2.3. Sampling method

25 plots were sampled, covering a total area of 12.4 ha. Plots were arbitrarily selected by APAF in the vicinity of Kpalimé and Badou (Fig. 1c). Detailed plot description is given in the Online Resource. In each plot, carbon stocks were measured, and semi-structured interviews were conducted with the farmers in order to investigate perceived benefits of agroforestry regarding production and income, biodiversity and resilience.

The main crop of the plot, as indicated by the farmer, was either cacao (15 plots), coffee (8 plots), oil palm (1 plot), banana (2 plots) or citrus (1 plot). The number of sampled plots differs for each type of main crop, which is representative of actual repartition within APAF fields. We did not distinguish between sweet banana and plantain and we aggregated all citrus species, although mostly orange trees were identified on field. Age of plantation was obtained from APAF records; all plantations were between 15 and 20 years old. Plot area was recorded with a GPS device (Garmin GPSMAP 62) by walking along boundaries. Agroforestry trees and companion crops' biomass was obtained in a non-destructive way using allometric equations according to the World Agroforestry Center methodology (Hairiah et al., 2010). In the whole plot, all plants pertaining to the agroforestry component were identified and measured: diameter at breast height (1.3 m above ground) was recorded for trees and bananas, while stem height was collected for palms. Trees with diameter below 5 cm and palms with stem below 20 cm were excluded. Species were identified, when possible, based on APAF technicians' knowledge and using local names. Sampled individuals were painted with a red mark to avoid double-counting.

2.4. Carbon stocks calculation

Tree diameter measurements were used to compute aboveground biomass (AGB) using the pan-tropical allometric model of Chave et al. (2005). The specific equation for moist forests was applied to all trees (Table 1). Average wood density values per species were taken from the Tree Functional Attributes and Ecological Database (World Agroforestry Center, n.d.). When a species was not found in the record, average value for the genera was used. When a tree could not be identified, weighted average wood density of all other tree individuals was used ($\rho_{average} = 0.529$ g/cm^3). AGB of oil palms and bananas was computed using species-specific equations (Table 1). Belowground biomass (BGB) was calculated from ABG using the model from Cairns et al. (1997) (Table 1). Total biomass was converted into carbon stocks using the default value of 0.47 for carbon fraction of biomass (Aalde et al., 2006). Carbon stocks were computed at tree, plot and whole sample area level using Microsoft Excel and the uncertainty lying in these results was estimated based on Taylor series expansion (see Online Resource).

2.5. Assessment of co-benefits and tradeoffs

Farmers' interviews were conducted in Ewé, audio-recorded with the permission of farmers and translated prior to analysis. They allowed to qualitatively assess benefits of agroforestry: yields and co-products, microclimate effects and wildlife observed on fields. It was not possible to compare main crop yield before and after agroforestry establishment, because interviewed farmers often did not keep track accurately of annual yields or were reluctant to communicate their profits. Using these inputs, co-benefits of each plot were scored relative to four sustainability goals: Adaptation to climate change (A), Biodiversity conservation (B), Climate change mitigation (C) and rural Development (D). The scoring method was inspired by the Management Index proposed by Wade et al. (2010). Scores were not compared to a baseline but rather normalized to their maximum in order to allow comparison between plots.

Farmer's perception of whether shade trees would attenuate microclimate extremes (temperature, wind, drought), limit erosion or allow degraded land rehabilitation were used to derive the adaptation score. Hence, it is mostly qualitative. The biodiversity score includes a mix of quantitative estimates, such as the number of tree species per hectare, percentage of native tree species, Shannon index for tree diversity (computed based on field survey), in addition to the number of fauna species reported by the farmers (see Online Resource). Plot's carbon stocks were taken as a proxy for climate change mitigation benefits. Rural development score took into account productivity, diversification and sustainability. A combination of indicators for main crop and co-product yields is essential to analyze agroforestry performance, since co-products revenues

Table 1

Allometric equations used to compute total biomass on field. AGB and BGB are expressed in kg; D (diameter at breast height) in cm; H (stem height) in m; ρ (wood density) in g/cm^3.

