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Impacts and Feedbacks of Land Use and Land Cover Patterns in Landscape on Ecosystem Processes and Microclimate: Case of a Cacao-Based Agroforestry System

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Authors' contributions

This work was carried out in collaboration between all authors. Authors AS, AK and OA designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Authors AS, CF, OA and OL managed the analyses of the study. Authors AS, AK and CF managed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

Climate change is a major threat to human welfare, biodiversity and ecosystem services. Climate change calls for changes in management of land and water resources. The coupling of and feedback from land use and land cover patterns in landscapes with ecosystem processes (nutrient cycling, water use, evaporation, heat and heat islands) and microclimate is known. Although information is inadequate from tropical land use practices such as intercropping, land rotation fallowing and agroforestry systems. However, understanding of the interactions of land cover patterns with ecosystem processes from cacao-based agroforestry landscapes may be useful in the development of strategies to advance adaptation and resilience to extreme weather shocks. Year

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round measurements were made of soil carbon contents and respiration, microbial biomass C, soil moisture and temperature regimes, soil organic matter pool, species specific carbon stocks, stand biomass, microclimatic-gradients in an agriculturally cultivated field and cacao-based agroforestry system of different ages. Our findings showed that land cover patterns and other elements in cultivated agricultural field and cacao-based agroforestry landscape modulated land surface-atmosphere fluxes and stocks of carbon, other biogeochemical cycles and microclimatic conditions. The results indicated that the high potentials of net gains in carbon (sources and sinks) from cacao-based agroforestry system is a promising CO2 mitigation strategy. Cacao-based agroforestry ecosystem contributes to terrestrial carbon budget (carbon stocks and fluxes), ameliorated weather conditions in addition to other ecological benefits and ecosystem health while the resultant enhanced carbon sequestration will reduce global warming. This information can be incorporated into existing strategies for addressing ecosystem (vegetation and soil) degradation and for agricultural, and forest land use plans in support of climate change adaptation and for rainforest ecosystem conservation.

Keywords: Agroforestry; cacao; ecosystem process; feedback; land use; landscape; microclimate.

1. INTRODUCTION

The global environmental change (GEC) include changes in land use and land cover and in soils and atmospheric composition, biodiversity, climate and weather events, sea level and ocean chemistry. In the circumstances of the GEC enhanced climatic extremes, it is important to mainstream climate change adaptation into land cover and land use practices in order to build resilient and climate-smart landscapes [1]. Unsustainable practices in landscapes are known to increase levels of greenhouse gas (GHG) emissions, intensities of heat islands (extreme thermal environments and heating below comfort levels) and evaporation (water use). These factors predispose plants to hydrothermal stress-induced mortality and dieback in tree species and loss of functional integrity of ecosystems processes [2].

Between 2000 and 2010, the atmospheric concentration of carbon dioxide (CO_2) has increased from 369 to 388 ppm, a 5.1% increase over the last 10 years, let alone 280 ppm in 1850 [3]. Land use changes and fossil fuel combustion are two important anthropogenic factors that have contributed to this increase. The influence of land management on the carbon (C) content in soils and plant biomass is well documented worldwide [4,5]. The establishment of Clean Development Mechanisms (CDM) is one of the instruments in the Kyoto Protocol, and it aims at the control of emissions of greenhouse gases [6]. This Instrument has led to increased interest in reducing CO_2 in the atmosphere through the establishment of Forest Based C sequestration (CS) Projects. Potential mechanisms to reduce C losses and increase C sinks include forest management by protecting and conserving the C pools within the forest-based ecosystems [7] (Brown 1996). Forests sequester more than 92% of the world’s C and between 20 and 100 times more C per hectare than agricultural lands [3,6] (UNFCC, 1998 IPCC, 2007). The Climate Change 2007 Synthesis Report proposes key mitigation practices in the agricultural sector [3].

