

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

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 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 can serve as 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 enhance 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, feedback, land use, landscape, 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" paradigm as 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. 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.

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

143 We adopted the method recommended by FAO. 1997 and Chavan and Rasal (2010) with
 144 slight modification into five stages as follows:
 145 The total (green) weight of tree based on tree species for tropical forest species, the weight of
 146 a tree is:
 147 W = Above-ground weight of the tree in kilogram (kg); D = Diameter of the trunk in inches;
 148 H = Height of tree in Meters.
 149 For trees with $D \leq 10$: $W = 0.25D^2H$ or trees with $D \geq 11$: $W = 0.15D^2H$ 1
 150
 151 The weight of the root system is estimated as 20% as much as the above-ground weight of the
 152 tree. The total green weight of the tree is determined as the product of the above-ground
 153 weight of the tree by 120 %. The dry weight of tree based was estimated based on the
 154 methods reported in the Extension Publication from the University of Nebraska (Chavan and
 155 Rasal, 2010). The mass of the content of carbon is estimated as 50% of the tree's total volume
 156 (DeWald et al., 2005). Therefore, the weight of carbon in the tree can be calculated as the
 157 product of tree dry weight by 50 %. The weight of carbon dioxide sequestered (CO_2) is
 158 composed of one molecule of Carbon and 2 molecules of Oxygen and The atomic weight of
 159 Carbon is 12.001115; The atomic weight of Oxygen is 15.9994). Hence,
 160
 161 The weight of CO_2 is $C + (2 * O) = 43.999915$ 2
 162 the ratio of CO_2 to C = $43.999915/12.001115 = 3.6663$ 3
 163
 164 Therefore, the weight of carbon dioxide sequestered in the tree was obtained as the product of
 165 the weight of carbon in the tree by 3.6663 (DeWald et al., 2005). The weight of CO_2
 166 sequestered in the tree per year was obtained as the ratio of the weight of carbon dioxide
 167 sequestered in the tree and the age of the tree. Aerial canopy biomass was assessed via the
 168 allometric relationship developed by Chave et al. (2005) after measuring the height and girth
 169 at breast height of all the trees in the sampling circle with a 10m radius circle (100 m²) and
 170 using species specific wood density data from ICRAF (2009). Tree biomass (W , dry weight)
 171 was estimated using the allometric equation (FAO, 1997, Chave et al., 2005) on the basis of
 172 stem diameter (D) at 1.3 m above the ground.
 173 The equation, specific to "Wet forest stand" of tropical areas is:
 174 Aerial biomass (in kg) = $0.0776 \times (\rho D^2 H)^{0.94}$ 4
 175 where ρ the wood specific density (in g/cm³), D the tree trunk diameter at breast height (in
 176 cm) and H the total tree height (in m). The coefficient c is based on the allometric
 177 relationship between tree height (H) and diameter (default value for $c = 0.62$).
 178
 179 These data were also used to calculate plot tree density and basal area. The aerial biomass of
 180 cacao, oil palm, plantain and banana and other economic timber and fruit tree species were
 181 estimated from allometric relationships based on Chave et al. (2005) for 10 plants per sample.
 182 The data on wood density was extracted from a wood density database created by ICRAF
 183 (World Agroforestry Centre 2010b).
 184 For cacao (*Theobroma cacao*) and banana (*Musasp.*) the following equations (van Noordwijk
 185 et al. 2002) were used.
 186
 187 Cacao : $0.281 * D^2.06$ 5
 188
 189 Banana : $0.03 * D^2.13$ 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 (Fison 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.

