Tropical and Subtropical Agroecosystems
E-ISSN: 1870-0462
ccastro@uady.mx
Universidad Autónoma de Yucatán
México

Agevi, Humphrey; Onwonga, Richard; Kuyah, Shem; Tsingalia, Mugatsia

CARBON STOCKS AND STOCK CHANGES IN AGROFORESTRY PRACTICES: A REVIEW

Tropical and Subtropical Agroecosystems, vol. 20, núm. 1, enero-abril, 2017, pp. 101-109
Universidad Autónoma de Yucatán
Mérida, Yucatán, México

Review [Revisión]

CARBON STOCKS AND STOCK CHANGES IN AGROFORESTRY PRACTICES: A REVIEW[1]

[ALMACENAMIENTO DE CARBONO Y CAMBIOS EN LAS RESERVAS POR PRACTICAS AGROFORESTALES: UNA REVISIÓN]

Humphrey Agevi[1*], Richard Onwonga[2], Shem Kuyah[3], Mugatsia Tsingalia[4]

1Department of Biological Sciences, Masinde Muliro University of Science and Technology (MMUST) P.O. Box 190-50100, Kakamega Kenya.
Email: hagevi@mmust.ac.ke
[2]Department of Land Resource Management and Agricultural Technology, University of Nairobi (UON)
[3]Department of Plant Sciences, Jomo Kenyatta University of Agriculture and Technology (JKUAT)
[4]Department of Biological Sciences, Moi University (MU)
**Corresponding author*

SUMMARY

Trees on farmlands and agricultural lands play a crucial role in small holder farmers' livelihoods in addition to carbon regulation through carbon sequestration. These trees have received much attention recently due to their contribution to climate change mitigation through carbon storage. Quantification of carbon stocks in these trees has always proven difficult due to the spatial extent of these trees and methodological difficulties encountered during measurement. This paper reviews a number of studies done in quantification of biomass and soil carbon stocks in agroforestry within tropics. Most appropriate method employed in determination of carbon stock changes is through use of allometric equations. The equations use parameters like diameter at breast height (DBH), height, crown area which can be measured during field inventory. DBH has always proven to be the best parameter to be used in the equation since it is easy to measure and it does not need expensive equipments. Apart from trees, soils in agricultural lands have the capacity to store carbon and help mitigate effects of climate change. It then identifies the gap that future research can be done for accurate carbon quantification.

Key words: Agroforestry; Carbon sequestration; Allometric equations; Biomass; Climate change.

RESUMEN

Los árboles de las tierras de cultivo y las tierras agrícolas desempeñan un papel crucial en los medios de subsistencia de los pequeños agricultores, además de la regulación del carbono mediante el secuestro del carbono. Estos árboles han recibido mucha atención recientemente debido a su contribución a la mitigación del cambio climático mediante el almacenamiento de carbono. La cuantificación de las reservas de carbono en estos árboles siempre ha resultado difícil debido a la extensión espacial de estos árboles y a las dificultades metodológicas encontradas durante la medición. Este artículo revisa una serie de estudios realizados en la cuantificación de la biomasa y las reservas de carbono del suelo en la agrosilvicultura dentro de los trópicos. El método más apropiado empleado en la determinación de las variaciones del stock de carbono es el uso de ecuaciones alométricas. Las ecuaciones utilizan parámetros como el diámetro a la altura del pecho (DBH), altura y área de la corona que se puede medir durante el inventario de campo. DBH ha demostrado siempre ser el mejor parámetro a ser utilizado en la ecuación puesto que es fácil de medir y no necesita equipos costosos. Aparte de los árboles, los suelos de las tierras agrícolas tienen la capacidad de almacenar el carbono y ayudar a mitigar los efectos del cambio climático. Se identifican las brechas que la investigación futura puede realizar para la cuantificación más exacta de carbono.

Palabras clave: Agroforestería; Secuestro de carbón; Ecuaciones alométricas; Biomasa; cambio climático.

[1] *Submitted December 20, 2016 – Accepted March 06, 2017.*

INTRODUCTION

Global warming is real and there is a growing interest in the role of different land use systems in stabilizing atmospheric CO_2 concentration (1PCC, 2014). Primary attention has been given to forests, which account for 45% of terrestrial carbon stocks and are responsible for 17% of annual radiative forcing through deforestation (IPCC, 2007, 2010). It is however, notable that trees in other land use systems such as farmlands have greater potential for emission/sequestration because of their spatial extent. A recent global survey has shown that over 45% of agricultural lands globally have more than 10% tree-cover (Zomer *et al*., 2009). Biomass carbon stocks in agricultural lands have also been shown to range between 3–18 t C ha^{-1} (Nair, 2012; Nair and Nair, 2014). Whereas research on carbon sequestration has traditionally been biased towards forests, recent initiatives are emphasizing the need to assess the role of trees outside forests, under different agroforestry practices (de Foresta *et al*., 2013). This includes trees under different agroforestry practices.