The coupling of land use and land cover patterns with ecosystem processes (nutrient cycling, water use, evaporation, heat fluxes) have societal correlates in addition to both human and environmental health implications. Models coupling surface and ecosystem level meteorology (temperatures and evapotranspiration) with land cover patterns have potentials for application in the quantification of land surface pattern-processes notably ecosystem energy (temperature) and water (evapotranspiration) balance, carbon budget and sequestration and their correlates with microclimate. The interactions of land use, vegetation land cover with ecosystem processes and microclimate have potentials to resolve adaptation challenges to climate change and variability of weather events. It is required to improve understanding of the” pattern-process” paradigm as applied to land use-vegetation and land cover-ecosystem- climate interactions and the feedbacks on climate system. Such an enhanced understanding would promote sustainability of ecosystems and enhanced adaptation to climate change. Across regions and environmental gradients, stand and ecosystem level, the impacts of vegetation land cover on ecosystem processes and microclimate (heat/temperature), water use (evapotranspiration) and C sequestration with implications for global carbon budget and warming is widely studied [5,8]. However, the scenarios of neighbourhood and ecosystem responses of land use and land cover elements (vegetation pattern)to climate change across environmental gradients in tropical agroecosystems is inadequately researched [1,5,8]. In particular, it is necessary to quantify land surface pattern-processes notably from tropical land use types such as intercropping, land rotation fallow and agroforestry landscapes and their correlates with socio-economic and ecosystem processes.

Tropical land use and land management practices are designed to increase soil C storage, restoration of degraded lands, and reduction of CH_4 and N_2O emissions. The storage of SOC in soils can be increased via afforestation, reforestation, restoration of degraded lands, improved silvicultural techniques, and the implementation of agroforestry practices in agricultural lands [5,9,10]. Agroforestry systems (AFS) rank high among the strategies, a properly designed and managed AFS can be effective CO_2 sinks, especially with the use of perennial crops and fast growing co-occurring tree species in the AFS ecosystems [5]. Agroforestry systems have to cope with changing climate and droughts which are predicted to become more frequent and more severe. Agroforestry systems (AFS) in which high amounts of organic materials are added to the soil, such as the shaded perennial-crop systems, have special relevance for carbon sequestration.

Vegetation gross primary production (GPP) results from the conversion of canopy absorbed photo synthetically active solar radiation to vegetation biomass. Vegetation gross primary production (GPP) is the principal mechanism for terrestrial ecosystem uptake and storage of atmospheric CO_2 and GPP is a major factor determining biosphere-atmosphere carbon interactions and climate feedbacks. Young trees sequester and store CO_2 rapidly for several decades, followed by annual increase of CO_2 and then decline, while, for example, the forests of "old" growth or virgin forests can release a quantity of CO_2 resulting from the decomposition of dead biomass, equal to the quantity fixed by tree biomass. For a typical tree in the forest, the amount of CO_2 sequestered is, on average, stored for 51% in the trunk, branches 30%, and 3% in leaves. The thick roots (diameter> 2mm) accumulate about 15-20% of total carbon [11]. The release of CO_2 determine life processes while tree maintenance is compensated by the quantity sequestered in the woody biomass and the amount of emissions avoided through the presence of trees that affect, for example the heating and cooling of buildings for the reduction of the Ecosystem Heat Island effect (EHI). The net reduction in CO_2 is simply the difference between the reductions in CO_2 emissions and the same, in metric tons (t). The net CO_2 balance in an agricultural and forest ecosystem = CO_2 (CO_2 Sequestred CO_2 emissions avoided) - CO_2 released.