Model	Equation		Source
AGB, pan-tropical model	$AGB = \rho \exp(-1.499 + 2.148 \ln(D) + 0.207 \ln(D)^2 - 0.0281 \ln(D)^3)$	(1)	Chave et al. (2005)
AGB, oil palm	$AGB = 0.1839\, H^{0.766}$	(2)	Khasanah et al. (2015)
AGB, banana	$AGB = 0.0001\, (\pi D)^{2.33}$	(3)	Nyombi et al. (2009)
BGB	$BGB = \exp(-1.0587 + 0.8836 \ln(AGB))$	(4)	Cairns et al. (1997)

are a primary factor of motivation for agroforestry adoption (Magcale-Macandog et al., 2006) and offset possible main crop yield decrease to result in higher overall farm income (Rahman et al., 2016). Productivity was assessed according to farmers' perception of yield trends. Income from agroforestry products (fruits, timber wood and fuelwood) was used as a proxy for diversification. Fruit and timber trees were counted in each plot (see details in Online Resource). For fruit trees, theoretical income was obtained by multiplying yearly yields by local prices. For timber trees, the value of a standing 20-year-old tree was used to get a potential yearly income. For fuelwood, annual consumption was assumed to be steadily provided by a 1-ha agroforestry field, so that yearly savings were normalized to plot size. Finally, farmers' perception of trends in soil fertility was used to assess agricultural system's sustainability over time.

For each sustainability goal A, B, C, and D, intermediary scores were normalized from 0 to 1 and averaged to get final goal scores. Total co-benefits score is obtained by summing up goal scores, ranging from 0 to 4, but it could be adjusted to specific priorities by weighting them differently. Score computing methodology is summarized in the Online Resource.

3. Results and discussion

3.1. Land-use transitions

Out of the entire study area (135 Mha), a total of 12 Mha (9%) changed the type of land cover between 1992 and 2015 (Fig. 2a). The main transition was open deciduous forest regrowth at the expenses of shrublands and savannahs (2.5 Mha). Savannahs were also converted to agricultural land over 1.4 Mha and have undergone the greatest loss in area (4.2 Mha). Evergreen forests declined by 1.6 Mha or 17% of their original extent in 1992, which is equivalent to a mean deforestation rate of 0.72% per year (Fig. 2a). This is in line with results from remote sensing studies for the period 1990–2010 (Achard et al.,