Agroforestry traditionally includes trees under different systems, including silvopastoral, agrisilvicultural, agrosilvopastoral systems (Nair *et al.*, 2009). The components of these systems include perennials such as trees and shrubs, crops and other herbaceous species, and animals. Agroforestry practices include woodlots, dispersed, hedgerows, boundary planting, home gardens, taungya among others. In addition to climate regulation function (through carbon sequestration), tree in agroforestry contribute to soil protection, water regulation, enhancement of local climate conditions, reduces impacts on natural forests and other environmental benefits (Mbow *et al*., 2014b). Integration of trees on farms has also been shown to improve land productivity and resilience of households through provision of diversified products for sustaining livelihoods (Kahiluoto *et al.,* 2014; Lasco *et al*., 2014; Mbow *et al.,* 2014a).

In spite of the high potential of agroforestry systems to generate ecosystem services, they have received disproportionately lower attention than forest ecosystems (Kumar and Nair, 2004; Mcneely and Schroth, 2006). Limited data on the contribution of agroforestry systems to C sequestration in sub-Saharan Africa and the lack of easily adoptable methodologies and verification process of C sequestration undermine smallholders' potential for sequestering carbon (Kahiluoto *et al*., 2014). Robust methods for carbon accounting are needed for estimating changes in carbon pools over time and ascertaining the role of agroforestry as an alternative strategy for C sequestration. It is therefore timely, that our current understanding of agroforestry is evaluated and its realistic potential as a biological approach to C sequestration assessed. In this review, we sought to comprehensively review the existing literature and studies done within agroforestry in order to (1) analyse the need for carbon stock determination within agroforestry; (2) relationship between tree diversity on lands and carbon stocks and (3) determine tree biomass and soil carbon stocks within agroforestry systems. In doing so, we aim to provide synthesis of relationship between tree diversity on farmlands and tree biomass and provide an overview of carbon stock and stock changes determination on farmlands with an aim of providing a gap that future research can be done for accurate carbon determination.

Literature review methodology

Peer-reviewed literature related to agroforestry and climate change was identified from two databases (Web of Science, and Scopus) using the search terms “agroforestry practises”, “carbon sequestration”, “biomass quantification on farmlands”, “soil organic carbon”, “allometric equations,” and “Trees on farms”. This was supplemented by search on Google and Google scholar to identify other published articles and find web pages that might provide references. Published articles, theses, reports, conference proceedings and working papers were examined to identify potential peer reviewed publications that had arisen from the work, or presence of relevant citations. Papers reviewed including the additional identified in reference section were limited to those published from 2000 to 2016 as they contain the current information studied under the topic of study and for practical reasons.. This was then narrowed down to studies within tropics in relation to carbon stock and stock changes. Data was compiled from a wide variety of studies that were conducted under diverse biophysical conditions using a range of methodologies for quantifying carbon stocks dynamics (e.g., different sampling protocols, soil properties, and climatic factors. A total of 400 peer reviewed journal articles that reported studies from different areas within the tropics were used. Reviewer bias was reduced by having each of the four (4) authors appraising a random sample of three (3) publications. Consequently, about 20% of the studies were assessed by two authors to determine the repeatability of the selection criteria. Therefore, overall figures on carbon stocks and dynamics shown are based on results obtained by different measurement techniques with inherent and contrasting sources of error. The information retrieved was analysed and is presented under the following headings. i) Agroforestry, ii) tree density and diversity, iii) Tree biomass estimation in agroforestry, iv) Carbon sequestration in agroforestry, v) Soil organic carbon stocks and agroforestry. Finally, a general overview of carbon stock and stock changes on farmlands is presented outlining the main findings and gaps on research.

