TRADE-OFFS IN TREE SPECIES SELECTION AND CARBON OFFSET ON FARMS ADJACENT TO KAKAMEGA-NANDI FOREST ECOSYSTEM IN KENYA †

[COMPENSACIONES EN LA SELECCIÓN DE ESPECIES DE ÁRBOLES Y COMPENSACIÓN DE CARBONO EN GRANJAS ADYACENTES AL ECOSISTEMA FORESTAL DE KAKAMEGA-NANDI, KENIA]

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SUMMARY

Background: Growing of trees on-farms has contributed significantly in easing pressure on the Kakamega–Nandi Forest Ecosystem. There are however concerns that *Eucalyptus* species is becoming the dominant tree in this landscape and may have adverse effects on the environment. **Objectives**: To determine the trade-offs in tree species selection and carbon offsets on farms in the margins of the Kakamega - Nandi Forest Ecosystem. **Methodology:** It employed a nested experimental design where the study area was divided into three 3x1 km sentinel blocks. Three different landscape models were chosen: *Eucalyptus* dominated tree stand, mixed tree stands and pure native tree stands. A sample plot comprised a main plot of 20m by 10m plot for measuring trees with a diameter at breast height (DBH) ≥ 10 cm, a sub-plot of 10m by 5m nested within the main plot for measuring saplings and shrubs of DBH less than 10cm. Data was collected on tree species type, stem DBH for trees, tree height, counts of trees, saplings and shrubs. The data was subjected to both exploratory and inferential statistical analysis using R Gui Version 4.2.1. Woody species diversity and carbon stocks were subjected to analysis of variance (ANOVA) at 5% significance level. **Results:** Native dominated tree stands had the highest biomass carbon (0.50-512.84 MgC ha^{-1}) followed by mixed tree stands (0.10-110.82 MgC ha^{-1}). *Eucalyptus* dominated was the least (0.10- 68.58 MgC ha^{-1}). The above ground biomass in the *Eucalyptus* dominated tree stands and mixed trees stands was significantly lower than in the adjacent native trees stands (p=0.001). The mean carbon estimated in the treatments was 2.62 MgC ha^{-1} in the *Eucalyptus* trees dominated stands, 3.09 MgC ha^{-1} in mixed trees species stands and 19.05 MgC ha^{-1} in native tree species stand. **Implications:** Increase in the concentration of *Eucalyptus* trees led to a reduction in tree diversity. Trees in the *Eucalyptus* dominated tree stand and mixed trees stand had significantly lower stem diameters, basal area and tree biomass than in the adjacent indigenous trees stand. The fast rate of growth of *Eucalyptus* trees may have ensured that the trees grow fast at the expense of other woody species due to water and nutrient competition. **Conclusion:** The study revealed a general trend of increasing biomass carbon with increasing tree size in all the treatments. The majority of large trees were found in native tree stand indicating that they store majority of biomass carbon stocks. Across the treatment, carbon sequestration in the trees was directly related to above ground biomass production.
Key words: on-farm trees; above ground biomass; trade offs.

RESUMEN

Antecedentes: El cultivo de árboles en las granjas ha contribuido significativamente a aliviar la presión sobre el ecosistema forestal de Kakamega-Nandi. Sin embargo, existe la preocupación de que las especies de eucaliptos se estén convirtiendo en los árboles dominantes en este paisaje y puedan tener efectos adversos en el medio ambiente. **Objetivo:** Determinar las compensaciones en la selección de especies de árboles y las compensaciones de carbono en fincas en los márgenes del ecosistema forestal Kakamega - Nandi. **Metodología:** Se empleó un diseño experimental anidado y el área de estudio se dividió en tres bloques centinela de 3x1 km. Se eligieron tres modelos de paisaje diferentes: una parcela de muestra compuesta por una parcela principal de 20 m por 10 m

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para medir árboles con un diámetro a la altura del pecho (DAP) ≥ 10 cm, una subparcela de 10 m por 5 m anidada dentro de la parcela principal para medir árboles jóvenes y arbustos de DAP inferior a 10 cm. Se recopilaron datos sobre el tipo de especie de árbol, el DAP del tallo de los árboles, la altura de los árboles, el recuento de árboles, árboles jóvenes y arbustos. Los datos se sometieron a análisis estadístico exploratorio e inferencial utilizando R Gui Versión 4.2.1. La diversidad de especies leñosas y las existencias de carbono se sometieron a análisis de varianza (ANOVA) con un nivel de significación del 5 %. **Resultado** Los rodales de árboles dominados por especies nativas tenían la biomasa de carbono más alta (0.50-512.84 MgC ha-1), seguidos de los rodales de árboles mixtos (0.10-110.82 MgC ha^{-1}). La biomasa dominada por eucaliptos fue la menor (0.10-68.58 MgC ha^{-1}). La biomasa aérea en los rodales de árboles dominados por eucaliptos y en los rodales de árboles especies nativass adyacentes (p=0.001). El carbono medio estimado en los tratamientos fue de 2.62 MgC ha^{-1} en los rodales dominados por eucaliptos, 3.09 MgC ha-1 en los rodales de especies de árboles mixtos y 19.05 MgC ha-1 en los rodales de especies nativas. **Implicaciones:** El aumento en la concentración de árboles de eucalipto condujo a una reducción en la diversidad de árboles. Los árboles en la masa arbórea dominada por eucaliptos y en la masa arbórea mixta tenían diámetros de tallo, área basal y biomasa arbórea significativamente más bajos que en la masa arbórea autóctona adyacente. La rápida tasa de crecimiento de los árboles de eucalipto puede haber asegurado que los árboles crecieran rápidamente a expensas de otras especies leñosas debido a la competencia por el agua y los nutrientes. **Conclusión:** El estudio reveló una tendencia general de aumento del carbono en la biomasa con el aumento del tamaño de los árboles en todos los tratamientos. La mayoría de los árboles grandes se encontraron en rodales de árboles nativos, lo que indica que almacenan la mayoría de las reservas de carbono de la biomasa. En todo el tratamiento, el secuestro de carbono en los árboles estuvo directamente relacionado con la producción de biomasa aérea.

Palabras clave: árboles en finca; biomasa aérea; compensaciones.

INTRODUCTION

Global climate change has tended to focus its attention on carbon (C) sequestration and off-take potentials on forest lands, largely due to the Kyoto Protocol stipulating that forest C stocks may be used to offset carbon emissions (Neilson *et al*., 2006; Finkral and Evans, 2008), leading to an increase in worldwide interest to manage forests for carbon sequestration (Woodbury, Smith and Heath, 2007). Several studies have found that growing trees to sequester carbon could provide relatively low-cost net emission reductions for a number of countries (Newell and Stavins, 2000; Keleş and Başkent, 2007). However, many of these studies have largely neglected ecological limitations, and trade-offs with other tree products and services (Seidl *et al.*, 2007). Focus on on-farm trees and their role in providing ecosystem services among them carbon sequestration has recently emerged (Kuyah and Rosenstock, 2015; Agevi *et al*., 2017). Trees in farmlands have greater potential for emission/sequestration because of their spatial extent. A recent global survey has shown that over 45% of agricultural lands have more than 10% tree-cover (Zomer *et al*., 2016) with farmers growing both native and exotic trees on their farms for various purposes (Nyaga *et al*., 2015; Agevi *et al*., 2019). The presence of trees on farmland helps to offset pressure on natural forests in addition to contributing to the improvement of productivity of agricultural and forest landscapes (Mugo, Mwangi and Omamo, 2018). The native trees can either be planted or grow naturally based on the soil seed bank or proximity to a natural forest stand from which seed dispersers like birds and simians frequently visit the adjacent farmlands. The trees are integrated on the farmland as woodlots, windbreaks, hedgerows and home gardens among others (Agevi *et al*., 2019). The amount of carbon stored in trees on farmlands is context specific and varies depending on factors such as agroforestry practices, type of species planted, age of agroforestry system, management influence, and environmental conditions (Luedeling, Sileshi and Dietz, 2011; Kuyah *et al*., 2014). In western Kenya, two studies estimated carbon in agroforestry systems to be 17 Mg ha^{-1} in above ground biomass (Kuyah *et al*., 2012b) and 5 $Mgha^{-1}$ in below ground biomass (Kuyah *et al*., 2012a; Mbow *et al*., 2014), totaling 22 Mg ha^{-1} of carbon in living biomass (Fuchs *et al*., 2022). This research was part of the Sustainable Land Management (SLM) project in western Kenya (Kakamega, Nandi and Vihiga counties) which involved adoption of practices by farmers that contribute to conservation of soil and increased amount of organic carbon in the soil which in turn results to higher yields.. The study was part of a baseline survey to determine the status of trees on farms and their potential uses in terms of carbon offset to help mitigate effects of global climate change. The study specifically assessed (i) the abundance of *Eucalyptus* trees species in relation to other tree species on farms, (ii) determined the above ground carbon stock potentials of *Eucalyptus* in relation to other tree species and established the carbon offset potential in order to advice farmers on carbon offset potential of different tree species.