In the humid tropics, small family-farms are at the heart of cacao industry, with five to six million smallholder farmers provide more than 85% of the world's cacao. Typically, each cacao farmer owns less than 2 ha of land and may grow approximately 1,000 cacao trees [7,8,12]. Year round measurements were made of soil carbon contents and respiration, microbial biomass C, soil moisture and temperature regimes, soil organic matter pool, species specific carbon stocks, stand biomass, microclimatic-gradients in an agriculturally cultivated field and cacao-based agroforestry system of different ages. What are the contributions of cacao-based agroforestry ecosystem to terrestrial carbon budget (greenhouse gas and carbon sequestration), amelioration of weather conditions, ecological benefits and ecosystem health, carbon stocks and sequestration and resultant effect global warming. It is imperative to improve the understanding of the pattern-process and the relationships between vegetation gross primary production and its net effect on potential carbon sink strength in agricultural and cacao-based agroforestry landscapes of the humid tropics. The interactions (impacts, coupling and feedbacks) of cacao-based agroforestry landscape as land use and land cover pattern with ecosystem processes and microclimate was examined. The aim was to investigate impacts of cacao-based agroforestry system in ameliorating weather conditions, improvement of carbon sequestration, other ecological benefits and ecosystem health. The findings may be incorporated into existing strategies for addressing ecosystem (vegetation and soil) degradation and for agricultural, and forest land use plans in support of climate change adaptation and for rainforest ecosystem conservation.

2. MATERIALS AND METHODS

Three sites comprising an agricultural field cultivated to arable/staple food crops, and cacao

(*Theobroma cacao* L.) fields 2 to 4 years and 25 to 40 years old shaded by either predominantly native fruit and timber tree species) were studied in each site. Important features of the study fields are: cacao plantation age, farm size and agricultural management including year of conversion of forest to cacao. This allows us to select cacao field plots that were under the same system ranging from 3 to 45 years old.

2.1 Determination of Tree Biomass and Carbon Dioxide Sequestered by Trees

We adopted the method recommended by FAO [4] and Chavan and Rasal [13] with slight modification into five stages as follows:

The total (green) weight of tree based on tree species for tropical forest species, the weight of a tree is:

W = Above-ground weight of the tree in kilogram (kg); D = Diameter of the trunk in inches; H = Height of tree in Meters.

For trees with D ≤ 10:

$$w = 0.25D2H \tag{1}$$

or trees with D ≥ 11:

$$w = 0.15D2 \tag{2}$$

0.25D2H or trees with D ≥ 11: W = 0.15D2H (1)

The weight of the root system is estimated as 20% as much as the above-ground weight of the tree. The total green weight of the tree is determined as the product of the above-ground weight of the tree by 120 %.The dry weight of tree based was estimated based on the methods reported in the Extension Publication from the University of Nebraska [13]. The mass of the content of carbon is estimated as50% of the tree's total volume [14]. Therefore, the weight of carbon in the tree can be calculated as the product of tree dry weight by 50 %.The weight of carbon dioxide sequestered (CO_2) is composed of one molecule of Carbon and 2 molecules of Oxygen and The atomic weight of Carbon is 12.001115; The atomic weight of Oxygen is 15.9994). Hence,

$$The\ weight\ of \mathrm{CO2\ is\ C} + (2 * 0) = 43.99991 \tag{3}$$

$$\text{The ratio of CO2 to C} = \frac{43.999915}{12.001115} = 3.666 \tag{4}$$

Therefore, the weight of carbon dioxide sequestered in the tree was obtained as the product of the weight of carbon in the tree by 3.6663 [14]. The weight of CO_2 sequestered in the tree per year was obtained as the ratio of the weight of carbon dioxide sequestered in the tree and the age of the tree. Aerial canopy biomass was assessed via the allometric relationship developed by [15] after measuring the height and girth at breast height of all the trees in the sampling circle with a 10m radius circle (100 m²) and using species specific wood density data from ICRAF [16]. Tree biomass (W, dry weight) was estimated using the allometric equation [4,15] on the basis of stem diameter (D) at 1.3 m above the ground.

The equation, specific to "Wet forest stand" of tropical areas is:

$$Aerial\ biomass\ (kg) = 0.077 * (\rho D^2 H)^{0.94} \tag{5}$$

where ρ the wood specific density (in g/cm3), D the tree trunk diameter at breast height (in cm) and H the total tree height (in m). The coefficient c is based on the allometric relationship between tree height (H) and diameter (default value for c = 0.62).

These data were also used to calculate plot tree density and basal area. The aerial biomass of cacao, oil palm, plantain and banana and other economic timber and fruit tree species were estimated from allometric relationships based on Chave et al. [15] for 10 plants per sample. The data on wood density was extracted from a wood density database created by ICRAF [16].

