

Impacts and feedbacks of land use and land cover patterns in landscapes on ecosystem processes and microclimate: Case of a cacao-based agroforestry landscape

Abstract

Climate change is a major threat to human welfare, biodiversity and ecosystem services, it calls for drastic changes in management of land and water resources. The coupling of and feedback from land use and land cover patterns 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, interactions of land cover patterns with ecosystem from cacao-based agroforestry system can serve as strategy for advancing adaptation and resilience to extreme weather shocks. 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. Our findings showed that land cover patterns and other elements in cultivated agricultural field and cacao-based agroforestry landscape modulated land surface atmosphere fluxes of carbon stocks and fluxes, other biogeochemical cycles and microclimatic conditions. Cacao-based agroforestry ecosystem contributes to terrestrial carbon budget (greenhouse gas and carbon sequestration) and ameliorated weather conditions, improved ecological benefits and ecosystem health, the resultant enhance carbon sequestration will reduce global warming. The results indicated that the high potentials of net gains in C sequestration from cacao-based agroforestry system is a promising CO₂ mitigation strategy. It is concluded that cacao-based agroforestry system ameliorated weather conditions, improved ecological benefits and ecosystem health, the resultant enhance carbon sequestration will reduce global warming. Such findings 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: *Land use, cacao agroforestry, landscape, feedback, ecosystem, microclimate*

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 (Agele et al., 2016). Unsustainable practices in landscapes are known to increase levels of 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 and loss of functional integrity of ecosystems processes (Haeberle et al., 2015).

Between 2000 and 2010, the atmospheric concentration of carbon dioxide (CO₂) has increased from 369 to 388 ppm, a 5.1% increase over the last 10 years, let alone 280 ppm in 1850 (IPCC, 2007). 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 (FAO, 1997, Nair et al., 2010). The establishment of Clean Development Mechanisms (CDM) is one of the instruments in the Kyoto Protocol to control emissions of greenhouse gases (UNFCCC 1998) has led to increased interest in reducing CO₂ in the atmosphere through 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 (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 (UNFCCC, 1998 IPCC, 2007). The Climate Change 2007 Synthesis Report proposes key mitigation practices in the agricultural sector (IPCC 2007).

The coupling of land use and land cover patterns with ecosystem processes (nutrient cycling, water use, evaporation, heat fluxes) have societal correlates with both human and environmental health implications. The feedback among land use-vegetation land cover-climate on the ecosystem processes is also reported (Nair et al., 2009, Agele et al., 2016). Models coupling surface and ecosystem level meteorology (temperatures and evapotranspiration) with land cover patterns have potentials for application for 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" paradigms applied to land use-vegetation and land cover-ecosystem-climate interactions and the feedbacks from land use-land cover on the climate system in order to promote the sustainability of ecosystems and enhanced adaptation to climate change. Across regions and environmental gradients, stand and environmental (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 (Nair et al., 2009, 2010).

However, the scenarios of neighbourhood and ecosystem responses of land use and land cover elements (vegetation pattern) to climate change across regional environmental gradients in tropical agroecologies is inadequately researched (Nair et al., 2009, 2010; Agele et al., 2016). In addition, 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 the correlates with socio-economic and ecosystem processes

Among the practices are proven land use and land management practices designed to increase soil C storage, restoration of degraded lands, improved livestock and manure management to reduce CH₄ and N₂O 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 (Lal 2004; Montagnini and Nair 2004; Nair et al., 2010). Agroforestry systems (AFS) rank high among the strategies, a properly designed and managed AFS can be effective CO₂ sinks, especially with the use of perennial crops and fast growing co-occurring tree species in the AFS ecosystems (Nair et al. 2010). 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 photosynthetically active solar radiation to vegetation biomass. Vegetation gross primary production (GPP) is the principal mechanism for terrestrial ecosystem uptake and storage of atmospheric CO₂ and GPP is a major factor determining biosphere-atmosphere carbon interactions and climate feedbacks. Young trees sequester and store CO₂ rapidly for several decades, followed by annual increase of CO₂ and then decline, while, for example, the forests of "old" growth or virgin forests can release a quantity of CO₂ 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 CO₂ 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 (Brown and Rasal, 2010). The release of CO₂ 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 CO₂ is simply the difference between the reductions in CO₂ emissions and the same, in metric tons (t). The net CO₂ balance in an agricultural and forest ecosystem = CO₂ (CO₂ Sequestered CO₂ emissions avoided) - CO₂ released.