MATERIALS AND METHODS

Study area

The study was conducted in the margins of the Kakamega-Nandi Forest Ecosystem where it covered farmlands located between 0-3 km from the forest boundary of Kakamega, Kibiri and South

Nandi Forests within Kakamega, Vihiga and Nandi counties respectively. Assessment sites within the margins of Kakamega Forest included Shamiloli, Mukulusu and Lukala. Assessment sites around Kibiri Forest included Makuchi, Makhanga and Blukhombe. Assessment sites surrounding South Nandi Forest included Cheboite, Burende and Mukoyuro (Figure 1). The study sites were farms of households where Sustainable Land Management (SLM) project interventions were being implemented within Kakamega, Vihiga and Nandi counties.

The area around Kakamega Forest experience a hot and wet climate characterized by an annual rainfall of 1,500 - 2,000 mm with a dry season between December and March (Althof, 2007; Agevi *et al*., 2016; Agevi *et al*., 2019). It had a mean minimum temperature range of 11 to 21° C and a mean maximum temperature range of 18 to 29° C (Althof, 2007; Otuoma *et al*., 2016). It is located between 0° 16’ N longitude and 34°45’E. The soils in Kakamega are classified as Acric Ferrasols (Fa). The Nandi Forest is located west of Kapsabet Town and east of Kakamega Forest at 0º.00´ and 0º15´N and 34º45´and 35º07´E (Njunge and Mugo, 2011). It’s within a transition zone between a tropical rainforest and tropical afro-montane forest. The transition is caused by the fact that the western part of the forest is an extension of the Kakamega Rainforest at 1,700 m above sea level, while the eastern part extends into the Rift Valley at an elevation of about 2,000 m above sea level (Otuoma *et al*., 2013). The increase in altitude causes a gradual change in species characteristics from tropical rainforest to tropical afro-montane forest (Heim and Smirenski, 2013). The area’s mean annual rainfall ranges from 1,600 to 2,000 mm, while the mean temperature is 19º C (Williams and Middleton, 2008). The area has a gently undulating terrain underlain by granitic and basement rocks, which weathered to give deep, well-drained soils (Woodbury, Smith and Heath, 2007; Heim and Smirenski, 2013). The forest is in the upper catchment of Kimondi and Sirua rivers, which merge downstream to (Hensel, Mitchell and Sowers II, 2006)form River Yala that drains into Lake Victoria (Hensel, Mitchell and Sowers II, 2006). More than 400 plant species, including 112 woody species, 300 bird species, and 7 native primate species live in the adjacent woodland, (Agevi *et al*., 2019). The forest's vegetation included primary woods that had been disturbed, secondary forests in various phases of development, mixed native plantations, and monoculture plantations that were both native and exotic(Tsingalia and Kassily, 2009; Adhiambo *et al*., 2019). The forest sustains a population of about 280,000 people who reside nearby and depend on it for timber, firewood, pasture, twines and vines, native fruits and vegetables, and so on, according to information from the Kenya National Bureau of Statistics. (Njuguna, 2019). The most prevalent of these species include *Strombosia scheffleri, Croton megalocarpus, Macaranga kilimandscharicum, Tabernaemontana stapfiana, and Celtis africana* (Njunge and Mugo, 2011). With over 60 different bird species, the forest is designated as an important bird area (Heim and Smirenski, 2013). 371 persons per km^2 reside within 0–3 kilometres of the forest boundary and depend on it for firewood, honey, pasture, building materials, herbal medicine, and native fruits and vegetables, according to the 2019 human population. Tree cultivation has a long history in the area, dating back to the 1940s, when *Eucalyptus* species were introduced to reverse rampant deforestation and provide scarce forest materials for domestic use (Shimamoto, Ubukata and Seki, 2004). Trees are estimated to occupy 30% of the land area with *Eucalyptus* being dominant with its main products being construction poles, timber and firewood (Warner, 1997). The average individual land holding is 0.05 hectares (Ekabten, 2017).

Research Design

A reconnaissance visit to the study sites revealed that a 3km transect from the forest edge into the farmlands tended to traverse native forest, mixed species stands comprising native trees, *Eucalyptus* and other exotic species, *Eucalyptus* dominated stands as one moved further into farmlands. The study selected stratified systematic sampling in order to assess the extent to which the observed variation in the concentration of *Eucalyptus* trees affected the three variables under investigation that is: pure *Eucalyptus* woodlot, a pure native tree stand and mixed stand of *Eucalyptus* native and other exotic tree stands. The study was carried out in three sentinel blocks, namely Kakamega, Kibiri and Nandi and the control within the forest. Each of the sentinel blocks comprised three sub-blocks which are the micro-catchments where sustainable land management (SLM) project interventions were being implemented within the three counties. In each sub-block, assessment was carried out in pure *Eucalyptus* woodlot, a pure native tree stand and mixed stand of *Eucalyptus* native and other exotic tree stands. The study employed a nested experimental design (Kuehl, 2000; Leech and Onwuegbuzie, 2007; Otuoma *et al*., 2016). The sub-plots were nested in the main plot while sub-blocks were nested in blocks.

A total of 90 plots (20×10m) were established and sampling done in them. A sample plot comprised a main plot of 20m by 10m for assessing trees with DBH ≥ 10 cm. Saplings and shrubs were assessed in sub-plots of 5m by 10m. For each site, counts per quadrat along the Transects were averaged and scaled up to hectare area to give estimates of abundance in units of stems ha^{-1} at each site.