Agroforestry, tree density and diversity

Tree densities in farming landscapes range from low cover of about 5% in the Sahel to more than 45% in humid tropical zones where cocoa, coffee and palm oil agroforestry systems prevail (Zoomer *et al*., 2009; Mbow *et al*., 2014). In sub- Saharan Africa, 15% of farms have been shown to contain a tree cover of at least 30% (Zoomer *et al*., 2009). This clearly demonstrates that trees on farmlands have high capacities to sequester carbon and mitigate effects of climate change. According to Negash (2013) and Negash and Starr (2015), trees on farmlands maintain a high number of species outside their native forest habitat. Several studies have also reported high number of plants species in tropical agroforestry systems (Nair *et al*., 2009). So far, more than 3000 tree species have been documented within agroforestry practises in the world over (Simons and Leakey 2004; Negash, 2013). There are considerable differences in species richness between agroforestry systems. The highest numbers of plant species occur in traditional agroforestry systems, followed by coffee systems, tree-crop systems and cocoa systems, suggesting that traditional agroforestry systems are better for conservation of species than non-traditional systems (Negash, 2013; Nair and Nair, 2014; Negash and Kanninen, 2015). This difference in species richness appears to result from different management practices. There are four tropical agroforestry practises that have recorded the highest number of plant species: (1) home gardens in west Java, Indonesia, (2) Home garden in Chagga, on the border between Tanzania and Kenya, (3) trees on agricultural lands around Mount Kenya, and (4) traditional home gardens, south-west Bangladesh. Kabir and Webb (2009) reported 419 plant species (59% native, including six species Red Listed by International Union for Conservation of Nature (IUCN)) in home gardens from six regions across south-western Bangladesh. In Kenya, studies on land use and especially in areas with high population densities and heavy intensities of agricultural land use, have reported that planted and managed trees and shrubs usually cover between 5-10% of agricultural lands (Sikuku *et al*., 2014). Although planted tree species are introduced, such as *Grevillea robusta*, *Eucalyptus sp*. Or *Acacia mearnsii*, a number of indigenous species such as *Markhamia sp*. *Croton sp*., and *Sesbania sesban* also feature in farmers' range of choices (Cheboiwo, 2004). Different tree species are used in different regions for instance, *Grevillea robusta* and *Cupressus lusitanica* in Central Kenya; yellow oleander (*Thevetia peruviana* L.), Tithonia (*Tithonia diversifolia* L.), Sesbania (*Sesbania sesban*), *Acacia mearnsii* in Western Kenya, *Casuarina equisetifolia* in the Coastal strip and *Markhamia platycalyx* in parts of Nyanza region. Sikuku *et al.* (2014) found out that of 29 indigenous species identified across the farms in Lugari sub-county of the Kakamega Country, a significantly higher number of farmers (35%) were planting *Markhamia lutea*. This was followed by *Spathodea nilotica* (33.3%) and *Croton macrostachyus* (18.3%). Exotic species most preferred by farmers were *Cupressus lusitanica* and *Grevillea robusta* in (85%) and (83%) on farms respectively, followed by *Pinus patula* and *Jacaranda mimosifolia* in 30% of the farms. Fewer farmers (28%) grew *Eucalyptus saligna.* It is evident that both exotic and indigenous species are preferred for in many forms of agroforestry practices. The choice of species, however, depends on geographical location, size of the farm and the purpose for which the species are grown.

Tree biomass estimation in agroforestry

In the estimation of tree biomass, the use of allometric equations is the most appropriate since it is non destructive. Tree parameters such as diameter at breast height (DBH), height crown area, wood density are measured and fitted in the allometric equations (Chavez *et al*., 2005; Chave *et al*., 2014; Zhang *et al*., 2016). According to Hunter *et al.* (2013), if total tree height is available, allometric models usually yield less biased estimates. However, tree height has often been ignored in carbon-accounting programs because measuring tree height accurately is difficult, especially in agroforestry where most trees do not have accurate architectural patterns that determine height. Whether or not to include tree height as a predictor of aboveground biomass (AGB), however, generated serious controversies in the global change community (Baccini *et al*., 2012). In studies done in western Kenya by Kuyah and Rosenstock (2014), it was found that inclusion of height, wood density or crown area in biomass equation changed biomass estimates by a trivial amount, less than 1.2 Mg or 1.3% of total biomass, from those obtained by using the diameter alone. This finding is in agreement with most studies (Basuki *et al*., 2009: Bastien-Henri *et al*., 2010; Henri *et al*., 2011; Agevi *et al*., 2016). Given the complexities and potential errors in measuring other parameters such as sloped topography or dense foliage when measuring height), which require specialised equipments (e.g. hypsonometer or clinometer for height), or destructive measurements (e.g. wood density), the use of DBH alone appears cost effective and robust for most purposes. According to Kuyah *et al.* (2012a), tree diameter is the most widely preferred predictor variable because it can be measured with ease and high accuracy, and explains over 95% of the variability observed in aboveground biomass. A study by Sileshi (2014) and Kuyah *et al*. (2016) in Miombo woodlands in Malawi and Zeng *et al*. (2016) found out that diameter at breast height was significantly correlated with the aboveground biomass of trees, accounting for over 95% of the variation in aboveground biomass. It was concluded that DBH alone is a robust proxy for trees on farm, because DBH only equations are simpler, less costly and provide more effective predictions in estimating biomass in agricultural lands. Kuyah *et al*. (2016,) has, however, noted that published models overestimate biomass - a demonstration of the need to consider the DBH range in applying biomass models. The application of models outside their DBH range will result in bigger errors, especially for the larger trees. Information on error breakdown is important since uncertainty in the resultant biomass depends on the size of the tree, and the individual trees of a particular size.