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 (Brown, 1997; Shapiro and Rosenquist, 2004, Nair et al., 2009). 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. The understanding of the pattern-process and quantification of the roles and relationships between vegetation gross primary production, and the net effect of GPP on potential carbon sink strength in an agricultural and cacao-based agroforestry system 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.

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.

Determination of tree biomass and carbon dioxide sequestered by trees

We adopted the method recommended by FAO, 1997 and Chavan and Rasal (2010) 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 $D \leq 10$: $W = 0.25D^2H$ or trees with $D \geq 11$: $W = 0.15D^2H$ 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 extension publication from the University of Nebraska (Chavan and Rasal, 2010). The mass of the content of carbon is estimated as 50% of the tree's total volume (DeWald et al., 2005). 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 CO_2 is $C + (2 * O) = 43.999915$ 2
the ratio of CO_2 to C = $43.999915/12.001115 = 3.6663$ 3

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 (DeWald et al., 2005). 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 Chave et al. (2005) 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 (2009). Tree biomass (W, dry weight) was estimated using the allometric equation (FAO, 1997, Chave et al., 2005) 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 (in kg) = $0.0776 \times (\rho D^2 H)^{0.94}$ 4

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. (2005) for 10 plants per sample. The data on wood density was extracted from a wood density database created by ICRAF (World Agroforestry Centre 2010b).

For cacao (*Theobroma cacao*) and banana (*Musasp.*) the following equations (van Noordwijk et al. 2002) were used.

$$\text{Cacao : } 0.281 * D^{2.06} \dots\dots\dots 5$$

$$\text{Banana : } 0.03 * D^{2.13} \dots\dots\dots 6$$

where D = diameter at breast height (cm)

$$\text{Tree volume} = \pi * H * D_b^2 + 4(D_m^2) + D_t^2 / 24 \dots\dots\dots 7$$

where π is 3.142, H is tree height, D_b is tree diameter @ base, D_m is tree diameter @ middle and D_t is tree diameter at the top.

$$\text{Tree biomass} = \text{Tree density} * \text{Tree volume} \dots\dots\dots 8$$

In this study, aerial biomasses of shade trees and cacao plants were converted into amount of carbon by assuming a ratio of 0.5 (IPCC, 2003). Trees and understory vegetation were assumed to contain 45% C of their biomass (FAO, 1997).

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 (FisonInstrument, CA, USA), following the dynamic flashcombustion 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.

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 °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. Results confirmed a general moderating effect of canopy on below-canopy microclimate with a decrease of air temperature of up to 4° C 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 condition patterns most likely 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 are proven practices/strategies to increase Carbon released and retained within ecosystem. Agroforestry systems fulfill role in reducing carbon (C) emissions and promoting C sequestration which would help to fulfil 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 making it unsuitable for recruitment of the hitherto dominant tree species. Cacao trees are the major carbon pools 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 CO₂ evolution, microbial biomass carbon and soil carbon of the land use/land cover classes. Seasonal differences in CO₂ 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 CO₂ 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 values were lowest and cultivated field and varied between 105 and 2.3 and 143 and 3.2 in 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 confirm the potential of cacao-based agroforestry system, particularly shaded with native fruit and timber tree species, to act as carbon sink. The results show that the biomass of cacao and shade trees represents a significant source of input to soil C. 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 of 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.