For cacao (*Theobroma cacao*) and banana (*Musas paradisaca*) the following equation of van Noordwijk et al. [17] was used.

$$Cacao: 0.281 * D2.06 \tag{6}$$

$$Banana: 0.03 * D2.13 \tag{7}$$

Where D is tree diameter at breast height (cm)

$$Tree\ volume = \quad HDb2 + 4(Dm2) + DT2/24 \tag{8}$$

where▯ is 3.142, Ht is tree height, Db is tree diameter @ base, Dm is tree diameter @ middle and Dt is tree diameter at the top.

$$Tree\ biomass = Tree\ density * tree\ volume \tag{9}$$

In this study, aerial biomasses of shade trees and cacao plants were converted into amount of carbon by assuming a ratio of 0.5 [3]. Trees and understory vegetation were assumed to contain 45% C of their biomass [4].

Soil samples were also collected in the central part of each plot at two depths (10 and 30 cm) with a cylindrical auger to measure soil moisture content and soil fraction larger than 2 mm. Only the superficial soil horizons were collected as a preliminary study on various soils representative of the watershed (data not presented) show that 70% of the soil carbon is concentrated in the top 30 cm.

Litter was also collected avoiding contamination by soil particles via washing in the laboratory. After oven drying, soil and litter carbon content were measured on aliquots by a non dispersive infrared sensor associated with a furnace (Total Organic Carbon V CSH – CSN and Solid Sample Module SSM 5000A, Shimadzu Scientific Instruments).

The C concentration of all the sub-samples (trunks, branches, twigs, roots, leaves) was determined by grinding the samples using Sample Mill and analysis for total C using an Elemental Analyzer (Fiscon Instrument, CA, USA), following the dynamic flash combustion technique. The weights of aboveground non-woody vegetation and dead trees on the ground for each quadrat were summed and divided by the sampling area.

The soil moisture (0–20 cm depth), soil surface temperature (0–5 cm depth), and air temperature above the soil (+5 cm) were measured every 2 h over a 24 month period. Percent soil organic C was converted to Mg ha^{-1}based on bulk density and mass of the soil within the top 15 cm depth (Nair et al. 2010).The aboveground: belowground C pools ratio show the preponderance of C pools belowground and the key role played by volcanic soils in the capture of large amounts of C. The huge litter fall and C input through its decomposition increases annual C input to soil C.

Litter fall and C input through decomposition annual C input to soil C pool through decomposition processes. Soil respiration values refer to total respiration, including tree root, mycorrhizae and microbial respiration, and annual decomposition losses of needles, fine roots, necromass, and coarse woody debris. Annual soil respiration for the three ecosystems was calculated from the monthly respiration rates presented in this study. Soil respiration values refer to total respiration, including tree root, mycorrhizae and microbial respiration, and annual decomposition losses of needles, fine roots, necromass, and coarse woody debris. Annual soil respiration for the three ecosystems was calculated from the monthly respiration rates presented in this study.