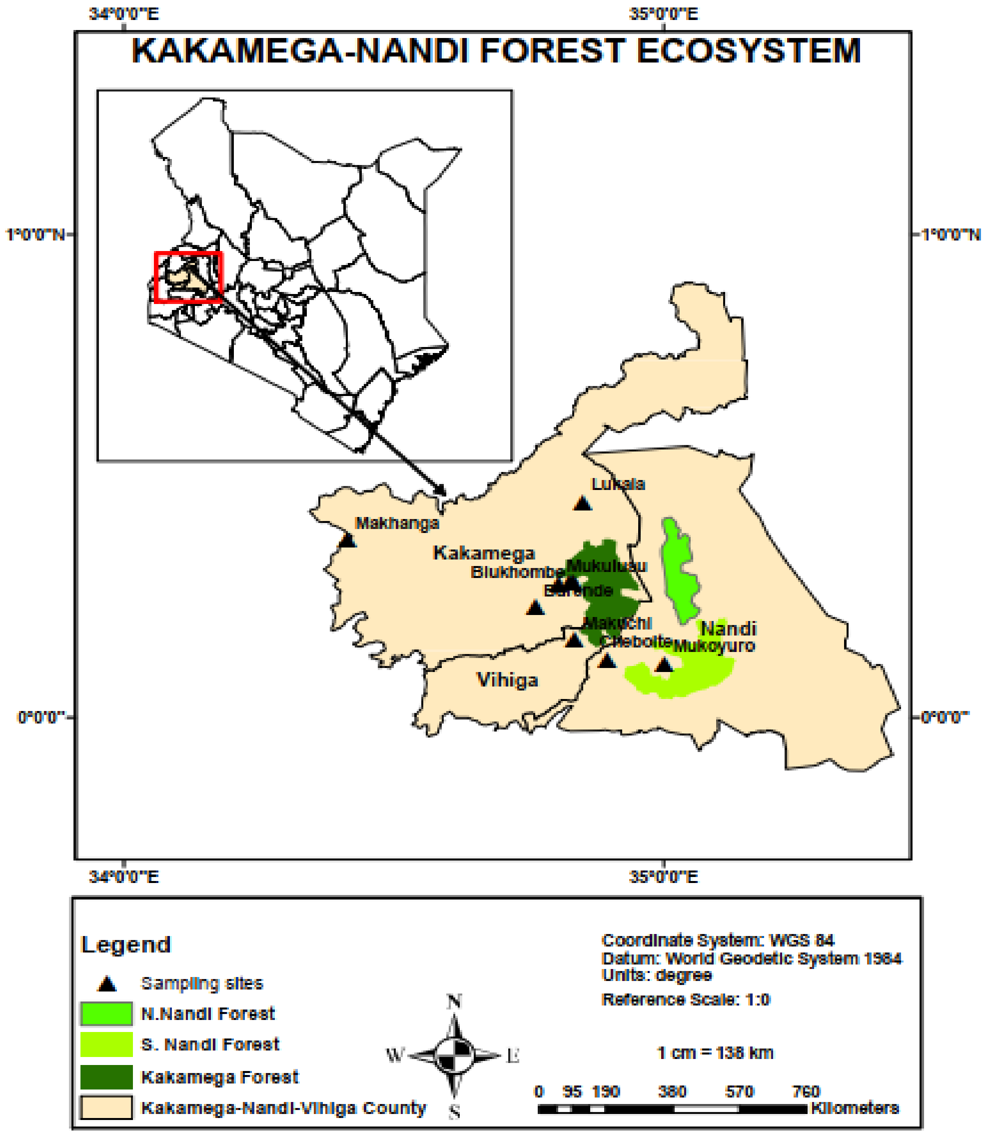

Figure 1. Study area showing Kakamega-Nandi Forests ecosystem, Kenya.

Sampling design

The transects traversed through farmlands, water catchments and along river lines. Parameters of assessment included woody species diversity and above ground carbon stocks. In each sub-blocks assessment entailed use of line transects to assess these parameters. Sample points were located systematically along a transect (Marques *et al.*, 2001). Three transects were laid within the 5 kilometers length and a 40 m width of a block, consisting of 5 quadrats per transect of 200 meters apart.

Data collection

An inventory of all trees in the plots was conducted recording data of diameter at breast height (DBH), species name and the number per plot and recorded in a data sheet. Where scientific names of the trees could not be established in the field, the local name was provided by para-taxonomists who participated in the data collection, and the later identified with the help of a taxonomist or a manual of woody tree species within and around Kakamega Forest. The tree species abundance was scaled up to a hectare. The stem DBH was measured at a height of 1.3 meters from the ground using a diameter tape. For trees of smaller diameter like the saplings and shrubs, diameter was measured using a Vanier caliper. Tree height was measured using a Suunto clinometer. Wood densities for tree species were obtained from the global database http://db.worldagroforestry.org/wd. For some species wood density was obtained from previous studies in the same area and also other areas with similar climatic conditions like the study area and with similar tree species type.

Biomass and above ground carbon (AGC) estimation

Species specific allometric equations by Tumwebaze *et al*. (2013) were used to estimate the biomass of *Grevillea robusta* ($AGB = 0.01 \times DBH^{1.81}$). The equation by Kuyah *et al*. (2013) for *Eucalyptus* spp $(AGB = 0.085 \times DBH^{2.471})$ was applied to trees of this genera. Biomass for the rest of the species was determined using the generic equation for trees in agricultural landscapes in western Kenya by $AGB = 0.091 \times DBH^{2.472}$) (Kuyah *et al*., 2012b). While for moist tropical forest trees the equation by Chave *et al.* (2005) was selected:

AGB= $\rho \times e^{(-1.499 + 2.148 \times \ln D) + (0.207 \times (\ln D)^2)-(0.0281)}$

Where, e is the constant 2.71828 for the exponential function, D is DBH and ρ is the specific wood density (grams cm^{-3}).

Individual tree biomass estimates in kg per tree were obtained using diameter measurements and allometric equations. A root-to-shoot ratio of 0.26 was used to calculate the below ground biomass (BGB) (Eggleston *et al*., 2006).

BGB= AGB* 0.26.

The total tree biomass was calculated by adding aboveground biomass (AGB) to belowground biomass. Estimates of tree biomass were added together to produce plot-level estimates in mega grams per hectare (Mg C ha^{-1}). The biomass estimates were converted to carbon using the IPCC's default carbon fraction in wood value of 0.46 (Eggleston *et al*., 2006). Tree biomass estimates were added together to obtain farm/plot level estimates in Megagrams per hectare (Mg ha^{-1}).

$$TB = ABG + BGB. TC = TB * 0.46$$

The total biomass estimates of individual trees was divided by respective plot area to obtain above ground biomass in Mg ha^{-1}. AGB estimates obtained were converted to above ground carbon stocks using the default carbon fraction value of 0.47 from Intergovernmental Panel on Climate Change (Eggleston *et al*., 2006). Above ground carbon stocks of trees within the same land use in the farm were divided by the area of the plot to obtain land use level carbon stocks. Above ground carbon stock at farm level was obtained by summing carbon stocks of all the trees in the entire plot divided by farm size. Each measured tree was identified with species name (scientific and local) and categorized into one of the identified land use type. The Shannon Wiener index was used to calculate the diversity of tree species (Risser and Rice, 1971) expressed as:

$$H' = -\sum (pi) \times \ln (pi)$$

Where: is the sum, pi is the quantity of individual species divided by the total number of species, ln represents natural log, and - is a negative that when multiplied by the equation yields a positive value as the index.

Shannon diversity index considers species richness (total number of different species), tree abundance (total number of trees) and the relative species abundance or evenness (count of trees for each species).
Species richness (S) was calculated as:

$$S = \sum ni$$

Where ni is the number of species in a community.

Equitability (evenness)

$$I = H'/H'_{max} \quad \sum_i^s = 1\, Pilnpi/lns$$

Where S represents the number of species, H' represents the Shannon diversity indices, and Pi represents the proportion of individuals found in the ith species.

A sample plot consisted of a 20m by 10m main plot for assessing trees with DBH 10 cm. Saplings and shrubs were evaluated in 5m by 10m subplots. Counts per quadrat along the transects were averaged and scaled up to hectare area for each site to provide a range of estimated stem abundance in units of ha^{-1}. The Jaccard index is the proportion of species in the two sites' total species list; that is, a Eucalyptus dominated woodlot, a pure native tree stand, and a mixed stand of *Eucalyptus*, native, and other exotic trees that is common to both sites. It was calculated as:

$$SJ = c/(a + b + c)$$

Where SJ denotes the similarity index, c denotes the number of species shared by the two sites, and a and b denote the number of species unique to each site.3.6.2 Carbon stocks. The Importance Value Index (IVI) was calculated for each woody species in the treatments as follows: The Important Value Index (IVI) is calculated as the sum of relative abundance, relative basal area, and relative frequency by dividing the frequency by the sum of the frequencies of all species, multiplied by 100)

Analysis of variance (ANOVA) was used to determine differences in species diversity and above ground carbon among the three sites, considered significant at $p<0.05$. Pearson correlation was done to establish relationship between tree abundance, diversity and richness with AGC and DBH with AGC. Using R Gui software version 4.2.1, all of the above data were subjected to analysis of variance (ANOVA) at the 5% significant level to determine possible variations in woody species diversity and aboveground carbon stock in Eucalyptus dominated woodlots, mixed tree stands, and native tree stands. Variances in species diversity and tree biomass between farm sites were considered significant at $p<0.05$ using analysis of variance (ANOVA). The Ryan-Einot-Gabriel-Welsch Multiple Range Test (REGWQ) was used in post hoc tests to determine the source of variation among means at the 5% significance level (Krull and Craft, 2009; Sokal and Rohlf, 2012; Holt *et al*., 2013).