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 with only little precipitation was low or would favor cacao (Kohler et al., 2010). In the report, the low stand transpiration rates further contributed to the relatively high tolerance of agroforestry to reduce rainfall throughfall as competition for available water resources is reduced. It is recognized that storage of SOC in soils can be increased directly by increasing C returns to the soil in the form of crop residues, manure, or other organic amendments, and indirectly by management practices that decrease soil organic matter (SOM) decomposition and erosion. 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 (Six et al. 2004; Gama-Rodrigues et al. 2010; Nair et al. 2010). 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 (Lal, 2005; Kohler et al., 2010). AFS could convert large landscapes into effective C sinks rather than C sources. Cacao-based agroforestry system is a low input sustainable practice, 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 (Lal, 2005, Thangataa and Hildebrand, 2012). 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 (Thangataa and Hildebrand, 2012).

Landscape approaches to carbon (C) accounting in agriculture, forest, 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 (Funder 2009, Nair et al., 2010, DeWald et al., 2013). Deforestation and other land use changes in developing countries are responsible for about 74% of greenhouse gas (GHG) emissions (Nair et al., 2010, Brown et al., 2012, DeWald et al., 2013). 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, bush fires and wood harvesting (Chidumayo 1987, 1997, Abbot and Homewood 1999, Brown et al., 2012)..

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 Nair et al. (2009) estimated potential sequestration rates of 5.9 Mg C ha⁻¹ year⁻¹ for cacao agroforests of Cameroon. Kuersten and Burschel (1993) 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 (*Coffeespp.*) and cacao (*Theobroma cacao*L.). The conversion of fallow land to agric 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 (Funder 2009, Nair et al., 2010, Ishaq et al., 2014). Following clearing, Solomon et al. (2000) 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

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 (Funder 2009, Nair et al., 2010, Chavan and Rasal, 2012, Ishaq et al., 2014). 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, 2001). in the same order of magnitude with that of a Robusta AFS shaded by Albizia spp. in West Africa and comparatively higher than Arabica AFS in Latin America (Muñoz and Beer, 2001, Harmand et al., 2007, Siles et al., 2010).

Conclusion

This study confirms the potential of cacao-based AFS shaded by native species of timber and fruit trees to act as C sink. Consequently, incentives and policies should be put in place to reward farmers maintaining a 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. 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. It is imperative to extend in order to better understand potential ecosystem and societal consequences of current and future climatic conditions. 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. 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. The tree biomass, litterfall and soil C sequestration in agroforestry systems is currently is unexplored and unappreciated has environmental benefits.

Climate change calls for drastic changes in management of land and water resources. Our findings which indicate possible net gains in C sequestration that could be used to promote agroforestry as a promising CO₂ mitigation strategy has implications for other cacao-growing regions and shaded-perennial agroforestry systems. The interactions of urban landscape - land cover patterns - climate – ecosystem is known. Such interactions have microclimate and societal correlates with both human health and environmental (ecosystem) implications. In particular, land use practices and land cover patterns are also drivers and regulators of ecosystem energy and water balance (heat and evapotranspiration rates). In order to sustainably manage the potential risks and challenges of global environmental change –enhanced microclimatic extremes, new and innovative solutions are required to improve environment performance of landscapes are required to mainstream resilience into land use and landscape management practices of the humid tropics in particular. Sustainable land use climate-smart and resilient landscapes to microclimatic extremes may be built via adoption of environment-friendly land use and management. Sustainable land use practices aimed at ameliorating weather extremes will improve ecological benefits (ecosystem health), conserve biodiversity, improve carbon sequestration and reduce global warming. In this respect, what and how capacity building in landscapes adaptable to changing climate and where capacity is lacking and the needs and practices for land use/management stakeholders to achieve environmental sustainability are required. In order to advance capacities to cope with climate variability and extreme weather shocks, it is imperative to harness land use, vegetation land cover, and microclimate interactions.