3. RESULTS AND DISCUSSION

The growing season was grouped into Major (April to mid-August) and Minor (mid-August to December) rainy season and the Dry (December to March) season. The minor season is characterized by more overcast sky and lower air temperatures and higher relative humidity compared with the major rainy season (Table 1). The rainy season had higher mean relative humidity averaged (71%) and lower air temperatures (32.8^{o}C) compared with the dry season. Also, higher air temperature and VPD and lower relative humidity were found for the unshaded open sun cacao compared with the shaded plants. Our results confirmed a general moderating effect of canopy on below-canopy microclimate with a decrease of air temperature of up to 4℃ and an increase of relative humidity of up to 11% (Table 1). The forest tree species in the sampled ecosystems moderated microclimate about twice as much as agricultural field. The moderating capacity was strongest particularly, during the dry season, and depended on the general weather situation. In the dry season, the deviations from the general seasonal weather conditions often occurred when soil moisture pools were depleted. Despite the moderating capacity, below-canopy microclimate did not lag behind agricultural field microclimate. Based on our results we conclude that natural recruitment of cacao and other tree species for afforestation/reforestation may ecosystem sensitively to climate change. The Kyoto Protocol establishes that land use, land use change and forestry (LULUCF) activities such as afforestation, reforestation, and deforestation (Article 3.3), and forest land management, cropland management, grazing land management. Revegetation practices and strategies are proven avenues to increase the amount of carbon released and retained within ecosystem. Agroforestry systems fulfill role in reducing carbon (C) emissions and promoting C sequestration which would help to fulfill the Kyoto Protocol requirements. Forest canopy moderates below-canopy air temperature and relative humidity (Table 1) and thus creates a specific microclimate for tree growth. Climate change will alter the moderating capacity of forest canopy. This may render the below-canopy conditions unsuitable for recruitment of the hitherto dominant tree species. Cacao trees are the major carbon pool and sink as they represent over 50% of the total carbon sequestered in the landscape by cacao and other timber and other fruit tree species (Fig. 1). However, the mature plantation (25 – 40 years old) sequestered over 3 times more carbon compared with the young (3 -4 years old field (Table 2). Table 3 presents the summary of the temporal trends in soil CO_2 evolution, microbial biomass carbon and soil carbon of the land use/land cover classes. Seasonal differences in CO_2 evolution, microbial biomass carbon and soil carbon were found among the land use/land cover classes. Highest and lowest values of these parameters were obtained in minor (August to December) and dry (December to March) seasons. The total values of the measured CO_2 evolution (18, 20 and 105), microbial biomass (26, 29 and 142) and soil carbon (16, 22 and 66) for the respective young (2 -4 years old) and mature (25- 40 years old cacao plantations and cultivated agricultural field respectively. The soil carbon and litter were lowest for cultivated field and values were 66 and 1.1 (for cultivated field) and 105 and 2.3 and 143 and 3.2 for the respective 3 – 4 and 25 – 40 years old cacao plantations. However, the total carbon pools/stocks were close between 3 – 4 years old plantation and cultivated field (Table 4). The contributions of cacao trees, timber and other fruit tree species, the soil and litter to total carbon sequestered in the landscapes were significant in this study. In fig. 2 and 3 are presented the carbon and carbon dioxide contents of component tree species in the cacao agroforestry system of the respective 3-4 and 25 – 40 years old fields. Profoundly highest values (over 7 fold increase were found for cacao trees compared with other economic tree species and very low values for oil palm and plantain/banana trees. Carbon sequestration varies with age of cacao field as function of tree biomass and litter layer. The results confirmed the potential of cacao-based agroforestry system, particularly shaded with native fruit and timber tree species, as carbon sinks.The results show that the biomass of cacao and shade trees represents a significant source of input of carbon to soil. The C captured in the biomass and deposited on the soil surface is indirectly sequestered as SOC following its decomposition. Furthermore, the soil has sink pools for C with microbial biomass and soil aggregates within them; but this pool is considered in estimates of C sequestration in soil and plant biomass in AFS. Continuous deposition of plant litter, fine roots, and root hairs are the principal inputs for C content in cacao AFS soils.

Table 1. Seasonal trends in relative humidity, temperature, vapour pressure deficit, leaf area index and photosynthetically active radiation among the land use land cover classes

LCLUC	PAR (*μmol/m^2/s*)			LAI			RH (%)			VPD (kPa)			Temp. (^{o}C)			Sunshine hour		
	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c
2–4 years old	755	957	1013	1.8	2.4	1.5	70	64	33	1.9	1.6	3.1	35	32	37	5.2	4.5	6.6
25-40 years old	471	669	921	1.8	2.6	1.8	77	80	39	1.5	1.1	2.4	31	28.5	31.6	5.2	4.5	6.6
Agric. Field	828	1123	1464	1.1	1.4	0.9	65	70	31	1.8	1.5	3.2	33	31.7	34.2	5.2	4.5	6.6