RESULTS

Tree species abundance

A total of 51 woody species of 26 families were recorded. Of these 8 species (15.4%, n=133) were encountered in *Eucalyptus* dominated tree stands, 29 species (55.8%, n=193) were recorded in mixed tree species stands, while 32 species (61.5%, n=143) were located in native tree species stands. Mature trees constituted 48.6% (n=228), while saplings and shrubs comprised 51.4% (n=241) of the woody species recorded. Family Myrtaceae had the highest number of woody plants at 50.3% (n=236) followed by Moraceae with 7.5% (n=35). Analysis of importance value indices (IVI) of woody species indicated that *Eucalyptus grandis* (Myrtaceae) was the most dominant woody species in the study area followed by *Bischofia javanica* (Phyllanthaceae) and *Psidium guajava* (Myrtaceae) in descending order. Analysis of the IVI of woody species across respective treatments, showed that *Eucalyptus grandis* was the most dominant species (93%) in *Eucalyptus* dominated tree stands followed by *Harungana madagascariensis* (2.3%) and *Persea americana* (2.1%). In mixed tree stands, the most dominant woody species were *Eucalyptus grandis* (43.2%), *Zanthoxylum gilletii* (10.2%) and *Grevillea robusta* (8.8%). In native tree stands, the most dominant woody species were *Bischofia javanica* (17.4%), *Ficus sur* (14.4%) and *Antiaris toxicaria* (11.0%). Species richness per treatment different significantly (Table 1).

Woody species diversity

The mean Shannon diversity index ranged between 0.43 and 2.89. Analysis of variance showed a significant variation in Shannon diversity index in *Eucalyptus* dominated tree stands (EDTS), mixed tree species stands (MTS) and native tree species stands (ITS) ($p < 0.001$) (Table 1). Post hoc tests indicated that the diversity index was significantly higher in the native tree stands (2.89) followed by mixed tree species stands (2.29), *Eucalyptus* dominated tree stands had the lowest index (0.43).

Jaccard similarity indices ranged between 11.1% and 22.2% (Table 2). This indicated that woody species within the three treatments were largely dissimilar. Nonetheless, mixed trees stands (MTS) and native trees stands (ITS) had a relatively higher similarity index (22.2%) which implied that the two vegetation types probably shared more woody species than *Eucalyptus* dominated tree stands. Similarly, mixed trees stands appeared to share relatively more woody species with *Eucalyptus* dominated tree stands (15.6%) than the case between native trees stands and *Eucalyptus* dominated tree stands (11.1%) (Table 2).

Table 1. Woody species richness and diversity in *Eucalyptus* dominated tree stands (EDTS), mixed tree species stands (MTS) and native tree species stands (ITS) in the Kakamega Nandi Forest Ecosystem.

Treatment	Richness	Abundance	Shannon
EDTS	1.89±0.35a	13.67±3.00a	0.27±0.09a
MTS	6.56±1.06b	21.44±4.63a	1.4±0.13b
ITS	6.67±0.73b	15.78±3.65a	1.41±0.26b
p	5.19e-05***	0.346	1.10e-05***

Different letters indicate significant differences across treatments at $p < 0.05$.

Table 2. Jaccard similarity indices for *Eucalyptus* dominated tree stand (EDTS), mixed trees stand (MTS) and native trees stand (ITS) in the Kakamega Nandi Forest Ecosystem.

	EDTS	MTS	ITS
EDTS	1		
MTS	0.15625	1	
ITS	0.1111	0.2222	1

Woody stand structure

Stem density

The species with the highest and lowest stem density in *Eucalyptus* dominated tree stands (EDTS) is *Eucalyptus grandis* and *Markhamia lutea* while in the mixed tree species stands (MTS) was *Eucalyptus grandis* and *Bischofia javanica* and native tree species stands (ITS) was *Bischofia javanica* and *Dracaena fragrans* in the Kakamega Nandi Forest Ecosystem. Stem density ranged between 124.61±5.41 stems ha^{-1} and 127.82±6.52 stems ha^{-1}. The variation was statistically insignificant ($p > 0.05$) among the three treatments. The overall tree DBH size classes ranged from < 2 cm to >87.9 cm across the different treatments. The mean tree DBH 10.9 cm, 12.2 cm and 17.7 cm. The DBH classes of woody species within specific treatments ranged between 2 and 59.5, 2 and 49 and 2 and 87.9 cm in the *Eucalyptus* trees dominated stand, mixed tree stand and native tree stand respectively (Figure 2). There was no significant variation ($p > 0.05$) in tree DBH between *Eucalyptus* dominated tree stands (EDTS) and mixed tree species stands (MTS). There was a significant difference ($p < 0.05$) in tree DBH between *Eucalyptus* dominated tree stands (EDTS), mixed tree species stands (MTS) and native tree species stands (ITS) in the Kakamega Nandi Forest Ecosystem. The tree species with the highest DBH in EDTS, MTS and ITS were *Eucalyptus grandis*, *Maesopsis eminii and Ficus sur* respectively. The distribution of diameter at breast height (DBH) classes in the study sites is shown in (Figure 2). Trees with DBH ranges of 0.1-10 cm in the study sites were the majority (51.4%) while 60.1-90 cm were the least (1.1%). The DBH distribution is an indication of uneven aged distribution of trees.

Aboveground carbon (AGC) stocks

The aboveground biomass ranged between 0.10 and 110.82 (Mg C ha^{-1}), between 0.10 and 68.58 (MgC ha^{-1}) between 0.50 and 512.84 (Mg C ha^{-1}) in the *Eucalyptus* trees dominated stand, mixed trees stand and native trees stand respectively. The above ground biomass in the *Eucalyptus* dominated tree stands and mixed trees stands was significantly lower than in the adjacent native trees stands (p=0.001) (Table 3).The below ground biomass ranged from 0.03 to 28.81 (Mg C ha^{-1}), 0.03 to 17.83 (Mg C ha^{-1}) and 0.01 to 133.344 (Mg C ha^{-1}) in the Eucalyptus trees dominated stand, mixed trees stand and native trees stand respectively. The below ground biomass in the *Eucalyptus* dominated tree stands and mixed trees stands was significantly lower than in the adjacent native trees stands (p=0.001) . The mean carbon estimated in the treatments was 2.62 (MgC ha^{-1}), 3.09 (MgC ha^{-1}) and 19.05 (Mg C ha^{-1}) in the *Eucalyptus* trees dominated stands, mixed trees species stands and native tree species stands respectively. The carbon estimated in the treatments ranged between 0.06 and 64.23 (MgC ha^{-1}), 0.06 and 39.75 (Mg C ha^{-1}) and 0.03 and 297.24 (Mg C ha^{-1}) in the *Eucalyptus* trees dominated stands, mixed tree species stands and native tree species stands respectively. The total biomass in the *Eucalyptus* dominated tree stand and mixed trees stand was significantly lower than the adjacent native trees stand (p=0.001).