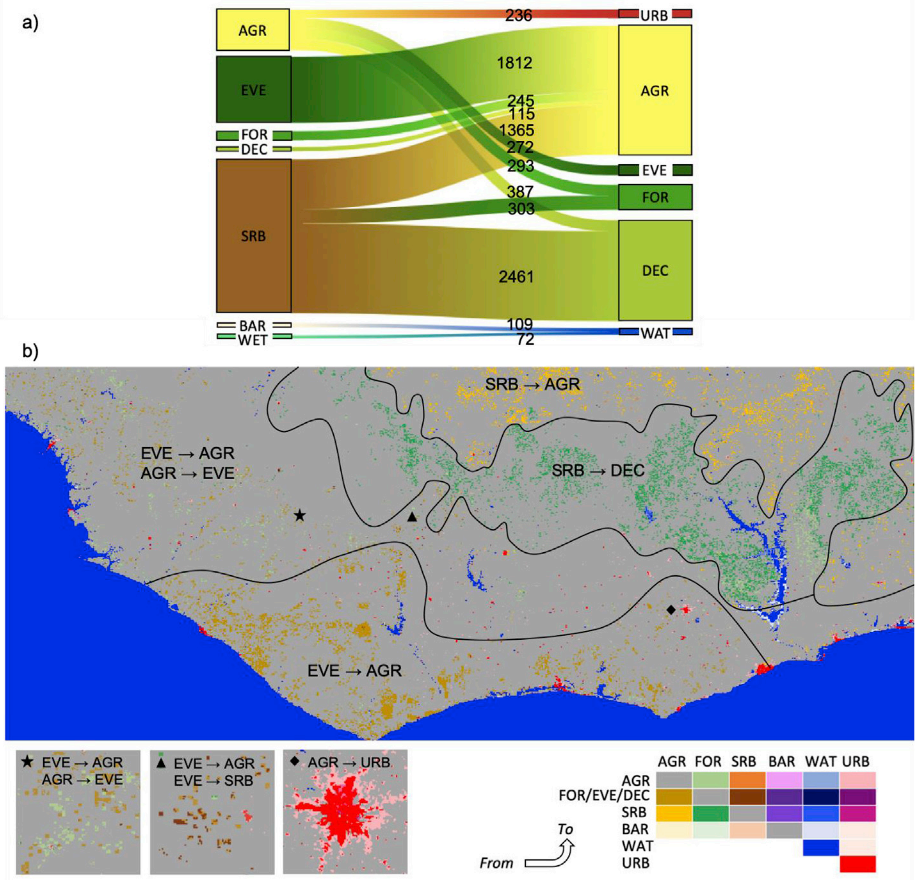

Fig. 2. Land-use transitions in West Africa between 1992 and 2015. **a** Sankey diagram of the main land-use changes using ESA CCI-LC color codes. Units in 1000 ha **b** Geographical mapping of the main land-use transitions. Urban areas and water bodies are also shown. For the three black symbols (triangle, star and diamond) in the large map, a zoom of the transitions is reported in the sub-panels. Legend displays the colors used in the map in a matrix way (transition from lines to columns). Legend: AGR = Agriculture, GRA = Grassland, WET = Wetland, URB = Urban, SRB = Shrub, BAR = Bare, WAT = Water, EVE = Tree cover, evergreen, DEC = Tree cover, deciduous, FOR = Forest non otherwise specified.

2014; Mayaux et al., 2013). Agricultural land has extended over savannahs and forests (mainly evergreen) on 3.4 Mha and factoring out agricultural losses due to urban and forest expansion, its net increase is 2.4 Mha.

These land transitions have a clear geographical pattern (Fig. 2b). Along the coastal belt, from Liberia to Ghana, deforestation (conversion of forest to cropland) is the dominant transition. In Northern Ghana and Togo, savannahs were converted to agricultural land. On the other hand, in the open deciduous forest belt spanning across Guinea, Ivory Coast, Ghana, Togo and Benin, shrublands transitioned to forest, indicating secondary forest regrowth. Finally, an intermediate zone can be distinguished in Guinea, Sierra Leone and Ivory Coast, where a mix of cropland expansion and abandonment occurred (Fig. 2b, sub-panels). More generally, deforestation coupled to forest degradation as well as urban expansion over cropland occurred throughout the study zone (Fig. 2b, sub-panels).

These land transitions show the potential and make the case for agroforestry. The land transition, i.e. shrubland regrowth to open deciduous forest, shows that climatic conditions are currently favorable to tree growth at the forest-savannah transition. While this is valid for present and short-term conditions and is more uncertain for the long-term, the study area (excluding its Northernmost part) is suitable to agroforestry practices (Asase and Tetteh, 2016; Duguma et al., 2001; Smith Dumont et al., 2014; Vaast and Somarriba, 2014). On the other hand, massive forest clearing throughout the study zone lead to ecosystem degradation and to increased pressure on forest remnants. Agroforestry establishment could reconnect forest patches that can be identified in Ghana and Côte d'Ivoire (Fig. 1b) and act as buffers around wild areas to reduce forest edge effects (Jose, 2009).

Regarding the 25 sampled plots in Togo, 16% of them are within pixels that had a land-use transition between 1992 and 2015 (conversion from shrubland or tree-crop mosaic to open deciduous tree cover). 64% of the plots are correctly classified with the ESA-CCI LC dataset as cropland, while the remaining are classified as open deciduous tree cover. All the plots classified as forest are located in the Northern area, near Badou, and plots near Kpalimé are classified as cropland. However, average plot size is 0.5 ha, whereas ESA-CCI LC pixel size is 0.9 ha, so a direct comparison is difficult, and it is likely that land cover type of the areas surrounding plots is responsible for the land cover class attributed to them.

3.2. *Carbon stocks*

The average carbon stock of agroforestry trees in the sampled plots is 83.7 ± 7.0 t C/ha, including above and belowground biomass (the uncertainty range represents the 95% confidence interval). This value is higher than previous pan-tropical estimates reported by Mutuo et al. (2005) but lower than average estimates from Albrecht and Kandji (2003). Carbon stocks exhibit a large variability across plots, ranging from 21 to 224 t C/ha (Fig. 3a). Error margin is particularly large for plots featuring huge trees such as kapoks (*Ceiba pentandra*), and this explains the large uncertainty range associated with a specific plot (e.g., number 17 in Fig. 3a). Among agroforestry trees, shade trees hold larger carbon stocks (830 kg C/tree) than fruit trees (210 kg C/tree) or oil palms (101 kg C/tree, Fig. 3b). Contribution of banana stems was found negligible (0.04% of the total carbon stocks), despite their abundance on field. Carbon stock of the agroforestry component varies slightly (6%) between coffee and cocoa plots (Fig. 3c) but is much lower for oil palm plots since these crops require more land, so that less trees are introduced on field. The low carbon stock held in banana plots indicates high trade-offs between shade and productivity for this crop, so that farmers prefer a more open canopy.

3.3. *Co-benefits and trade-offs*

Farmers' interviews highlight the importance of the co-products from agroforestry trees to smallholders. Fuelwood was home consumed and sold, so that agroforestry alleviates pressure on forests not only at farm-scale, but also at village-scale. Timber wood represented a growing capital highly valued by farmers. However, fruits (excluding banana and oil palm nuts) were of little importance: they were seldom home consumed and had a low price.