Major (a) and Minor (b) rainy season and dry (c) season, relative humidity (RH), temperature (T) and vapour pressure deficit (VPD), *photosynthetically active radiation (PAR: μmol/m^2/s), leaf area index (LAI)*

Table 2. Basal area and sequestered carbon by cacao and other tree species biomass

	Cacao trees in plantation			Timber plus fruit tree species
	20 – 40 years	2 – 4 years	Total	
Basal area (m^2/ha)	27.6	8.8	35	30.2
Sequestered carbon	183	58.4	213	184

Table 3. Temporal trends in soil CO_2 evolution, microbial biomass carbon andsoil carbon of the land use/land cover classes

LCLUC Types	Soil CO_2			Microbial biomass C			Soil carbon		
	a	B	c	a	b	c	A	b	c
2 – 4 years old field	6.0	7.4	5.2	6.8	6.3	5.9	36	47	22
25 – 40 years old field	8.9	9.5	7.2	9.7	11.2	8.1	49	62	31
Cultivated field	5.3	6.2	4.4	5.4	6.0	4.3	22	30	14

The growing season was grouped into a: Major (April to mid August) and b: Minor (mid August to December) rainy season and c: Dry (December to March) season

Table 4. Carbon pools /stock in cacao agroforestry landscapes of different ages

LCLUC Types	Carbon contents				
	Cacao trees	Other tree species	Soil carbon	Litter carbon	Total carbon in landscape
Cacao AFS (3 - 4 yrs old)	1956471	496927	105	2.3	2453505.3
Cacao AFS (25 - 40 yrs old)	3266346	745181	143	3.2	4011673.2
Agricultural field	---	246346	66	1.1	246413.1