References

- Abbot JIO, Homewood K (1999) A history of change: causes of Miombo woodland decline in a protected area in Malawi. *J Appl Ecol* 36:422–433
- Agele SO, Iremiren GO, Aiyelari OP, Famuwagun IB. 2016. Mainstreaming adaptation, resilience and disaster risk reduction into extension of frontiers of cacao to marginal soils and climate of the humid tropics in the wake of climate and weather variabilities. *11th Annual International Symposium on Environment*, Athens, Greece. Athens Institute for Education and Research www.atiner.gr
- Brakas SG, Aune JB. 2011. Biomass and Carbon Accumulation in Land Use Systems of Claveria, the Philippines. In: Kumar BM, Nair PKR (eds) Carbon sequestration potential of agroforestry systems: Opportunities and challenges, vol 8, *Advances in Agroforestry*. Springer, Dordrecht Heidelberg, London, New York, pp 163
- Brown S, Lugo AE. 1982. The storage and production of organic matter in tropical forest and their role in the global carbon cycle. *Biotropica* 14(3):161
- Brown S. 1997. Estimating biomass and biomass change of tropical forests: a primer. *FAO Forestry paper* 134, Rome, 55 p

- 418 Brown S, Grais A, Ambagis S, Pearson T. 2012. Baseline GHG emissions from the
419 agricultural sector and mitigation potential in countries of East and West Africa. CCAFS
420 Working paper no. 13. CGIAR research program on climate change, agriculture and food
421 security (CAFS). Copenhagen, Denmark. www.cafs.cgiar.org
422 .
- 423 Chavan BL, Rasal GB. 2010. Sequestered Standing Carbon Stock in Selective Tree Species
424 Grown in University Campus at Aurangabad, Maharashtra, India. *International Journal of*
425 *Engineering Science and Technology*, 2, 3003-3007.
- 426
- 427 Chavan B. Rasal G. 2012. Total Sequestered Carbon Stock of *Mangifera indica*. *Journal of*
428 *Environment and Earth Science* 2(1): 37-48
429
- 430 Chave J, Andalo C, Brown S, Cairns M, Chambers J, Eamus D, Fölster H, Fromard F,
431 Higuchi N, Kira T, Lescure JP, Nelson B, Ogawa H, Puig H, Riéra B, Yamakura T. **2005**.
432 Tree allometry and improved estimation of carbon stocks and balance in tropical forests.
433 *Oecologia*. 145:87-99.
- 434 Chidumayo EN (1997) Miombo ecology and management: an introduction. Intermediate
435 Technology Publications in association with the Stockholm Environment Institute,
436 London, 166p
437
- 438 Chidumayo EN (2002) Changes in Miombo woodland structure under different land tenure
439 and
440 use systems in central Zambia. *J Biogeogr* 29:1619–1626
441
- 442 DeWald, S., Josiah, S., & Erdkamp, B. (2013). Heating With Wood: Producing, Harvesting
443 and Processing Firewood. University of Nebraska—Lincoln Extension, Institute of Agriculture
444 and Natural Resources. <http://www.ianrpubs.unl.edu/epublic/live/g1554/build/g1554.pdf>
445
- 446 Dossa E, Fernandes E, Reid W, and Ezui K. **2008**. Above- and belowground biomass,
447 nutrient and carbon stocks contrasting an open-grown and a shaded coffee
448 plantation. *Agroforestry Systems*. 72:103-115.
- 449 FAO. 1997. Estimating biomass and biomass change of tropical forests: a primer, Rome,
450 Italy: FAO Forestry Paper No. 134.
451
- 452 Gama-Rodrigues EF, Nair PKR, Nair VD, Gama-Rodrigues AC, Baligar V, Machado RCR
453 (2010). Carbon storage in soil size fractions under two cacao agroforestry systems in Bahia,
454 Brazil. *Environ Manag* 45:274–283
455
- 456 Haeberle, K. H., Agele, S.O. Matyssek, R. and Hennlich, M. 2016. Aspects of Water
457 Relations and Gas Exchange of Katsura and Tilia Seedlings Subjected to Wet-Dry Cycles :
458 Indication of Strategies for Whole Plant Drought Tolerance. *International Journal of Plant &*
459 *Soil Science* 10(2), 1 -13
- 460 Harmand JM, Hergoualc'h K, De Miguel S, Dzib B, Siles P, and Vaast P. 2007. Carbon
461 sequestration in coffee agroforestry plantations of Central America. In *Proceedings of the*
462 *21st ASIC Colloquium*; Montpellier; ASIC; Paris, pp. 1071-1074.