234 Results and Discussion

235 The growing season was grouped into Major (April to mid August) and Minor (mid August
236 to December) rainy season and the Dry (December to March) season. The minor season is
237 characterized by more overcast sky and lower air temperatures and higher relative humidity
238 compared with the major rainy season (Table 1). The rainy season had higher mean relative
239 humidity averaged (71 %) and lower air temperatures (32.8 °C) compared with the dry
240 season. Also, higher air temperature and VPD and lower relative humidity were found for the
241 unshaded open sun cacao compared with the shaded plants. Our results confirmed a general
242 moderating effect of canopy on below-canopy microclimate with a decrease of air
243 temperature of up to 4° C and an increase of relative humidity of up to 11 % (Table 1). The
244 forest tree species in the sampled ecosystems moderated microclimate about twice as much
245 as agricultural field. The moderating capacity was strongest particularly, during the dry
246 season, and depended on the general weather situation. In the dry season, the deviations from
247 the general seasonal weather condition patterns most likely occurred when soil moisture
248 pools were depleted. Despite the moderating capacity, below-canopy microclimate did not
249 lag behind agricultural field microclimate. Based on our results we conclude that natural
250 recruitment of cacao and other tree species for afforestation/reforestation may ecosystem
251 sensitively to climate change. The Kyoto Protocol establishes that land use, land use change
252 and forestry (LULUCF) activities such as afforestation, reforestation, and deforestation
253 (Article 3.3), and forest land management, cropland management, grazing land management.
254 Revegetation are proven practices/strategies to increase Carbon released and retained within
255 ecosystem. Agroforestry systems fulfill role in reducing carbon (C) emissions and promoting
256 C sequestration which would help to fulfill the Kyoto Protocol requirements. Forest canopy
257 moderates below-canopy air temperature and relative humidity (Table 1) and thus creates a
258 specific microclimate for tree growth. Climate change will alter the moderating capacity of
259 forest canopy. This may render the below-canopy conditions making it unsuitable for
260 recruitment of the hitherto dominant tree species. Cacao trees are the major carbon pools as
261 they represent over 50% of the total carbon sequestered in the landscape by cacao and other
262 timber and other fruit tree species (Fig. 1). However, the mature plantation (25 – 40 years old)
263 sequestered over 3 times more carbon compared with the young (3 – 4 years old field (Table
264 2). Table 3 presents the summary of the temporal trends in soil CO₂ evolution, microbial
265 biomass carbon and soil carbon of the land use/land cover classes. Seasonal differences in
266 CO₂ evolution, microbial biomass carbon and soil carbon were found among the land
267 use/land cover classes. Highest and lowest values of these parameters were obtained in minor
268 (August to December) and dry (December to March) seasons. The total values of the
269 measured CO₂ evolution (18, 20 and 105), microbial biomass (26, 29 and 142) and soil
270 carbon (16, 22 and 66) for the respective young (2 – 4 years old) and mature (25– 40 years old
271 cacao plantations and cultivated agricultural field respectively. The soil carbon and litter
272 were lowest for cultivated field and values were 66 and 1.1 (for cultivated field) and 105 and
273 2.3 and 143 and 3.2 for the respective 3 – 4 and 25 – 40 years old cacao plantations.
274 However, the total carbon pools/stocks were close between 3 – 4 years old plantation and
275 cultivated field (Table 4). The contributions of cacao trees, timber and other fruit tree species,
276 the soil and litter to total carbon sequestered in the landscapes were significant in this study.
277 In fig. 2 and 3 are presented the carbon and carbon dioxide contents of component tree
278 species in the cacao agroforestry system of the respective 3–4 and 25 – 40 years old fields.
279 Profoundly highest values (over 7 fold increase were found for cacao trees compared with
280 other economic tree species and very low values for oil palm and plantain/banana trees.
281 Carbon sequestration varies with age of cacao field as function of tree biomass and litter
282 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 agroforest 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 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 (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, Brown and Lugo, 1982, 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 (*Coffea* 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 (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 (Brown, 1997; Braka and Aune, 2011). 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) and Dossa et al. (2008) 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 (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 tree biomass, litterfall and soil C sequestration in agroforestry systems is currently is unexplored and unappreciated has environmental benefits. The findings 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. 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 –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. 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. 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.