Agroforestry was reported to mitigate land degradation. A degraded plot that could not support coffee production was planted with shade trees to enrich soil in carbon and nitrogen, so that a coffee plantation could be established under the canopy after a few years. Another plot where cocoa yields declined was left to secondary forest regrowth instead of being converted to staple crop production. Adverse side-effects were also reported, including competition between agroforestry trees and main crop and diseases affecting trees. Many farmers noted an increased presence of wild animal species such as rats or grasscutters, which were hunted and eaten or sold as bushmeat. Finally, farmers had the perception that agroforestry trees, and especially nitrogen-fixing trees, increased soil fertility. However, a recent study suggested that although soil N and C content are significantly higher under shade tree canopy, these parameters do not show differences at plot level when shade cover increases, so that overall benefits on yields are uncertain (Blaser et al., 2017).

Overall, quantified co-benefits of agroforestry vary 4.5-fold across plots (Fig. 4a). Biodiversity scores are evenly distributed while adaptation benefits are very scattered. Plots can be grouped in 3 categories (Fig. 4b): (α) plots with high carbon stocks but poor rural development and adaptation potential, (β) plots with relatively high carbon stocks combined with a good rural development and adaptation potential, and (γ) plots that score low in all categories. Thus, a synergy emerges between rural development benefits and adaptation benefits.

No clear relationship is found between biodiversity and carbon storage: biodiversity benefits are nearly constant at high carbon stocks, but they can also be large at low carbon stocks (Fig. 4b). This is in contradiction with studies investigating possible synergies between agroforestry and biodiversity conservation (Middendorp et al., 2018; Wade et al., 2010), but it

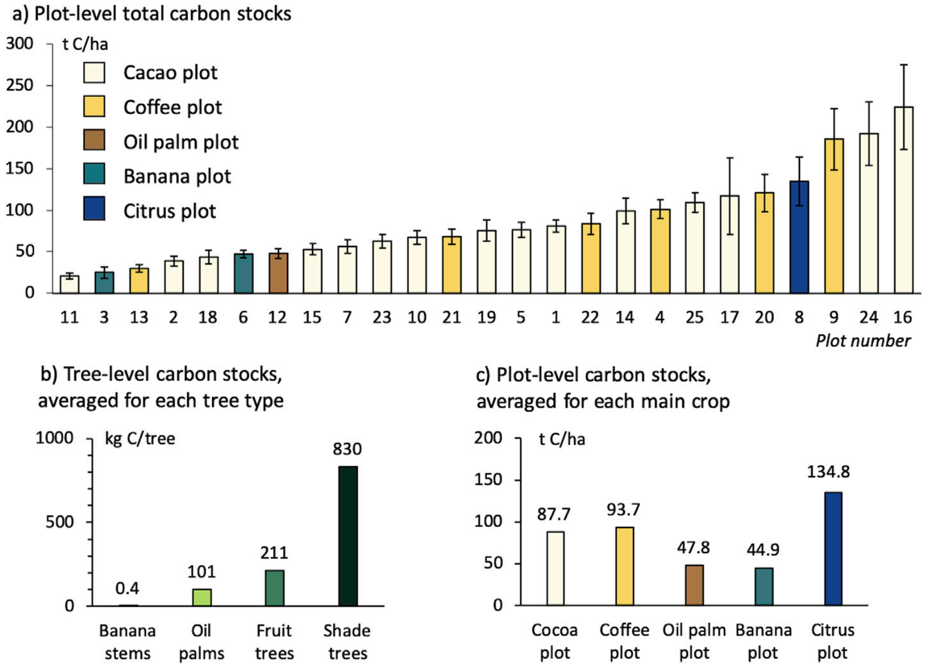

Fig. 3. Carbon stocks from above- and belowground biomass in agroforestry trees and companion plants. **a** Total carbon stocks in each plot. Bars represent uncertainty associated with computed values, showing 95% confidence intervals. **b** Average per tree sorted by tree type. **c** Average per plot sorted by main crop.

aligns with studies arguing that biodiversity does not show immediate responses to new tree planting (Betts et al., 2017; Lautenbach et al., 2017). However, biodiversity conservation benefits, such as species richness and ecological services, cannot be reasonably evaluated on 0.5-ha plots and would benefit from a landscape-level approach, where agroforestry establishment would increase connectivity between forest and agricultural patches and improve landscape matrix (Barrios et al., 2018).