463 ICRAF.**2009**. Wood density database. *www.worldagroforestry.org/Seal?q=node/109*.

464 Ingram JSI, Fernandes ECM (2001) Managing carbon sequestration in soils: concepts and
465 terminology. *AgricEcosyst Environ* 87:111–117

466

467 IPCC. **2003**. Good practice guidance for land use, land-use change and forestry. *www.ipcc-*
468 *nggip.iges.or.jp*.

469 .

470 IPCC (2007) Climate change 2007: impacts, adaptation and vulnerability. In: Parry ML,
471 Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (eds) Contribution of working
472 group II to the fourth assessment report of the intergovernmental panel on climate change.
473 Cambridge University Press, Cambridge, UK, p 976

474

475 Ishaq S. Enejil*, Ofoegbu Obinna1, Emmanuel T. Azua 2014. Sequestration and Carbon
476 Storage Potential of Tropical Forest Reserve and Tree Species Located within Benue State of
477 Nigeria *Journal of Geoscience and Environment Protection*, 2, 157-166.
478 <http://dx.doi.org/10.4236/gep.2014.22022>

479

480 Jarecki MK, Lal R (2003) Crop management for soil carbon sequestration. *Critical Review*
481 *Plant Science* 22:471–502

482

483 Lemmon PE. **1956**. A spherical densiometer for estimating forest overstory density. *Forest*
484 *Science*. 315-321.

485 Kohler, M., Schwendenmann, L. and Holscher, D. 2010. Throughfall reduction in a cacao
486 agroforest: tree water use and soil water budgeting. *Agricultural and Forest*
487 *Meteorology* 150, 1079–1089

488

489 Lal R (2004) Soil sequestration in dryland ecosystems. *Environ Manag* 33:528–544

490

491 Lal R (2010) Managing soils and ecosystems for mitigating anthropogenic carbon emissions
492 and
493 advancing global food security. *Bioscience* 60:708–721

494

495 Montagnini F, Nair PKR (2004) Carbon sequestration: an under-exploited environmental
496 benefit
497 of agroforestry systems. *AgroforestSyst* 61:281–295

498

499 Muñoz F, Beer J (2001) Fine root dynamics of shaded cacao plantations in Costa Rica.
500 *AgroforestSystems* 51:119–130

501

502 Negash M, Starr M, Kanninen M, Berhe L (2013b) Allometric equations for estimating
503 aboveground biomass of *Coffea Arabica* L grown in the Rift Valley escarpment of Ethiopia.
504 *AgroforestSyst* 87:953 – 966. Doi 10.1007/s10457-011-9408-1

505

506

507 Nair PKR, Kumar BM, Nair VD (2009) Agroforestry as a strategy for carbon sequestration. *J*
508 *PlantNutrition and Soil Science* 172:10–23