Carbon sequestration in agroforestry

A number of studies have shown that agroforestry in the tropics has higher C densities than field crops or pasture (Albrecht and Kandji, 2003; Nair *et al.*, 2009; Nair, 2012). Currently, agroforestry is estimated to be practiced on an estimated 1000 billion hectares globally. Zoomer *et al.* (2009) estimated agroforestry to cover 1 billion ha of which 32% is in South America, 19% in sub-Saharan Africa, 13% in south-east Asia and the reminder in Europe and North America (Table 1). Agroforestry sequesters from 30 to 322 Pg C yr^{-1} (Jose and Bardhan, 2012). An additional 12,000 t C yr^{-1} could be sequestered, increasing to 17,000 Mg C yr^{-1} by 2040, if tree management practices are improved. Extensive reviews by Luedeling and Neufeldt (2012) for West African Sahel countries (from arid Sahara desert to humid region Guinea) showed biomass C stocks ranging from 22.2 to 70.8 Mg C ha^{-1}. According to Nair *et al.* (2009), available estimates of C stored in agroforestry range from 0.29 Mg C $ha^{-1}yr^{-1}$ for a fodder bank agroforestry system in West African Sahel to 15.21 Mg C $ha^{-1}yr^{-1}$ above ground and 30 to 300 Mg C ha^{-1} up to 1 m depth in the soil (Nair *et al*., 2011).

A study by Mutuo *et al*., (2005) of agroforestry systems in humid tropics showed that they could sequester up to 70 Mg C ha^{-1} in aboveground biomass. Negash (2013) found out that trees on farms accounted for 74 % of the total aboveground biomass, an indication that most carbon is stored in trees in agricultural lands. The average aboveground C storage potential of agroforestry systems in semiarid, sub-humid, humid and temperate regions has been estimated to be 9, 21, 50 and 63 Mg C ha^{-1}, respectively (Montagnini and Nair 2004). Estimates of aboveground C-sequestration potential (CSP) are based on the assumption that 45% to 50% of branch and 30% of foliage dry weight constitute C (Shepherd and Montagnini, 2001; Schroth *et al*., 2002; Nair *et al*., 2011). Oelbermann *et al.* (2004) reviewed the potential to sequester C in aboveground components in agroforestry systems is estimated to be 2.1 × 109 Mg C y^{-1} in tropical and 1.9 × 109 Mg C y^{-1} in temperate biomes. In sub-Saharan African, C sequestration in agroforestry systems (park land, live fence, and home gardens) range from 0.2 to 0.8 Mg C ha-1 y -1 while in rotation woodlots C sequestration ranges from 2.2 to 5.8 Mg C ha^{-1} y^{-1} (Luedeling *et al.* 2011). The C sequestration potential in biomass and soil of agroforestry systems in East and West Africa is estimated to be 6–22 Mg CO_2 ha^{-1} y^{-1} (Brown *et al*. 2012) (Table 2).

Table 1: Area of coverage under agroforestry practices

Region	Area under coverage (%)
South America	32
Sub-Saharan Africa	19
South East Asia	13
Europe and North America	36

Source: Zoomer *et al*., (2009)

Table 2: Range of tree biomass held by trees in different regions

Author	Region	Biomass ($MgCha^{-1}$)
Montagnini and Nair (2004)	Semi arid region	9
	Sub-humid	21
	Humid	50
	Temperate	63
Mutuo *et al*. (2005)	Humid	70
Nair *et al*. (2009)	West African countries	0.29-15.21
Luedeling and Neufedt (2012)	West African countries	22.2-70.8
Kuyah *et al.* (2012)	Western Kenya-E. Africa	13-19

In general, temperate agroforestry systems have lower C sequestration rates compared to tropical agroforestry systems (Nair *et al*. 2009; Srivastava *et al.* 2012). High density of carbon in agricultural lands including agroforestry is related to the high tree diversity that increases plant production hence increased biomass. It also depends on species composition and the rotation age, tree species selection and management intensity, and site condition (soil, topography, and rainfall), land use types among others (Mbow *et al*., 2014b). Nair *et al.* (2010) elaborated on the need for rigorous and consistent procedures to measure the extent of C sequestration in agroforestry systems, pointing out accurately that the current methods of estimating C varied widely and the estimations were based on several assumptions. Accordingly, large-scale global models based on such measurements and estimations were more likely to result in serious under- or overestimations of C in agroforestry practices. This is because of several erroneous assumptions, operational inadequacies and inaccuracies commonly found in the current literature. Consequently, several practical recommendations for researchers have been provided, that include using accurate description of the methods and procedures among others. This would help other researchers to examine their datasets and incorporate them into larger databases to help agroforestry earn its deserving place in mainstream efforts in climate change mitigation.