Plots with high carbon stocks tend to have less rural development benefits (in terms of incomes from crop yields): this trade-off, already reported by other studies (Middendorp et al., 2018; Steffan-Dewenter et al., 2007; Wade et al., 2010), underlines the conflicting goals of international policies for climate change mitigation and local farmers regarding agroforestry (i.e., maximize the use of land for carbon storage against crop productivity). In Africa, it is suggested that food security and rural development goals associated with adaptation strategies should be prioritized over climate change mitigation objectives (Mbow et al., 2014a). Nonetheless, cluster (β) seems to indicate a multiple-win situation, where trade-offs are minimized, and all goals are achieved at a medium to high level. Such a form of agroforestry is highly beneficial to both farmers (fostering self-sufficiency and resilience to climate change) and the environment (storing on average 80.4 t C/ha in biomass and hosting various tree species).

In order to explain differences in co-benefit scores across the plots, influence of shade composition, measured as percentage of each tree category (shade tree, fruit tree, oil palm, banana) in the agroforestry component, was investigated. Plots featuring 50%—75% shade trees tended to have higher co-benefits, while plots with over 75% shade trees had medium co-benefits and plots featuring mostly companion crops (bananas and oil palms) had the smallest co-benefits (Fig. 5). Consequently, forms of agroforestry that include shade trees – in particular nitrogen-fixing trees, fertilizing soils, and timber species, representing stored capital – are preferable over the sole inclusion of companion crops. Yet, this assumption is valid only up to some extent, since competition with main crop can jeopardize agroforestry benefits. Most beneficial systems feature various types of agroforestry trees and companion crops fulfilling different roles — shade provision, soil fertilization, fruit production —, providing various types of habitats and allowing to develop alternative adaptation strategies. Consequently, plant functional diversity appears as the main driver for successful agroforestry systems. Multistrata forests established on perennial crop plantations to mimic natural forests are particularly prone to such diversity, which gives confidence in the potential for large-scale agroforestry establishment on perennial crop plantations.

3.4. Agroforestry's regional potential for carbon sequestration

An estimate of the carbon sequestration potential (CSP) from a large-scale deployment of shaded agroforests in our study region was performed and compared to the regional anthropogenic emissions from fossil fuels and deforestation. For each main crop, we considered the average carbon stocks per hectare in agroforestry trees from the field study (Fig. 3c) and applied