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. *Advances in Agroforestry*. Volume 8. 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
- Brown S, Grais A, Ambagis S, Pearson T. 2012. Baseline GHG emissions from the agricultural sector and mitigation potential in countries of East and West Africa. CCAFS Working paper no. 13. CGIAR research program on climate change, agriculture and food security (CCAFS). Copenhagen, Denmark. www.ccafs.cgiar.org
- Chavan BL, Rasal GB. 2010. Sequestered Standing Carbon Stock in Selective Tree Species Grown in University Campus at Aurangabad, Maharashtra, India. *International Journal of Engineering Science and Technology*, 2, 3003-3007.
- Chavan B, Rasal G. 2012. Total Sequestered Carbon Stock of *Mangifera indica*. *Journal of Environment and Earth Science* 2(1): 37-48
- Chave J, Andalo C, Brown S, Cairns M, Chambers J, Eamus D, Fölster H, Fromard F, Higuchi N, Kira T, Lescure JP, Nelson B, Ogawa H, Puig H, Riéra B, Yamakura T. 2005. Tree allometry and improved estimation of carbon stocks and balance in tropical forests. *Oecologia*. 145:87-99.
- Chidumayo EN (1997) Miombo ecology and management: an introduction. Intermediate Technology Publications in association with the Stockholm Environment Institute, London, 166p

- DeWald, S., Josiah, S., & Erdkamp, B. (2013). Heating With Wood: Producing, Harvesting and Processing Firewood. University of Nebraska—Lincoln Extension, Institute of Agriculture and Natural Resources. <http://www.ianrpubs.unl.edu/epublic/live/g1554/build/g1554.pdf>
- Dossa E, Fernandes E, Reid W, and Ezui K. **2008**. Above- and belowground biomass, nutrient and carbon stocks contrasting an open-grown and a shaded coffee plantation. *Agroforestry Systems*. 72:103-115.
- FAO. 1997. Estimating biomass and biomass change of tropical forests: a primer, Rome, Italy: FAO Forestry Paper No.134.
- Gama-Rodrigues EF, Nair PKR, Nair VD, Gama-Rodrigues AC, Baligar V, Machado RCR (2010). Carbon storage in soil size fractions under two cacao agroforestry systems in Bahia, Brazil. *Environ Manag* 45:274–283
- Haeberle, K. H., Agele, S.O. Matyssek, R. and Hennlich, M. 2016. Aspects of Water Relations and Gas Exchange of Katsura and Tilia Seedlings Subjected to Wet-Dry Cycles : Indication of Strategies for Whole Plant Drought Tolerance. *International Journal of Plant & Soil Science* 10(2), 1 -13
- Harmand JM, Hergoualc'h K, De Miguel S, Dzib B, Siles P, and Vaast P. 2007. Carbon sequestration in coffee agroforestry plantations of Central America. In *Proceedings of the 21st ASIC Colloquium*; Montpellier; ASIC; Paris, pp. 1071-1074.
- ICRAF. **2009**. Wood density database. www.worldagroforestry.org/Sea/?q=node/109.
- Ingram JSI, Fernandes ECM (2001) Managing carbon sequestration in soils: concepts and terminology. *Agric Ecosyst Environ* 87:111–117
- IPCC. **2003**. Good practice guidance for land use, land-use change and forestry. www.ipcc-nggip.iges.or.jp.
- IPCC (2007) Climate change 2007: impacts, adaptation and vulnerability. In: Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (eds) Contribution of working group II to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, UK, p 976
- Ishaq S. Eneji^{1*}, Ofoegbu Obinna¹, Emmanuel T. Azua 2014. Sequestration and Carbon Storage Potential of Tropical Forest Reserve and Tree Species Located within Benue State of Nigeria *Journal of Geoscience and Environment Protection*, 2, 157-166. <http://dx.doi.org/10.4236/gep.2014.22022>
- Jarecki MK, Lal R (2003) Crop management for soil carbon sequestration. *Critical Review Plant Science* 22:471–502
- Lemmon PE. **1956**. A spherical densiometer for estimating forest overstory density. *Forest Science*. 315-321.