Soil organic carbon stocks and agroforestry

Soil is the largest pool of terrestrial organic carbon in the biosphere, storing more C than is contained in plants and the atmosphere combined (Post and Kwon, 2000) and a relatively stable pool of various organic and inorganic C fractions. They play a key role in the global carbon budget and greenhouse effect. Studies by Lal (2004) found out that the total quantity of organic C in soils is approximately 1500 Pg, which is approximately twice the C content present in the atmosphere. The amount of soil organic carbon (SOC) in agroforestry systems differs with regions, agroforestry systems and soil depths (Negash, 2013). Studies in Brazil have also shown that SOC stocks to 1 m depth could reach 408 Mg C ha-1 for silvopastoral systems (Nair *et al.*, 2010). SOC stocks in the 0−40 cm layer were the highest for silvopastoral systems, followed by tree crop, coffee and traditional systems. Most studies showing improvements of SOC in agroforestry systems have concentrated on changes in the topsoil layer, 0–30 cm, where the largest C pools are detected (Makumba *et al*., 2007; Oelbermann and Voroney, 2007). The SOC stocks in agroforestry systems are noticeably high compared to the SOC stocks of other ecosystems and soils. A study of silvopastoral systems with slash pine (*Pinus elliottii*) + bahiagrass (*Paspalum notatum*), and an adjacent open pasture with bahiagrass at four sites, representing spodosols and ultisols, in Florida, USA, Haile *et al*. (2008) reported that SOC across four sites in whole soil at different depth classes up to 120cm below surface was higher under silvopasture by an overall average of 33% near trees and 28% in the alleys between tree rows as compared to adjacent open pasture. The results suggest that most of SOC in deeper soil profiles are from tree components (C3 plants) in the pasture systems, and therefore the tree-based pasture system has greater potential for C sequestration compared with the treeless system. In comparing three agrorestry systems in Ethiopia, Negash *et al.* (2015) found out that altitude affects SOC. The highest SOC stocks were at high latitudes (343 Mg C ha^{-1}) and the lowest biomass C stocks were at low latitudes (121 Mg C ha^{-1}). Several factors affect the SOC to biomass C ratio in agroforestry systems including how long the agroforestry system has been practiced, tree species included and rotation age (Montagnini and Nair 2004), elevation and climate (Soto-Pinto *et al*., 2010), soil type (Lal, 2004), silvicultural management (e.g. planting density, pruning, thinning), and land-use history (Nair et al., 2009). The maintenance of high SOC levels ensures the productivity of the systems, and indirectly provides the livelihood and supports a high population density.

Litterfall also contributes to C stock accumulation in soil. It is the most important known pathway connecting vegetation and soil, and is a good indicator of aboveground productivity (Köhler *et al.* 2008, Silva *et al.* 2011). Little has been reported on the contribution of litterfall production in agroforestry systems. The impact of any agroforestry system on soil C sequestration depends largely on the amount and quality of input provided by tree and non tree components of the system and on properties of the soils themselves, such as soil structure and their aggregations. Changes in vegetation component, litter, and soil characteristics modify the C dynamics and storage in the ecosystem which in turn may lead to alterations of local and regional climate systems. Studies done in republic of Congo found that litterfall and litter decomposition greatly affected SOC. Litter decomposition accounted for 44% of soil CO_2 flux in the in agroforestry stands (Nouvellon *et al*., 2012) an indication that quality and quantity of litter greatly affects SOC. Litterfall production and quality varies with stand characteristics (tree size, species, foliar biomass and age), geographic location (climate), site soil, season, and management practice (Liu *et al.*, 2004; Starr *et al.*, 2005; Dawoe *et al*., 2010; Murovhi *et al*. 2012).

Overview of carbon stock and stock changes on farmlands

Tree biomass estimation has been done in forest ecosystems and pure stand selection. Whereas trees in other land uses including agroforestry play a key role in climate change mitigation, it is until recently that such trees received much attention (Kuyah and

Rosenstock, 2015). There is thus more that needs to be done in terms of research in such trees to ascertain the relationship between tree species, tree biomass soils, climate and attitude and how this have impact in mitigating climate change effects. Tree diversity determination in agroforestry systems and its role in carbon sequestration is very critical. These trees have an impact in the quality of soil organic matter and hence the quality of soil organic matter. The influence of soils, climate needs to be determined as they influence the type of species growing in a region and hence the sequestration potential.

Tree biomass estimation in agricultural lands poses a challenge due to the tree architecture and methodological difficulties involved. There is need therefore for a combination of methods to be used and compared with previous findings in the same area that will give the clear tree biomass. For this to be enhanced there is need for accurate measurements of tree parameters that will be fitted in the allometric equation. Tree diameter has mostly been measured and used as the only parameter in most allometric equations. This is because it can be measured with ease and high accuracy, and explains over 95% of the variability observed in aboveground biomass. There is need however to compare both allometric equations that uses only DBH or combine tree diameter with other tree variables like height, wood density and so on (Henry *et al*., 2011). It is also important to compare a number of developed allometric equations since the equations mostly differ with tree species and geographic region where they were mostly employed. Since most equations use conversion factor developed by IPCC, it is important to develop local conversion factors or use locally developed equations that suits the conditions and species of the site under investigations (IPCCC, 2014). The findings of tree biomass in different tree species in agroforestry are able to give the sequestration potential. There is however need to compare which form of agroforestry stores more carbon based on the cumulative amounts of tree biomass in each of the agroforestry type identified and based on the age of trees as determined by its diameter. Tree biomass alone cannot provide the sequestration potential of agroforestry. This is because apart from trees, soils are also carbon reservoirs. There is thus the need to determine the soil carbon stocks and the same be compared with areas that differ in altitude, climate among other factors. Since trees play a key role in determining the quality of carbon stored in soils, there is need to also review the soil storage potential based on tree species diversity, climatic factors and management practises conducted on these trees and also in soils. Simulations through modelling needs also to be combined with field inventory under tier three of IPCC to accurate results of how agroforestry can mitigate climate change by acting as carbon sinks. Changes in soil C stocks are slow under field conditions, taking several years to assess. This is because long-term field experiments including soil C measurements are rare in the developing world leaving modelling as the best practical means of making projections for most developing countries and climate change interventions.