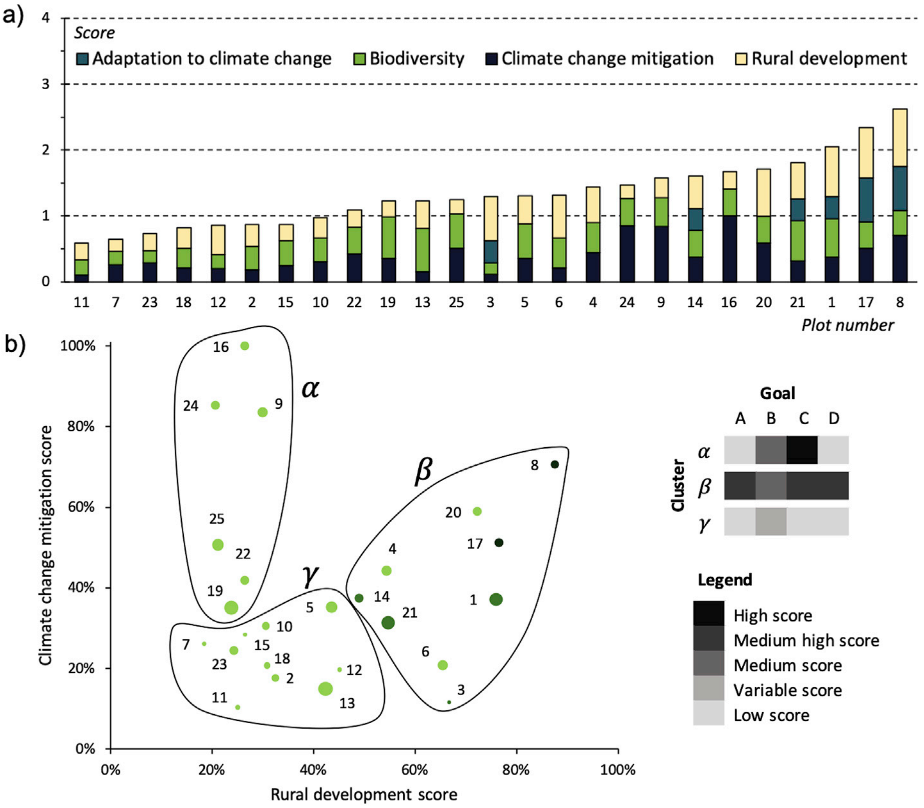

Fig. 4. Assessment of agroforestry co-benefits. **a** Quantification of co-benefits per each plot. **b** 4-dimensional representation of the scores. Green-darker shades show higher adaptation scores, while larger circles show higher biodiversity scores. Black lines group plots relative to their co-benefits within three clusters α, β, and γ ($\alpha =$ high carbon stocks but low productivity, β medium to high carbon stocks and good productivity, γ low carbon stocks and productivity). Schemes on the right describes clusters' relative strengths and weaknesses in relation with the goals A (Adaptation to climate change), B (Biodiversity), C (Climate change mitigation), and D (rural Development), with the associated legend.

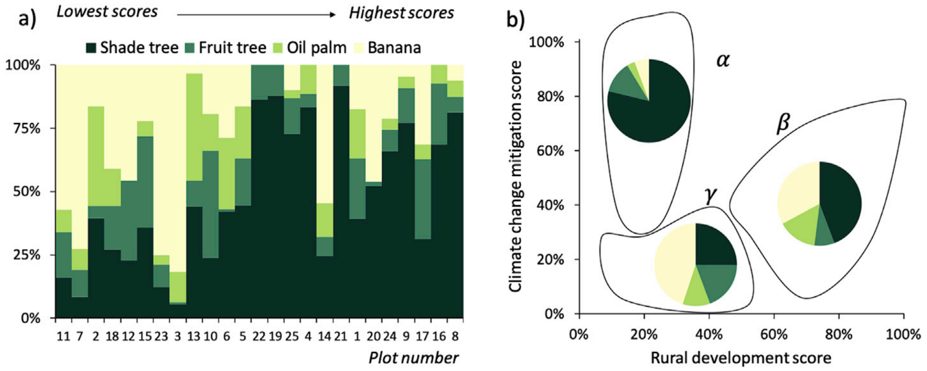

Fig. 5. Shade composition influence on co-benefits of agroforestry. **a** Shade composition of plots, from lowest to highest co-benefits score. **b** Average shade composition of each cluster α, β, and γ (defined in Fig. 4), linking shade composition with agroforestry co-benefits.

them to the existing cultivated area of the specific crop (FAOSTAT, 2017). These levels of carbon stocks are assumed to be reached 20 years after tree planting, in line with the average lifetimes of the studied agroforestry plots. Annual CSP was compared to anthropogenic CO_2 emissions of Guinea, Liberia, Sierra Leone, Côte d'Ivoire, Ghana, Togo and Benin. Emissions from deforestation and forest degradation were retrieved from Baccini et al. (2017) and averaged from 2003 to 2014, while emissions from fossil fuel consumption or industrial processes were obtained from Janssens-Maenhout et al. (2017) and refer to 2016.

Over West Africa, establishing agroforestry on existing perennial crop plantations can sequester up to 736 Mt C over the next two decades (Fig. 6). This represents 1.66 times the anthropogenic emissions. However, national CSPs are contrasted across the seven countries of interest. Côte d'Ivoire holds by far the largest potential, followed by Ghana. These two countries are the world's largest cocoa producers and are in a post-forest transition stage where their deforestation rates slowed down or reversed (Duan and Tan, 2019; Hosonuma et al., 2012). Based on their large agricultural land areas and slow deforestation rates, they have a relatively high CSP compared to their emissions. Since a large share of tropical forests have been cleared for cocoa cultivation in the last decades (Asubonteng et al., 2018; Barima et al., 2016), agroforestry establishment can provide a range of co-benefits in addition to climate change mitigation: better connectivity between forest remnants, fuelwood self-sufficiency, soil fertilization and crop protection against climate extremes. Whether large-scale conversion to shaded agroforests will alleviate pressure on remaining forest depend on a range of socio- and macroeconomic factors, but it has been suggested that agroforestry conversion reduces deforestation and forest degradation (Kumar, 2016; Rahman et al., 2017).