509

- 510 Nair PKR, Nair VD, Kumar BM, Showalter JM (2010) Carbon sequestration in agroforestry
511 systems. *AdvAgron* 108:237–307
512
513
- 514 Schroeder P (1994) Carbon storage benefits of agroforestry systems. *AgroforestSyst* 27:89 -
515 97
516
- 517 Siles P, Harmand JM, Vaast P. **2010**. Effects of *Inga densiflora* on the microclimate of coffee
518 (*Coffea arabica* L.) and overall biomass under optimal growing conditions in Costa
519 Rica. *Agroforestry Systems*. 78 (3): 269-286.
- 520
- 521 Six J, Bossuyt H, Degryze S, Denef K (2004) A history of research on the link between
522 (micro)
523 aggregates, soil biota, and soil organic matter dynamics. *Soil Tillage Res* 79:7–31
524
- 525 Solomon D, Lehmann J, Zech W (2000) Land use effects on soil organic matter properties of
526 chromicluvisols in semi-arid northern Tanzania: carbon, nitrogen, lignin and carbohydrates.
527 *AgricEcosyst Environ* 78:203–213
528
- 529 Thangataa PH, Hildebrand PE (2012) Carbon stock and sequestration potential of
530 agroforestry systems in smallholder agroecosystems of sub-Saharan Africa: Mechanisms for
531 reducing emissions from deforestation and forest degradation (REDD+). *AgricEcosyst*
532 *Environ* 158:172 -183. doi: 10.1016/j.agee.2012.06.007
533
534
- 535 UNFCCC (2006) Revised simplified baseline and monitoring methodologies for selected
536 small-scale afforestation and reforestation project activities under the clean development
537 mechanism. Bonn. Available at
538 [http://cdm.unfccc.int/UserManagement/FileStorage/CDMWF_](http://cdm.unfccc.int/UserManagement/FileStorage/CDMWF_AM_A3II6AX6KGW5GGB7M6AI98UD3W59X4)
539 [AM_A3II6AX6KGW5GGB7M6AI98UD3W59X4](http://cdm.unfccc.int/UserManagement/FileStorage/CDMWF_AM_A3II6AX6KGW5GGB7M6AI98UD3W59X4). Accessed 7 Feb 2011
540
- 541 UNFCCC (2007) Report of the conference of parties on its thirteenth session, Bali, Indonesia.
542 United nations framework convention on climate change, Geneva
543
- 544 vanNoordwijk M, Rahayu S, Hairiah K, Wulan YC, Farida A, Verbist B (2002) Carbon stock
545 assessment for a forest-to-coffee conversion landscape in Sumber-Jaya
546 (Lampung, Indonesia): From allometric equations to land use change analysis. *Science in*
547 *China* 45:75– 86. <http://www.globalcarbonproject.org>
548
- 549 Verchot LV, Noordwijk MV, Kandji S, Tomich T, Ong C, Albrecht A, Mackensen J,
550 Bantilan C, Anupama KV, Palm C (2007) Climate change: linking adaptation and mitigation
551 through agroforestry. *Mitigation and Adaptation Strategies to Global Change* 12:901–918.
552 doi:10.1007/s11027-007-9105-6
553
554
555
556
557
558

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 Types	PAR ($\mu\text{mol}/\text{m}^2/\text{s}$)	LAI	RH (%)	VPD (kPa)	Temp ($^{\circ}\text{C}$)	Sunshine hour
a b c a b c a b c a b c a b c a b c						
2 – 4 years old field	587 745 987	1.6 2.3 1.4	7471 361.6 1.32	932 30.4 34	5.2 4.5 6.6	
25 – 40 years old field	471 669	921 1.8 2.6	1.877 80 391.5	1.1 2.4 312	8.5 31.6	
Agric. Field	828 1123	1464 1.1 1.4	0.85 65 70 311.8	1.53 2.33	31.7 34.2	

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: $\mu\text{mol}/\text{m}^2/\text{s}$), leaf area index (LAI),