CONCLUSIONS

Tree on farm have a vital role in mitigating the effects of climate change. Both soils and trees are significant. Their impact needs to be researched further to investigate other dynamics and interlinkages that will effectively and accurately measure the carbon storage potential of agricultural lands. Tree biomass held in trees vary from one region to the other and is dependant on species density, age, climatic factors and soil factors. In Subsharan Africa, it ranges from 0.29-15.2MgCha^{-1}. The amount of soil organic carbon (SOC) in agroforestry systems differs with regions, agroforestry systems and soil depths. It ranges from 30-300 MgCha^{-1}. It is important also to determine the effect of tree diversity, edaphic factors, and climatic factors on sequestration potential in agroforestry systems. This can be achieved through determination of changes in biomass in different agrorestry systems in different geographic regions.

REFERENCES

Agevi, H., Tsingalia, M., Wabusya, M., Kigen, C., Kawawa, R., Obiet, L., and Tarus, G. 2016. Diversity and Biomass Variation in Masinde Muliro University of Science and Technology. Researchjournali's Journal of Forestry 3(3):1-11. http://www.researchjournali.com/view.php?id=2784

Albrecht, A., Kandji, S.T, 2003. Carbon sequestration in tropical agroforestry systems. Agriculture Ecosystem and Environment 99:15–27. doi:10.1016/S0167-8809(03)00138-5.

Baccini, A., Goetz, S.J. and Walker, W.S.2012. Estimated carbon dioxide emissions from tropical deforestation improved by carbon-density maps. Nature Climate Change, 2: 182–185.

Bastien-Henri, S., Park, A., Ashton, M., Messier, C. 2010. Biomass distribution among tropical trees species grown under differing regional climates. Forest Ecology and Management 260: 403–410.

Basuki, T.M., Van Laake, P. E., Skidmore, A. K. and Hussin, Y.A. 2009. Allometric equations for estimating the above-ground biomass in tropical lowland Dipterocarp forests. Forest Ecology and Management 257(8):1684-1694

Beer, J., Muschler, R., Kass, D. and Somarriba, E. 1998. Shade management in coffee and cacao plantations. Agroforestry Systems 38:139–164.

Brown, S., Grais, A., Ambagis, S. and 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. Available online at: www.ccafs.cgiar.org

Brown, S. 1997. Estimating biomass and biomass change of tropical forests: a primer. (FAO Forestry Paper 134). Food and Agriculture Organization of the United Nations (FAO), Rome

Brown, S. and Lugo, A.E. 1982. The storage and production of organic matter in tropical forest and their role in the global carbon cycle. Biotropica 14(3):161−187.

Chave, J., Réjou-Méchain, M., Búrquez, A., Chidumayo, E., Colgan, M.S., Delitti, W.B., Duque, A., Eid, T., Fearnside, P.M. and Goodman, R.C., 2014. Improved allometric models to estimate the aboveground biomass of tropical trees. Global Change Biology 20:3177-3190. DOI: 10.1111/gcb.12629

Chave, J., Andalo, C., Brown, S., Cairns, M.A., Chambers, J.Q., Eamus, D., Fo¨lster H, Fromard, F., Higuchi, N., Kira, T., Lescure, J.P., Nelson, B.W., Ogawa, H., Puig, H., Rie´ra, B. and Yamakura, T. 2005. Tree allometry and improved estimation of carbon stocks and balance in tropical forests. Oecologia 145(1):87–99.

Cheboiwo, J. K. 2004. Economic and Non-Economic Determinants of Farm Forestry Development in Western Kenya: A Case of Uasin Gishu and Vihiga. D. Phil. Thesis, Moi University, Kenya.

Dawoe, E.K., Isaac, M.E. and Quashie-Sam, J. 2010. Litterfall and litter nutrient dynamics under cocoa ecosystems in lowland humid Ghana. Plant Soil 330:55–64.

de Foresta, H., Somarriba, E., Temu, A., Boulanger., Feuilly, H. and Gauthier, M. 2013. Towards the Assessment of Trees Outside Forests. In: Resources Assessment Working Paper 183. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy

Haile, S. G., Nair, P. K. R. and Nair, V. D. 2008. Carbon storage of different soil-size fractions in Florida silvopastoral systems. Journal of Environmental Quality 37: 1789–1797.