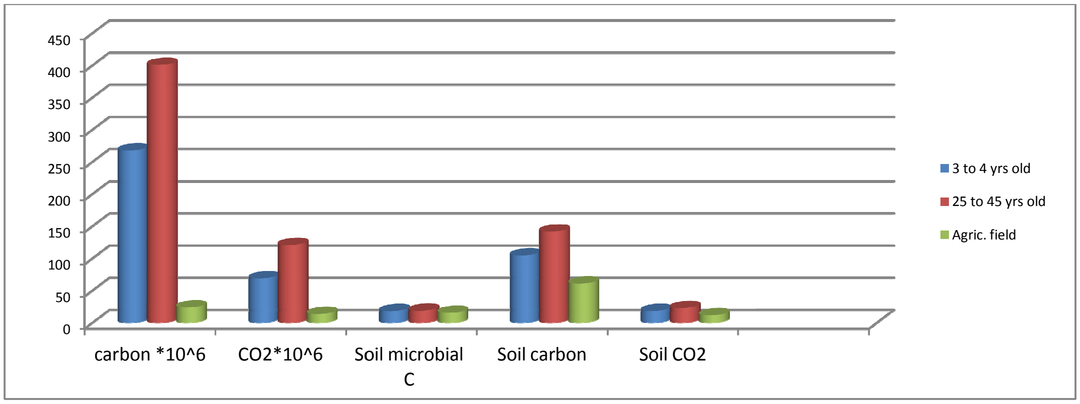

Fig. 1. Tree and soil contents of carbon, CO2 and microbial biomass carbon

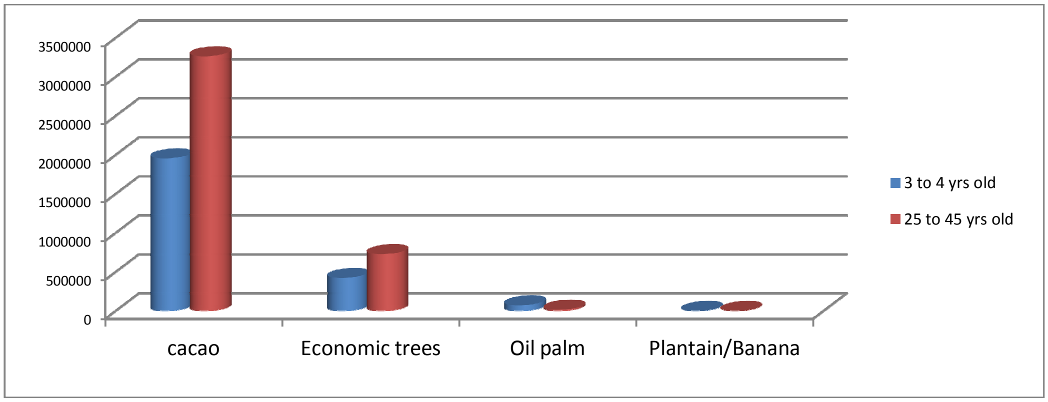

Fig. 2. Carbon contents of component tree species in the cacao agroforestry system

Ecologically beneficial shade trees may reduce/provoke competition for soil moisture. Studies have suggested that competition between shade trees and cacao for water during long periods when rainfall was low [18]. In cacao-based agroforestry system, low stand transpiration rates further contributed to the relatively high tolerance of the agroforest and its ability to reduce rainfall throughfall [18]. This phenomenon reduces competition for

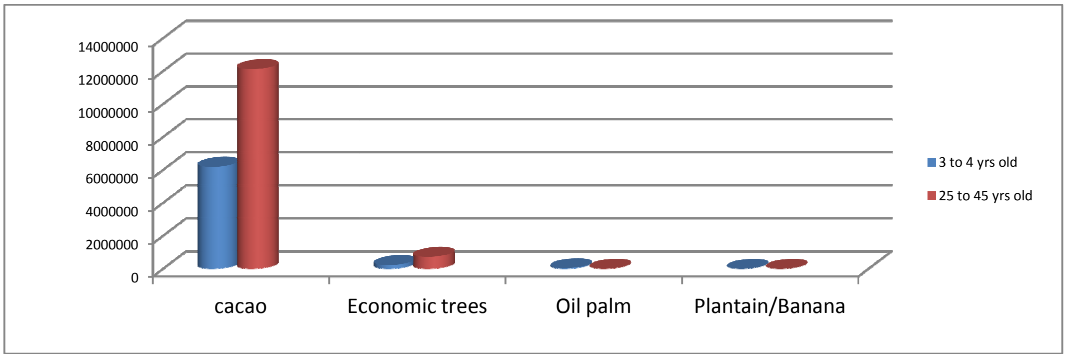

Fig. 3. Carbon dioxide contents of component tree species in the cacao agroforestry system

available water resources. It is recognized that storage of SOC in soils can be increased directly by increasing C returns to the soil in the form of plant residues, or organic amendments, and indirectly by management practices that decrease soil organic matter (SOM) decomposition and erosion of topsoil. Carbon released from the decomposition of litterfall that is continuously deposited on the soil surface in cacao-based AFS (and other shaded perennial crop systems) is retained (sequestered) in the soil [5,19,20]. In addition to the environmental benefits of GHG mitigation and biodiversity conservation, the C sequestered in cacao AF systems could also provide an added income stream for cacao farmers around the world. Cacao AFS are comparable to natural forests with respect to the accumulation of high amounts of SOC [18,21,22]. AFS could convert large landscapes into effective C sinks rather than C sources. Cacao-based agroforestry system is a low input sustainable practices, which minimize vegetation and soil disturbances, promote the presence of perennial vegetation, recover or recycle of nutrients, and contribute to the preservation of C and N pools [21,23].Cacao-based agroforestry system appears to be a sustainable land use management practice that preserves and increases soil C pools, contributes to reduce atmospheric CO2 with high potential to offset GHG emissions [23].

Landscape approaches to carbon (C) accounting in agriculture, forestry and other land uses are being promoted as a win-win option for integrating climate change mitigation with land use system and livelihoods. Deforestation and degradation of forests raise concerns about accelerated GHG emissions in the tropics and call for measures to meet the needs of local communities in an environment friendly and sustainable manner [5,14,24]. Deforestation and other land use changes in developing countries are responsible for about 74% of greenhouse gas (GHG) emissions [5,14,25]. Tree C stocks can be used to approximate aboveground C gains. Carbon stocks of natural and agricultural ecosystems are generally lower than potential stocks, due to a range of human activities, such as C-depleting farming practices (e.g. ridging of soils, burning of crop residues, and inadequate fertilizer use), charcoal production, bus fires and wood harvesting [25,26,27,28,29].