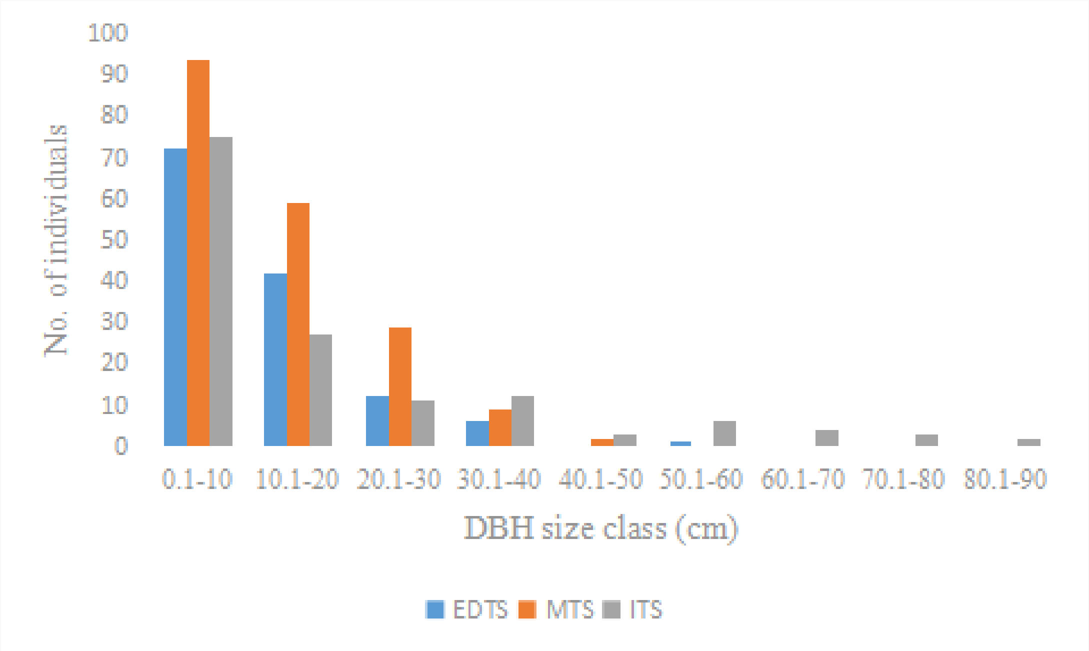

Figure 1. Diameter at breast height (DBH) size class distribution for *Eucalyptus* trees dominated stand, mixed tree stands and indigenous tree stand.

Table 3. Above ground biomass, below ground biomass, total biomass and total carbon (Mean ± SD) of *Eucalyptus* dominated tree stand (EDTS), mixed tree s stand (MTS) and native trees stand (ITS) in Kakamega Nandi Forest Ecosystem.

Treatment	AGB ha^{-1}	BGB ha^{-1}	TC ha^{-1}
EDTS	4.54±0.95b	1.18±0.25b	2.62±0.55b
MTS	5.34±0.61b	1.39±01.074b	3.09±0.35b
ITS	32.87±6.76a	8.55±1.76a	19.05±3.92a
p	1.43e-08***	1.43e-08***	1.43e-08***
Signif. Codes;	0.001'***'	0.001'***'	0.001'***'

Different letters indicate significant differences across treatments at $p < 0.05$.

Increase in the concentration of *Eucalyptus* trees led to a significant reduction in carbon stocks (Mg Cha^{-1}) ($F_{(1, 15)} = 27.198$; $p < 0.001$). However, the regression model for the relationship showed a fairly weak positive correlation (Figure 3). This may have been caused by the fact that there were other intervening factors that contributed to the recorded reduction in carbon stocks.

DISCUSSIONS

The native species were the most dominant on farmland. However, *Eucalyptus* an exotic *spp* had the highest abundance of trees. These findings agree with those of (Simons and Leakey, 2004; Kindt *et al*., 2006; Agevi *et al*., 2019; Agevi, 2020). *Eucalyptus* have shown a high adaptability to the soil environment and fast growth rate that have made it successful and it now occupies most of the total are (Kindt *et al*., 2006). However, they end up depleting soil nutrients leading to loss of soil fertility (McMahon *et al*., 2019). The preference that the species was given could have been based on the faster growth rates which gives farmers a high economic value that improves livelihoods of these communities. These values include construction timber, fuel, pulp, plywood, poles, firewood, charcoal, essential oils, productions of plant growth regulators, for tannin extracts and industrial chemical additives (Coppen, 2002). *Eucalypts* on farms are also important in providing products that would otherwise be sourced from natural forests (Kanyi *et al*., 2015) hence reducing pressure on the existing forest as it reduces deforestation rates greatly (Iiyama *et al*., 2014). Growing of *Eucalypts* is expected to expand due to high demand for wood for renewable energy, carbon sequestration and mitigating climate change (Stape, Binkley and Ryan, 2004; Nkem *et al*., 2007; Cochrane *et al*., 2009).

The low species diversity in the *Eucalyptus* dominated tree stand shows that only a few woody species were dominant in the treatment (*Eucalyptus*, n=122/133) at 91.7% of the woody species abundance. The Shannon index found in the treatments

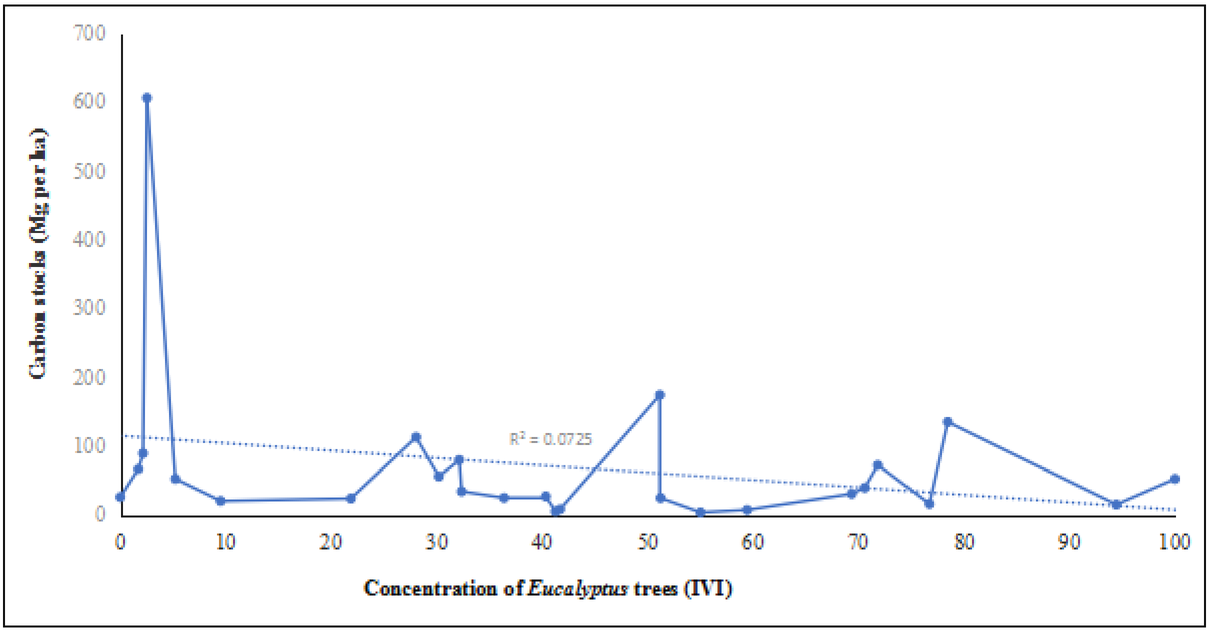

Figure 3. Relationship between abundance of *Eucalyptus* and carbon stocks.

of this study was lower than those studies elsewhere in (H'= 3.06–3.28 and 1.76-2.71) (Mekonnen, Asfaw and Zewudie, 2014; Eyasu, Tolera and Negash, 2020). These observations confirm report by (Grainger, 1996) that the biodiversity of a natural forest is often greater than that of *Eucalyptus* species plantations as the species composition of natural ecosystems are very diverse, whilst that of *Eucalyptus* species plantations is limited. *Eucalyptus* species plantations have been found to modify the species diversity due to its allelopathic effects (Wang, LeMay and Baker, 2007; Pandey, 2009). Also high tree species diversity in the forest is because the forests are protected areas with limited access and experience loss at lower rates than non-protected areas like the farms (Wade *et al*., 2020).