Henry, M., Picard, N., Trotta, C., Manlay, R.J., Valentini, R. and Bernoux, M.2011. Estimating tree biomass of sub-Saharan African forests: a review of available allometric equations. Silva Fenn 45:477-569.

Hunter, M.O., Keller, M., Vitoria, D., Morton, D.C. 2013. Tree height and tropical forest biomass estimation. Biogeosciences Discussions, 10: 10491–10529.

IPCC: Summary for policymakers, in: Climate Change 2014. Mitigation of Climate Change, contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P., Kriemann, B., Savolainen, J., Schlomer, S., von Stechow, C., Zwickel, T., and Minx, J. C., Cambridge University Press, Cambridge, UK and New York, NY, USA, pp.1–30

IPCC, 2010. Use of models and facility-level data in greenhouse gas inventories. Proceedings of the IPCC Expert Meeting on Use of Models and Measurements in Greenhouse Gas Inventories. Sydney, NSW, Australia.

IPCC, 2007. Climate change 2007. Impacts, adaptation and vulnerability. In: Parry ML, Canziani OF, Palutikof JP, van der Plant Soil 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.

Jose, S. and Bardhan, S. 2012. Agroforestry for biomass production and carbon sequestration: An overview. Agroforestry Systems 86:105–111. doi:10.1007/s10457-012-9573-x

Köhler, L., Hölscher, D. and Leuschner, C. 2008. High litterfall in old-growth and secondary upper montane forest of Costa Rica. Plant Ecology 199:163–173.

Kumar, B.M. and Nair, P.K.R.2004. The enigma of tropical home gardens. Agroforestry Systems 61: 135–152.

Kuyah, S., Sileshi, G.W. and Rosenstock, T.S. 2016. Allometric Models Based on Bayesian Frameworks Give Better Estimates of Aboveground Biomass in the Miombo Woodlands. Forests 7: 13; doi:10.3390/f7020013

Kuyah, S., and Rosenstock, T.S., 2015. Optimal measurement strategies for aboveground tree biomass in agricultural landscapes. Agroforestry systems 89: 125-133. DOI 10.1007/s10457-014-9747-9.

Kuyah, S., Dietz, J., Muthuria, C., Jamnadassa, R., Mwangi, P, Coe, R. and Neufeldt, H. 2012a. Allometric equations for estimating biomass in agricultural landscapes: I. aboveground biomass. Agricultural Ecosystems and Environment 158:216–224

Kuyah, S., Muthuri, C., Jamnadass, R., Mwangi, P., Neufeldt, H. and Dietz, J. 2012b. Crown area allometries for estimation of aboveground tree biomass in agricultural landscapes of western Kenya. Agroforestry Systems 86(2):267–277.

Lal, R. 2004a. Soil carbon sequestration impacts on global change and food security. Science 304: 1623-1627.

La Scala, N., Lopes, A., Spokas, K., Archer, D., Reicosky, D.C. 2009. Short-term temporal changes of bare soil CO2 fluxes after tillage described by first-order decay models. European Journal of Soil Science 60: 258–264.

Lemma, B., Kleja, D.B., Olsson, M., Nilsson, I., 2007. Factors controlling soil organic carbon sequestration under exotic tree plantations: a case study using the CO2FIX model in southwestern Ethiopia. Forest Ecological Management 252, 124–131.

Liu, C., Westman, C., Berg, B., Kutsch, W., Wang, G.Z., Man, R., Ilvesniem, H. 2004. Variation in litterfall-climate relationships between coniferous and broadleaf forests in Eurasia. Global Ecology and Biogeography 13:105–114.

Luedeling, E., Sileshi, G., Beedy, T. and Dietz, J. 2011. Carbon sequestration potential of agroforestry systems in Africa. In: Kumar, B.M. and Nair, P.K.R. (Eds.). Carbon sequestration potential of agroforestry Systems: opportunities and challenges. Advances in Agroforestry. Springer Netherlands. p. 61−83.

Makumba, W., Akinnifesi, F. K., Janssen, B., Oenema, O. 2007: Long-term impact of a gliricidia-maize intercropping system on carbon sequestration in southern Malawi. Agricultural Ecosystem and Environment 118: 237–243.

Masera, O.R., Garza-Caligaris, J.F. and Kanninen, M. 2013. Modeling carbon sequestration in afforestation, agroforestry and forest management projects: the CO2FIX V.2 approach. Ecological Modelling 164(2–3), 177–199.

Mbow, C., Smith, P., Skole, D., Duguma, L. and Bustamante, M. 2014b. Achieving mitigation and adaptation to climate change through sustainable agroforestry practices in Africa. Current Opinion on Environmental Sustainability 6: 8–14.

Mcneely, J.A. and Schroth, G. 2006. Agroforestry and biodiversity conservation traditional practices, present dynamics, and lessons for the future. Biodiversity Conservation 15: 549–554.

Montagnini, F. and Nair, P.K.R. 2004. Carbon sequestration: An underexploited environmental benefit of agroforestry systems. Agroforestry Systems 61:281–295.