- Kohler, M., Schwendenmann, L. and Holscher, D. 2010. Throughfall reduction in a cacao agroforest: tree water use and soil water budgeting. *Agricultural and Forest Meteorology* 150, 1079–1089
- Lal R (2004) Soil sequestration in dryland ecosystems. *Environ Manag* 33:528–544
- Lal R (2010) Managing soils and ecosystems for mitigating anthropogenic carbon emissions and advancing global food security. *Bioscience* 60:708–721
- Montagnini F, Nair PKR (2004) Carbon sequestration: an under-exploited environmental benefit of agroforestry systems. *AgroforestSyst* 61:281–295
- Muñoz F, Beer J (2001) Fine root dynamics of shaded cacao plantations in Costa Rica. *AgroforestSystems* 51:119–130
- Negash M, Starr M, Kanninen M, Berhe L (2013b) Allometric equations for estimating aboveground biomass of *Coffea Arabica* L grown in the Rift Valley escarpment of Ethiopia. *AgroforestSyst* 87:953 – 966. Doi 10.1007/s10457-011-9408-1
- Nair PKR, Kumar BM, Nair VD (2009) Agroforestry as a strategy for carbon sequestration. *J PlantNutrition and Soil Science* 172:10–23
- Nair PKR, Nair VD, Kumar BM, Showalter JM (2010) Carbon sequestration in agroforestry systems. *AdvAgron* 108:237–307
- Schroeder P (1994) Carbon storage benefits of agroforestry systems. *AgroforestSyst* 27:89 - 97
- Siles P, Harmand JM, Vaast P. **2010**. Effects of *Inga densiflora* on the microclimate of coffee (*Coffea arabica* L.) and overall biomass under optimal growing conditions in Costa Rica. *Agroforestry Systems*. 78 (3): 269-286.
- Six J, Bossuyt H, Degryze S, Denef K (2004) A history of research on the link between (micro) aggregates, soil biota, and soil organic matter dynamics. *Soil Tillage Res* 79:7–31
- Solomon D, Lehmann J, Zech W (2000) Land use effects on soil organic matter properties of Chromic luvisols in semi-arid northern Tanzania: carbon, nitrogen, lignin and carbohydrates. *Agric Ecosyst Environ* 78:203–213
- Thangataa PH, Hildebrand PE (2012) Carbon stock and sequestration potential of agroforestry systems in small holder agroecosystems of sub-Saharan Africa: Mechanisms for reducing emissions from deforestation and forest degradation (REDD+). *AgricEcosyst Environ* 158:172 -183. doi: 10.1016/j.agee.2012.06.007

UNFCCC (2006) Revised simplified baseline and monitoring methodologies for selected small-scale afforestation and reforestation project activities under the clean development mechanism. Bonn. Available at http://cdm.unfccc.int/UserManagement/FileStorage/CDMWF_AM_A3II6AX6KGW5GGB7M6AI98UD3W59X4. Accessed 7 Feb 2011

UNFCCC (2007) Report of the conference of parties on its thirteenth session, Bali, Indonesia. United nations framework convention on climate change, Geneva

vanNoordwijk M, Rahayu S, Hairiah K, Wulan YC, Farida A, Verbist B (2002) Carbon stock assessment for a forest-to-coffee conversion landscape in Sumber-Jaya (Lampung, Indonesia): From allometric equations to land use change analysis. *Science in China* 45:75– 86. <http://www.globalcarbonproject.org>

Verchot LV, Noordwijk MV, Kandji S, Tomich T, Ong C, Albrecht A, Mackensen J, Bantilan C, Anupama KV, Palm C (2007) Climate change: linking adaptation and mitigation through agroforestry. *Mitigation and Adaptation Strategies to Global Change* 12:901–918. doi:10.1007/s11027-007-9105-6

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

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

	<u>Cacao trees in plantation</u>			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 CO₂ evolution, microbial biomass carbon and soil 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 the c: Dry (December to March) season.

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

LCLUC Types	<u>Carbon contents</u>				
	Cacao trees	Other tree spp.	Soil	Litter	Total 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