Studies by (Henry *et al*., 2011; Matocha *et al*., 2012) shows that tree diversity is usually low in some farm lands due to dominance of some tree species, the finding agrees with this study where the dominant tree species was *Eucalyptus* species within the EDTS. Agricultural lands and especially within the tropics have diverse of woody trees compared to other areas (Guyassa and Raj, 2013). Low tree diversity on farms than the forest could be due to proximity to roads which has given a better market access to wood products (Abebe *et al*., 2013). Tree species diversity in EDTS however can be increased using anthropogenic sources of native or exotic planting material (planted or grafted), which are usually produced on-farm or off-farm tree nurseries (Oloo *et al*., 2013).

Five of the eight wood species recorded from the *Eucalyptus* dominated tree stand were also recorded in the mixed trees stand and four of the eight wood species recorded from the *Eucalyptus* dominated tree stand were also recorded in the native trees stand while nine of the twenty nine wood species recorded from the mixed tree stand were also recorded in the native trees stand in the study area. However, Jaccard similarity index indicates a higher dissimilarity of woody species between the treatments. This is due to farmers introducing exotic trees for various purposes in the *Eucalyptus* dominated tree stand and mixed trees stand and hence, retaining native woody species available in the native tree stand ((Mensah *et al*., 2016; Eyasu, Tolera and Negash, 2020).

The present mean woody species density for the three treatments was higher than those reported by Yitebitu, (2009) and (Yakob, Asfaw and Zewdie, 2014) at 78 trees ha^{-1} and 113 trees ha^{-1} respectively, but lower than reported for Arbegona (705 trees ha^{-1}) by Muktar, (2006). The tree density of the treatments was within the range of what was reported in the agroforestry system in southern Ethiopia (86–1082 trees ha^{-1}) (Abebe *et al*., 2013). Stand basal area was found to have a strong influence on aboveground carbon stock (Mensah *et al*., 2016). The results indicated that forest stands with larger basal area had relatively more aboveground carbon stock than those with smaller basal area. Since stand basal area is a function of both stem DBH and stem density, the latter had been confirmed to have negligible effect on aboveground carbon stock, the results suggest that the contribution of basal area was attributable to stem DBH. This observation is consistent with those of (Chaturvedi, Raghubanshi and Singh, 2011; Omeja *et al*., 2011, Anon., 2023), which reported that large trees, though less abundant, often store more aboveground carbon than smaller ones, which are normally significantly more abundant in tropical forest stands. The larger stem DBH of native tree stand was attributed by variation of stand age. Omeja *et al*., (2011), older tree stands comprise relatively larger trees and hence the increase in biomass and basal area (ITS) as opposed to mortality of tree stems within the *Eucalyptus* dominated tree stand and the mixed tree stand since they were found on farms where there is stages of successional change in the old-growth of trees.

The results show that the number of individuals decreases as the DBH of the individual increases. This result is similar to the findings of other studies that compared trees on farm in relation to natural forest (Gebrehiwot and Hundera, 2014; Eyasu, Tolera and Negash, 2020). There was a negative exponential or inverted 'J' distribution pattern exhibited in the diameter class distribution of these trees. This implies that the majority of the species had the highest number of individuals at relatively low DBH and height classes with a gradual decrease towards high DBH and height size classes(Fashing and Mwangi Gathua, 2004; Senbeta and Denich, 2006; Gebrehiwot and Hundera, 2014). This indicates a healthier tree population of the woody species under the treatments(Abebe *et al*., 2013; Kawawa *et al*., 2016). Despite the saplings being the majority not all of them grow to maturity because of the allelopathic effect from some of the larger species for instance, the *Eucalyptus* species which are the most in the *Eucalyptus* dominated tree stand in study area (Kawawa *et al*., 2016). However, species with the absence of saplings are under threat of local extinction (Gurmessa, Soromessa and Kelbessa, 2012). Anthropogenic activities affect the seed dispersal mechanisms, fruiting, germination and regeneration of the species(Omeja, Obua and Cunningham, 2004; Obiri, 2011). Thus, management and conservation priority should be given to species with no or few saplings.

Woody species with a highly important value index (IVI) like *Eucalyptus* trees (93%) is considered more important than those with low IVI. This is likely due to their wider economic role (Seta and Demissew, n.d.) and the ecological requirement of the life strategy of the species (Neelo *et al*., 2015).

IVI is also an important parameter that reveals the prioritizing of species for conservation (Zegeye, Teketay and Kelbessa, 2006; Berhanu *et al*., 2016; Tadele, Moges and Dananto, 2018). Species with high IVI value need low priority for conservation effort whereas those with low IVI value need high conservation effort. Therefore, most of the woody species in the treatments had low IVI (<10%) values and hence, need conservation priority.

Increase in the dominance *Eucalyptus* trees in the landscape led to a significant reduction in the number of other woody species ($F_{(1,\ 9)}$ = 6; p< 0.001). The dominance of *Eucalyptus* tree *species* could be due to allelopathy. *Eucalyptus* species has allelopathic effect on other species growing around it and this leads to loss of understorey biodiversity hence low species richness (Li *et al*., 2010). This effect suppresses the tree performance reducing the other species abundance (Vilà *et al*., 2011) due to resource use and competition (Hejda, Pyšek and Jarošík, 2009). Allelopathy reduces the crops output and in some extreme cases it kills the entire plant due to water and nutrient competition as per studies by Malik and Sharma which suggest that *Eucalyptus* impose significant environmental costs in the EDTS due to their ability to out compete crops and other vegetation for water and nutrients. Allelopathic effect of *Eucalyptus* can be countered by planting trees with high tolerance like *Markhamia lutea* and *Diospyros mespiliformis* as per studies by (Kawawa *et al*., 2016). A study by Tang *et al*., (2007) has shown that most of the understorey species in a *Eucalyptus* plantation comprises of tree seedlings and saplings. Anthropogenic activities affect the seed dispersal mechanisms, fruiting, germination and regeneration of the species (Omeja, Obua and Cunningham, 2004; Obiri, 2011). Despite the saplings being the majority not all of them grow to maturity because of the allelopathic effect from some of the larger species for instance, the *Eucalyptus* species which are the most in the study area (Kawawa *et al*., 2016).

Tree biomass carbon stocks

In total, *Eucalyptus* dominated agricultural landscapes in Western Kenya were estimated to stock 11.7 ± 0.01 Mg of carbon per hectare in live tree biomass, on average (Kuyah *et al*., 2013), (16 MgC ha^{-1}) (Henry *et al*., 2009), (86.6 MgC ha^{-1}) (Dimobe *et al*., 2018) and 85.0±12.55 Mg C ha^{-1} (Oeba *et al*., 2018). The results of this study 2.62±0.55 Mg C ha^{-1} were lower than those of (Kuyah *et al*., 2013) and Oeba *et al*., (2018) in *Eucalyptus* dominated stands. Studies by Chen *et al*., (2015) found out that the fast-growing species, such as *Eucalyptus*, accumulated more carbon in plant biomass whose results concurs with this study. The carbon allocation pattern between above- and below-ground compartments also varied with plantation type and stand age. The native tree stand had the highest carbon concentration as compared to the other study sites on the farmland. The fast rate of growth of *Eucalyptus* trees may have ensured that their carbon stocks do not go too low compared to that of other woody species. Similarly, some of the woody species that were being replaced by *Eucalyptus* may not have been huge in size hence may not have necessarily had the largest carbon stocks. This highest biomass could be the result of higher tree density with relatively large sizes (Kuyah *et al*., 2014; Agevi *et al*., 2019). Recent studies by Otuoma *et al*., (2016) put carbon stocks within different tree plantations to be between 195 to 345 Mg/ha of above ground Biomass. Increasing the number of species also increased carbon storage(Ruiz-Jaen and Potvin, 2011), this was observed in the Native tree stand. Otuoma *et al*. (2016) found significant variation in above ground carbon stock which was attributed to variation to stand age. Omeja *et al*., (2011) illustrated that older tree stands comprise relatively larger trees and hence the increase in biomass.