Murovhi, N.R., Materechera, S.A. and Mulugeta, S.D. 2012. Seasonal changes in litter fall and its quality from three sub-tropical fruit tree species at Nelspruit, South Africa. Agroforestry Systems. 86:61-71. doi 10.1007/s10457-012-9508-6.

Mutuo, P.K., Cadisch, G., Albrecht, A., Palm, C.A. and Verchot, L. 2005. Potential of agroforestry for carbon sequestration and mitigation of greenhouse gas emissions from soils in the tropics. Nutrient Cycling in Agroecosystems 71:43−54.

Nair, P.K.R. 2012. Carbon sequestration studies in agroforestry systems: a reality-check. Agroforestry Systems 86:243–253. doi:10.1007/s10457-011-9434-z

Nair, P. K. R., Vimala, D., Nair, B., Kumar, M. and Showalter, J. M. 2010. Chapter Five: Carbon Sequestration in Agroforestry Systems. Advanced Agronomy 108: 237-307.

Nair, P.K.R., Kumar, B.M. and Nair, V.D. 2009. Agroforestry as a strategy for carbon sequestration. Journal of Plant Nutrition and Soil Science 172: 10–23. doi:10.1002/jpln.200800030.

Nyaga, J., Barrios, E., Muthuri, C.W., Öborn, I., Matiru, V. and Sinclair, F.L. 2015. Evaluating factors influencing heterogeneity in agroforestry adoption and practices within smallholder farms in Rift Valley, Kenya. Agriculture, Ecosystems and Environment 212: 106 – 118. http://doi.org/10.1016/j.agee.2015.06.013

Negash, M. and Starr, M. 2015. Biomass and soil carbon stocks of indigenous agroforestry systems on the south-eastern Rift Valley escarpment, Ethiopia. Plant and Soil 393:95-107. DOI 10.1007/s11104-015-2469-6

Negash, M and Kanninen, M. 2015. Modelling biomass and soil carbon sequestration of indigenous agroforestry systems using CO2FIX approach. Agriculture, Ecosystems and Environment 203:147–155.

Negash, M. 2013. The indigenous agroforestry systems of the south-eastern Rift Valley escarpment, Ethiopia: their biodiversity, carbon stocks, and litterfall. Tropical Forestry Reports No. 44. Doctoral Thesis. University of Helsinki

Oelbermann, M., Voroney, R. P. 2007. Carbon and nitrogen in a temperate agroforestry system: Using stable isotopes as a tool to understand soil dynamics. Ecological Engineering 29: 342–349.

Oelbermann, M., Voroney, R.P. and Gordon, A.M. 2004. Carbon sequestration in tropical and temperate agroforestry systems: A review with examples from Costa Rica and southern Canada. Agriculture, Ecosystems and Environment 104:359-377.

Post, W.M., Izaurralde, R.C., Mann, L.K., and Bliss, N. 2001. Monitoring and verifying changes of organic carbon in soil. Climate Change 51: 73-99.

Post, W.M.M. and Kwon, K. C. C. 2000. Soil carbon sequestration and land-use change: processes and potential. Global Change Biology 6: 317–27

Schroth, G., D'Angelo, S. A., Teixeira, W. G., Haag, D., and Lieberei, R. 2002. Conversion of secondary forest into agroforestry and monoculture plantations in Amazonia: consequences for biomass litter and soil carbon stocks after 7 years. Forest Ecology and Management 163: 131–150.

Shepherd, D., Montagnini, F. 2001. Carbon sequestration potential in mixed and pure tree plantations in the humid tropics. Journal of Tropical Forestry and Science 13: 450–459.

Sikuku, F. O., Apudo, M.G. and Ototo, G.O. 2014. Factors Influencing Development of Farm Forestry in Lugari District, Kakamega County, Western Kenya. Journal of Agriculture and Veterinary Science. 7:6-13.

Silva, A.K.L. Vasconcelos, S.S., de Carvalho, C.J.R. and Cordeiro, I.M.C. 2010. Litter dynamics and fine root production in *Schizolobium parahyba var. Amazonicum* plantations and regrowth forest in Eastern Amazon. Plant and Soil 347:377–386.

Starr, M., Saarsalmi, A., Hokkanen, T., Merilä, P. and Helmisaari, H-S. 2005. Models of litterfall production for Scots pine (*Pinus sylvestris* L.) in Finland using stand, site and climate factors. Forest Ecology and Management 205:215–225.

Zhang, C., Peng, D.L., Huang, G and Zeng, W.S. 2016. Developing Aboveground Biomass Equations Both Compatible with Tree Volume Equations and Additive Systems for Single- trees in Poplar Plantations in Jiangsu Province, China. Forests 7: 32; doi:10.3390/f7020032

Zomer, R.J, Trabucco, A., Coe, R. & Place, F. 2009. Trees on Farm: analysis of global extent and geographical patterns of agroforestry. ICRAF Working Paper no. 89. Nairobi, Kenya: World Agroforestry Centre.