On the other hand, Sierra Leone, Guinea and up to some extent Liberia are classified as pertaining to a pre-transitional stage (Duan and Tan, 2019; Hosonuma et al., 2012) and are characterized by high deforestation rates and relatively smaller cultivated areas. Their agroforestry CSP is consequently lower than their national emissions. As shown in Fig. 2, deforestation is triggered by cropland establishment. Hence, perennial crop plantations occur on newly cleared, fertile land with a high productivity where agroforestry conversion is not likely to benefit yields. Alternatively, thinning of natural forest canopy to establish cocoa or coffee seedlings would retain more trees than in a monoculture plantation, but carbon stocks and biodiversity richness of such agroforestry systems are still far behind those of natural forest (Norris et al., 2010). Consequently, a land-sparing strategy with main crop intensification and forest protection may be more beneficial. However, such a program may be difficult to implement, as enforcement of forest reserves is poor throughout the study area (Barima et al., 2016; Enaruvbe et al., 2019; IUCN, 2015). On the other hand, if shifting cultivation is the main driver for deforestation, as suggested by Fig. 2b, agroforestry adoption may alleviate forest foraging for fuel and food by providing readily available wood, fruits and nuts (Rahman et al., 2017). A better understanding of deforestation dynamics and drivers – from swidden agriculture to commercial monoculture – would allow to more accurately estimate the potential of agroforestry in this region.

Finally, Benin and to some extent Togo are located in the Dahomey gap between the Upper and Lower Guinean Forest humid zones (Schroth et al., 2016) and are in a post-forest transition stage (Duan and Tan, 2019; Hosonuma et al., 2012), so that these two countries hold both very little tropical forest and perennial crop areas. Their CSP is comparable to their deforestation and forest degradation emissions but is outweighed by emissions from fossil fuels and industrial uses. However, although the carbon sequestration benefits may not be relevant here, associated co-benefits – notably land reclamation – are highly desirable in these countries where the same fields are continuously cultivated with little fertilization. In addition, fuelwood production may greatly contribute to local farmers' energy security and income.

4. Limitations and uncertainties

In order to better capture agroforestry's potential for farmers, biodiversity conservation and carbon storage, this work builds on several datasets of various size and origin: satellite land cover data, local carbon measurements, national statistics on cultivated areas, and farmers' perception of agroforestry benefits and adverse effects. Results transferred across different scales and combined from different sources have inherent uncertainties, yet the various aspects of agroforestry can only be assessed by applying different lenses to the issue – from local to regional level, and from quantitative or qualitative approaches. Any scoring of agroforestry co-benefits or adverse effects inevitably includes value judgements. In order to

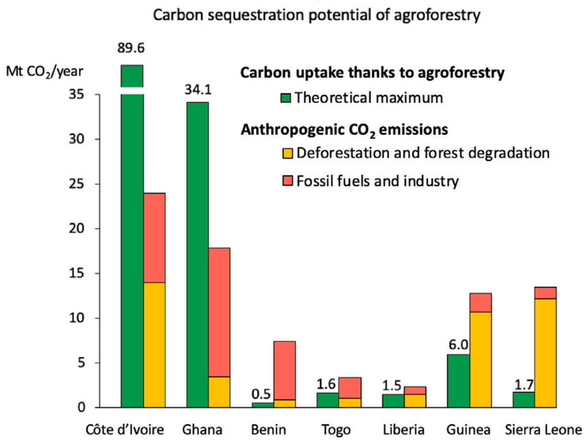

Fig. 6. Carbon sequestration potential of agroforestry (shaded agroforests on cocoa, coffee, oil palm, banana and citrus plantations) in West Africa, in Mt CO_2/year. National CO_2 emissions from deforestation and fossil fuel comsuption are shown for comparison (Baccini et al., 2017; Janssens-Maenhout et al., 2017).

minimize inherent variability, we chose several indicators for each goal, selecting widely-used metrics that could be compared against existing literature and reproduced in future studies. Interviews with farmers have their own sources of uncertainties. For example, they were not conducted in the authors' language and because farmers may have biases depending on their individual perceptions and different knowledge of their fields. However, interview data allowed us to gather insights on aspects that could have not been otherwise evaluated, and we combined wherever possible interview metrics with survey metrics to lower their impact on overall scores.

4.1. Uncertainty in carbon stocks and large-scale potential

Above-ground biomass carbon stocks are quantified with relatively lower uncertainty than below-ground carbon stocks. We correlated below-ground biomass to above-ground biomass using default equations (see Methods), and we estimated that below-ground carbon biomass represents on average 12% of total tree biomass. More sophisticated approaches and invasive field measurements are needed to achieve more accurate predictions.