Native tree stand had a larger DBH classes with more potential for C storage (Agevi *et al*., 2017) due to more accumulated biomass (Omeja, Obua and Cunningham, 2004). Hereafter, diameter of tree (DBH) and height distribution is not only enough to describe the variations of carbon stock in the landscape, species biodiversity (i.e. Shannon) was also a determiner which has a significant effect on carbon stocks (Lexerød and Eid, 2006; Baishya, *et al*., 2009). High tree density enhances carbon sequestration in vegetation, although excessively high stand densities can adversely affect tree growth and productivity through competition effects, resulting in lower carbon sequestration (Ramachandran Nair *et al*., 2010). The highest biomass C storage characterizes the native tree stands of tropical region in comparison to any other terrestrial ecosystems (Brahma *et al*., 2018; Olorunfemi *et al*., 2019), which ranges from 30 to 255 Mg C ha^{-1}(Brown, 2002; Houghton and Hackler, 2006; Bombelli *et al*., 2009; Olorunfemi *et al*., 2019). In the present study, the biomass C stock under native tree stand (19.05 Mg ha^{-1}) was lower than those reported previously for the North East India (NEI) (Borah *et al*., 2014; Rabha, 2014; Brahma *et al*., 2018; Ahirwal *et al*., 2021; Baishya *et al*., 2009).

The average above ground biomass carbon stocks estimated within the *Eucalyptus* dominated tree stand and mixed tree stand in this study was lower than the average 9 Mg/ha of carbon Henry *et al*., (2011) and 17 Mg/ha of carbon Kuyah *et al*., (2012a) and Reppin *et al*., (2020) reported for agricultural landscapes of western Kenya. Variations in estimates in the present study and those reported elsewhere e.g. (Abebe *et al*., 2013; Mattsson *et al*., 2015; Agevi *et al*., 2017; Kumar and Mutanga, 2017; Agevi, 2020) among others can be attributed to management influence, plant diversity, and stand quality. In addition, the age of the trees, management practices, human and natural disturbances factors influence the above ground and below ground carbon stored (Tilahun, Damnyag and Anglaaere, 2016). Carbon stocks vary greatly under different biophysical and socioeconomic characteristics, typical of smallholder farms in western Kenya (Kuyah *et al*., 2012b), and un-uniform methods of quantification (Ramachandran Nair *et al*., 2010). Generally, much carbon in the tropical forests is stored in live biomass rather than the soils in contrast to other biomes in which soils are the dominant carbon storage as revealed by (Gallery, 2014).

The tree carbon was less on the farms as compared to the forest across the different quadrats which comprise mainly native trees in old primary forest. The lower tree carbon in the on-farm study sites could be attributed to the fact that most of the trees in these sites are mainly exotic like the *Eucalyptus* species and are known to have a lower carbon sequestration capability as compared to the native species (Meunpong *et al*., 2010; Iiyama *et al*., 2014). The low tree carbon concentration among the on-farm trees could be attributed to the low soil fertility as described by (Yadav, Bisht and Bhatt, 2017) in the study conducted in North-Western Himalayas, India which found low biomass carbon stock as linked to the variations in species diversity, tree stand quality, soil fertility, trees management strategies, age, structure and carbon concentration in various components.

Increased carbon sequestration has an additional climate change mitigation benefit; they help to alleviate the pressure exerted on the natural forest by the surrounding communities, preserving existing carbon stocks (Mattsson *et al*., 2015). High tree density enhances carbon sequestration in vegetation, although excessively high stand densities can adversely affect tree growth and productivity through competition effects, resulting in lower carbon sequestration (Ramachandran Nair *et al*., 2010). The accurate estimate of forest biomass is crucial for many applications, the most common being the commercial use of wood to the global carbon (C) cycle (Bombelli *et al*., 2009). DBH alone was used in the study to determine plant biomass in the study as demonstrated by researchers like(Chave *et al*., 2005; Kuyah *et al*., 2012b; Agevi *et al*., 2019) who found it to be satisfactory when estimating biomass unlike including total tree height.

CONCLUSIONS

The study revealed a general trend of increasing biomass carbon with increasing tree size in all the treatments. The majority of large trees were found in native tree stand indicating that they store majority of biomass carbon stocks. Across the treatment, carbon sequestration in the trees was directly related to above ground biomass production.

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Conflict of interest. The authors declare that they have no conflict of interest.

Compliance with Ethical Standards. The work did not require approval by a (bio)ethical committee as it did not involve the human subjects.

Data availability. The Data is available upon request with the corresponding author hagevi@mmmust.ac.ke

Author contribution statement (CRediT)
P. Muigai, H. Agevi, J. Otuoma, C. Onyango, F. Muyekho and G. Ayaga – conceptualization, Methodology, **G. Ayaga** - Funding acquisition, **H. Agevi** and **J. Otuoma** - Supervision.

REFERENCES

Abebe, T., Sterck, F.J., Wiersum, K.F. and Bongers, F., 2013. Diversity, composition and density of trees and shrubs in agroforestry homegardens in Southern Ethiopia. *Agroforestry Systems*, [online] 87(6), pp.1283–1293. https://doi.org/10.1007/s10457-013-9637-6.

Adhiambo, R., Muyekho, F., Creedbc, I.F., Enanga, E., Shivoga, W., Trick, C.G. and Obiri, J., 2019. Managing the invasion of guava trees to enhance carbon storage in tropical forests. [online] https://doi.org/10.1016/j.foreco.2018.10.010.

Agevi, H., Mwendwa, K., Koros, H., Mulinya,C., Kawawa, R., Kipkorir,K.D.,Wabusya, M., Khanyufu, M. and ,Jawuoro, S. 2016. PELIS Forestry Programme as a Strategy for Increasing Forest Cover and Improving Community Livelihoods: Case of Malava Forest, Western Kenya.*American Journal of Agriculture and Forestry,* 4(5), pp. 128-

135. http://doi.org/10.11648/j.ajaf.20160405.13

Agevi, H., 2020. *Determination of Species Abundance, Diversity and Carbon Stocks in Kakamega Forest Ecosystem*. PhD Thesis. Moi University.

Agevi, H., Onwonga, R., Kuyah, S. and Tsingalia, M., 2017. Carbon stocks and stock changes in agroforestry practices: a review. *Tropical and Subtropical Agroecosystems*, 20, pp. 101-109. https://www.revista.ccba.uady.mx/ojs/index.php/TSA/article/view/2291/1057

Agevi, H., Tsingalia, H., Muyekho, F., Obiri, J., Mukoya, W. and Onwonga, R., 2019. On-farm tree abundance and biomass carbon stocks of Grevillea robusta and Eucalyptus saligna on farms around Kakamega Forest. *American Journal of Agriculture and Forestry*, 7(5), pp. 162-167. http://doi.org/10.11648/j.ajaf.20190705.11

Ahirwal, J., Nath, A., Brahma, B., Deb, S., Sahoo, U.K. and Nath, A.J., 2021. Patterns and driving factors of biomass carbon and soil organic carbon stock in the Indian Himalayan region. *Science of The Total Environment*, [online] 770, p.145292. https://doi.org/10.1016/j.scitotenv.2021.145292.

Althof, A., 2007. Human Impact on Flora and Vegetation of Kakamega Forest, Kenya : structure, distribution and disturbance of plant communities in an East African rainforest. PhD Dissertation, Koblenz-Landau University.

Anon. 2023. *Carbon storage in tropical forests correlates with taxonomic diversity and functional dominance on a global scale - Cavanaugh - 2014 - Global Ecology and Biogeography - Wiley Online Library*. [online] https://onlinelibrary.wiley.com/doi/full/10.1111/geb.12143 [Accessed 20 June 2023].