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

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

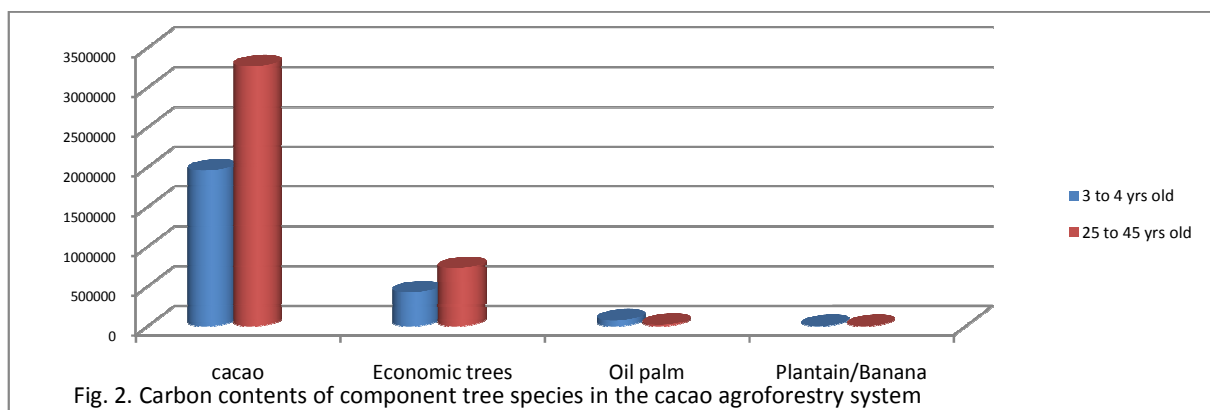
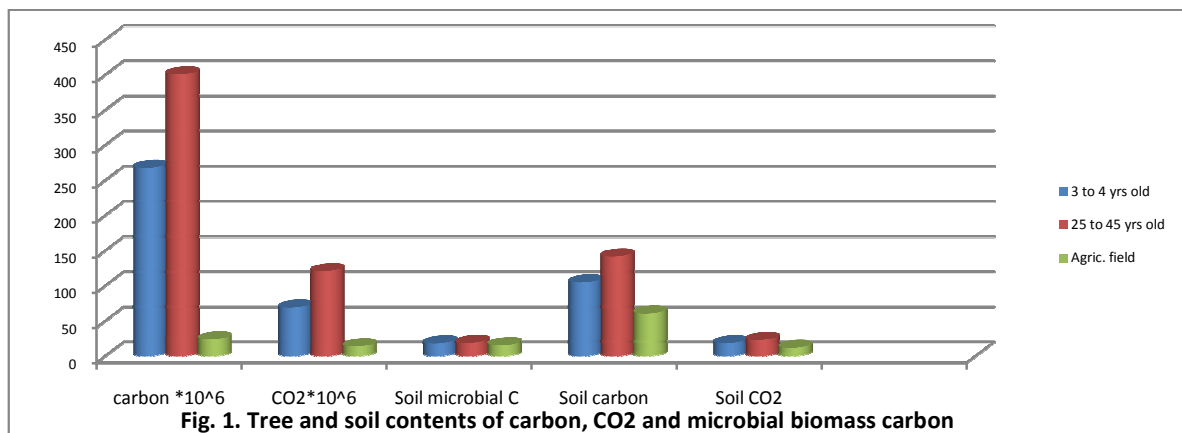
Table 3. Temporal trends in soil CO_2 evolution, microbial biomass carbon and soil carbon of the land use/land cover classes.

LCLUC Types	Soil CO_2	Microbial biomass C	Soil carbon
ab c a b c 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	8.79 57.2 9.7	11.2 8.1 49	62 31
Agricultural 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 the c: Dry (December to March) season.

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

LCLUC Types	Cacao Carbon	Other tree spp.	Soil carbon	Litter carbon	Total
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
Agric. Field	---	246346	66	1.1	246413.1



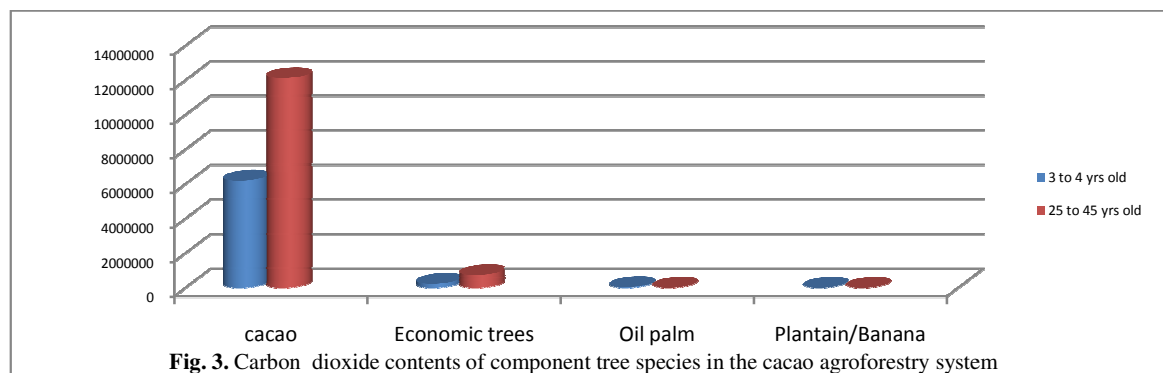


Fig. 3. Carbon dioxide contents of component tree species in the cacao agroforestry system

613