Our analysis did not consider any potential changes in soil carbon stocks from agroforestry. Soil carbon stocks are very spatially heterogeneous and their estimation is complex and subject to uncertainties regarding both methodology and dynamics (Hairiah et al., 2010). Soil carbon stocks can be affected by agroforestry, depending on the type of trees, tree density, and local climate (Nair et al., 2009). In general, agroforestry systems have soil carbon stocks that are intermediary between those of agriculture and forest (Chatterjee et al., 2018; De Stefano and Jacobson, 2018), but it is unclear if shade tree integration on perennial tree-crop plantation has a significant effect on soil carbon storage (Blaser et al., 2018). Indeed, soil carbon stocks improvements are more significant under the shade tree crown and might not be relevant when averaged over the whole parcel (Blaser et al., 2017). In the study's context, soils were usually exhausted, so that shade tree introduction can be expected to have an overall positive effect on soil carbon stocks, and local farmers typically reported benefits to soil fertility and nutrients from agroforestry.

Results in Fig. 6 are based on the assumption that carbon stocks from our study plots can be extrapolated to all of West Africa, although tree growth rates might change according to gradients in local climate conditions. The climate in the areas of our crops is tropical humid, similar to that in Ghana and Côte d'Ivoire. However, Liberia, Guinea and Sierra Leone are usually wetter and mainly covered by forests, whereas Benin and the rest of Togo are dryer and covered with savannah. Hence, our estimates of CSP might actually be underestimated in the West and overestimated in Benin. Yet, it represents a maximum theoretical potential because it assumes no plantations are already under agroforestry. The actual extent of agroforestry in West Africa is, to the best of our knowledge, unknown, but recent studies (Asubonteng et al., 2018; Tutu Benefoh et al., 2018) performed agroforestry detection and mapping by remote sensing, which could, if applied at a regional scale, help to better quantify CSP.

4.2. Impacts of climate change

Most farmers were aware of microclimatic effects of their trees, but their perceptions must be examined in the light of a changing climate. Results from Schroth et al. (2016) predict that higher temperatures will shift the area suitable to cocoa cultivation southwards during the next decades. As a result, reduced suitability is expected around the forest-savannah transition zone, which lies at the North of the study zone and around the Dahomey gap over Togo and Benin (Schroth et al., 2016). Furthermore, climate change is predicted to reduce suitable areas for coffee in Mesoamerican lowlands (de Sousa et al., 2019), so that similar patterns (target crop shift from coffee to cocoa) can be expected in West Africa. Agroforestry establishment can be an adaptive strategy to temperature rise, with shade trees lowering understory plant temperature and providing income diversification; yet some of the most common agroforestry trees are vulnerable to warmer and dryer conditions (de Sousa et al., 2019). Water availability reduction may prevent shade tree establishment over the area most affected by climate change, in Northern Ghana, Côte d'Ivoire and Liberia as well as in Togolese lowlands (Schroth et al., 2017). Findings from West Africa and South America indeed exhibit a greater resilience to extreme drought stress of full-sun cocoa and coffee over shaded systems (Abdulai et al., 2018; Padovan et al., 2015). Progressive yield decline or tree mortality may lead farmers to adopt unshaded cultivation or shift to annual crops, which would be detrimental to on-field carbon stocks. Thus, planting of new agroforestry trees in this area should take into account potential climate changes and select tree species that can better adapt to it and provide the largest benefits to the crops beneath.

5. Conclusion

This work builds on the experience from Togolese agroforests to quantify and assess co-benefits and trade-offs of agroforestry for four sustainability goals. As agroforestry systems are multidisciplinary in essence, various approaches and data sources are used to achieve an overview of the potential benefits, trade-offs, and scale-effects. Agroforestry systems maximize co-benefits when they feature various types of agroforestry trees and companion crops fulfilling different roles, such as shade provision, soil fertilization, fruit production, or timber value, because they provide diversified habitats, income sources, and allow alternative adaptation strategies. Plant functional diversity is thus a main driver for successful agroforestry systems. Our results show that large-scale agroforestry programs in Western Africa tailored to local context can offer win-win solutions to face multiple environmental and societal challenges. In particular, agroforestry can represent an option to foster farmer's income security in a context of unstable international market prices. While pesticides and fertilizers are often too expensive to be applied at recommended rates, shade and nitrogen-fixing trees represent a low-cost option to mitigate pest incidence and improve soil fertility. Barriers to the implementation of agroforestry exist. An individual farmer might face challenges to convert its own field to agroforestry, due to the lack of knowledge, funds and time, and because of the inherent risks associated with the adoption of a new practice. The establishment of farmer communities and rural development projects supported by local authorities and international organizations can overcome these barriers by informing about the co-benefits of agroforestry and assisting farmers in planting and maintenance of new trees on agricultural fields, thereby adding a social dimension to the multiple agroforestry co-benefits.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gecco.2020.e00919.

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