In particular in comparison with cacao-based agroforestry system, C stocks in agricultural systems are low. Agroforestry practices with perennial vegetation could be designed to protect and enhance C sequestration on sensitive landscape locations such as highly vulnerable areas for nonpoint source losses and steep slopes. Improved agroforestry practices that are strategically placed on agricultural landscapes will eventually allow development of suitable mitigation strategies to enhance C sequestration [9] estimated potential sequestration rates of 5.9 Mg C ha^{-1} year^{-1} for cacao agroforests of Cameroon. Kuersten and Burschel [30] provide estimates of the amounts of C sequestered by fuelwood production in AFS of 0.5–2.0 Mg C ha^{-1} year^{-1} for shade trees in Coffee (*Coffee* spp.) and cacao (*Theobroma cacao* L.). The conversion of fallow land to agricultural fields reduced C stocks in the top 150 cm of soil from 82.5 Mg C ha^{-1} to 49.0 Mg C ha^{-1} in fallow land and to 52.2 Mg C ha^{-1} in agricultural soil [5,24,31]. Following clearing, Solomon et al. [32] reported a 56% reduction of soil C content in the cultivated fields in a semiarid area in Tanzania. The total potential C sequestration by cacao-based agroforestry of about 7 Mg C ha^{-1} year^{-1} could offset significant fraction of the current CO2 emissions (1,600 Tg C year^{-1} from burning fossil fuel such as coal, oil, and gas) by 34%.

Agroforestry is a promising practice to sequester C while providing numerous environmental, economical, and social benefits [7,33].

Both deforestation and degradation of forests raise concerns about accelerated GHG emissions in the tropics and call for measures to meet the needs of local communities in an environment friendly and sustainable manner [5,31,32]. The total carbon sequestered (in the range of 140-220 t/ha, In the cacao age group studied are above the median C sequestration potential of AFS estimated at 95 t/ha for tropical AFS by Muñoz and Beer [22] and Dossa et al. [34] were in the same order of magnitude with that of a Robusta AFS shaded by Albizia spp. in West Africa which were however comparatively higher than Arabica AFS in Latin America [22,35,36].

4. CONCLUSION

This study confirms the potential of cacao-based AFS shaded by native species of timber and fruit trees as both C source and sink. Consequently, incentives and policies should be put in place to reward farmers maintaining high density and diversity of native tree species and hence to preserve the largest range possible of ecosystem services, including carbon sequestration, provided by these ecosystems. In addition to the environmental benefits of GHG mitigation and biodiversity conservation, the C sequestered in cacao AF systems could also provide an added income stream for cacao farmers. The tree biomass, litterfall and soil C sequestration in agroforestry systems is currently not adequately unexplored and unappreciated despite the huge environmental benefits. The findings indicate possible net gains in C sequestration that could be used to promote agroforestry as a promising CO_2 mitigation strategy, which would have implications for other cacao growing regions and shaded-perennial agroforestry systems. Land use practices and land cover patterns are also drivers and regulators of ecosystem energy and water balance (heat and evapotranspiration rates).Based on our results we conclude that natural recruitment of cacao and other tree species for afforestation/reforestation may enhance ecosystem resilience to climate change. In order to sustainably manage the potential risks and challenges of global environmental change in particular, microclimatic extremes, new and innovative solutions to improve environment performance of landscapes are required. The biophysical findings from the land use, vegetation land cover, and microclimate interactions may advance capacities to cope with climate variability and extreme weather shocks. The information generated has implications for adaptation planning and policy issues and for mainstreaming climate change adaptation and disaster risk reduction in land use and landscape management. This information will be useful input in the construction and evaluation of global model predictions regarding the nature and stability of the terrestrial carbon sink, and potential biosphere response and associated climate feedbacks to global warming.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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