Baishya, R., Barik, S.K. and Upadhaya, K., 2009. Distribution pattern of aboveground biomass in natural and plantation forests of humid tropics in northeast India. *Tropical Ecology*, 50(2), 295-304.

Berhanu, Y., Negatu, L., Beyene, F. and Angassa, A., 2016. Impact of resettlement on vegetation status and rangeland condition in southwestern Ethiopia. *African Journal of Agricultural Research*, [online] 11(7), pp.533–542. https://doi.org/10.5897/AJAR2015.10526.

Bombelli, A., Henry, M., Castaldi, S., Adu-Bredu, S., Arneth, A., de Grandcourt, A., Grieco, E., Kutsch, W.L., Lehsten, V., Rasile, A., Reichstein, M., Tansey, K., Weber, U. and Valentini, R., 2009. An outlook on the Sub-Saharan Africa carbon balance. *Biogeosciences*, [online] 6(10), pp.2193–2205. https://doi.org/10.5194/bg-6-2193-2009.

Borah, N., Athokpam, F.D., Garkoti, S.C., Das, A.K. and Hore, D.K., 2014. Structural and compositional variations in undisturbed and disturbed tropical forests of Bhuban hills in south Assam, India. *International Journal of Biodiversity Science, Ecosystem Services & Management*, [online] 10(1), pp.9–19. https://doi.org/10.1080/21513732.2013.873823.

Brahma, B., Pathak, K., Lal, R., Kurmi, B., Das, M., Nath, P.C., Nath, A.J. and Das, A.K., 2018. Ecosystem carbon sequestration through restoration of degraded lands in Northeast India. *Land Degradation & Development*, [online] 29(1), pp.15–25. https://doi.org/10.1002/ldr.2816.

Brown, S., 2002. Measuring carbon in forests: current status and future challenges. *Environmental Pollution*, [online] 116(3), pp.363–372. https://doi.org/10.1016/S0269-7491(01)00212-3.

Chaturvedi, R.K., Raghubanshi, A.S. and Singh, J.S., 2011. Carbon density and accumulation in woody species of tropical dry forest in India. *Forest Ecology and Management*, [online] 262(8), pp.1576–1588. https://doi.org/10.1016/j.foreco.2011.07.006.

Chave, J., Andalo, C., Brown, S., Cairns, M.A., Chambers, J.Q., Eamus, D., Fölster, H., Fromard, F., Higuchi, N. and Kira, T., 2005. Tree allometry and improved estimation of carbon stocks and balance in tropical forests. *Oecologia*, 145, pp.87–99.

Chen, Y., Liu, Z., Rao, X., Wang, X., Liang, C., Lin, Y., Zhou, L., Cai, X. and Fu, S., 2015. Carbon Storage and Allocation Pattern in Plant Biomass among Different Forest Plantation Stands in Guangdong, China. *Forests*, [online] 6(3), pp.794–808. https://doi.org/10.3390/f6030794.

Cochrane, K., De Young, C., Soto, D. and Bahri, T., 2009. Climate change implications for fisheries and aquaculture. *FAO Fisheries and aquaculture technical paper*, 530, p.212.

Coppen, J.J., 2002. *Eucalyptus: the genus Eucalyptus*. London:CRC Press.

Dimobe, K., Mensah, S., Goetze, D., Ouédraogo, A., Kuyah, S., Porembski, S. and Thiombiano, A., 2018. Aboveground biomass partitioning and additive models for Combretum glutinosum and Terminalia laxiflora in West Africa. *Biomass and Bioenergy*, [online] 115, pp.151–159. https://doi.org/10.1016/j.biombioe.2018.04.022.

Eggleston, H.S., Buendia, L., Miwa, K., Ngara, T. and Tanabe, K., 2006. 2006 IPCC guidelines for national greenhouse gas inventories - A primer. Prepared by the National Greenhouse Gas Inventories Programme. H.S. Eggleston, K. Miwa, N. Srivastava and K. Tanabe, eds. Kamiyamaguchi, Hayama:IGES.

Ekabten, B.E., 2017. *Spatial land use management strategy on sustainable livelihood in Vihiga County, Kenya*. Moi University.

Eyasu, G., Tolera, M. and Negash, M., 2020. Woody species composition, structure, and diversity of homegarden agroforestry systems in southern Tigray, Northern Ethiopia. *Heliyon*, 6(12), p.e05500. http://doi.org/10.1016/j.heliyon.2020.e05500

Fashing, P.J. and Mwangi Gathua, J., 2004. Spatial variability in the vegetation structure and composition of an East African rain forest. *African Journal of Ecology*, [online] 42(3), pp.189–197. https://doi.org/10.1111/j.1365-2028.2004.00512.x.

Finkral, A.J. and Evans, A.M., 2008. The effects of a thinning treatment on carbon stocks in a northern Arizona ponderosa pine forest. *Forest Ecology and Management*, 255(7), pp.2743–2750.

Fuchs, L.E., Orero, L., Ngoima, S., Kuyah, S. and Neufeldt, H., 2022. Asset-based adaptation project promotes tree and shrub diversity and above-ground carbon stocks in smallholder agroforestry systems in Western Kenya. *Frontiers in Forests and Global Change*, 4, p.231. http://doi.org/10.3389/ffgc.2021.773170

Gallery, R.E., 2014. Ecology of Tropical Rain Forests. In: R.K. Monson, ed. *Ecology and the Environment*. [online] New York, NY: Springer. pp.247–272. https://doi.org/10.1007/978-1-4614-7501-9_4.

Gebrehiwot, K. and Hundera, K., 2014. Species composition, Plant Community structure and Natural regeneration status of Belete Moist Evergreen Montane Forest, Oromia Regional state, Southwestern Ethiopia. *Momona Ethiopian Journal of Science*, [online] 6(1), pp.97–101. https://doi.org/10.4314/mejs.v6i1.102417.

Grainger, A., 1996. An evaluation of the FAO tropical forest resource assessment, 1990. *Geographical Journal*, pp.73–79.

Gurmessa, F., Soromessa, T. and Kelbessa, E., 2012. Structure and regeneration status of Komto Afromontane moist forest, East Wollega Zone, west Ethiopia. *Journal of Forestry Research*, [online] 23(2), pp.205–216. https://doi.org/10.1007/s11676-012-0242-8.

Guyassa, E. and Raj, A.J., 2013. Assessment of biodiversity in cropland agroforestry and its role in livelihood development in dryland areas: A case study from Tigray region, Ethiopia. *International Journal of Agricultural Technology*, 9, pp.829–844.

Heim, W. and Smirenski, S.M., 2013. The Amur bird project at Muraviovka Park in Far East Russia. *BirdingASIA*, 19, pp.31–33.

Hejda, M., Pyšek, P. and Jarošík, V., 2009. Impact of invasive plants on the species richness, diversity and composition of invaded communities. *Journal of Ecology*, [online] 97(3), pp.393–403. https://doi.org/10.1111/j.1365-2745.2009.01480.x.

Henry, M., Picard, N., Trotta, C., Manlay, R., Valentini, R., Bernoux, M. and Saint-André, L., 2011. Estimating tree biomass of sub-Saharan African forests: a review of available allometric equations. *Silva Fennica*, 45(3), pp.477–569.

Henry, M., Tittonell, P., Manlay, R.J., Bernoux, M., Albrecht, A. and Vanlauwe, B., 2009. Biodiversity, carbon stocks and sequestration potential in aboveground biomass in smallholder farming systems of western Kenya. *Agriculture, ecosystems & environment*, 129(1–3), pp.238–252.

Hensel, P.R., Mitchell, S.M. and Sowers II, T.E., 2006. Conflict management of riparian disputes. *Political Geography*, 25(4), pp.383–411.

Holt, D.V., Wolf, J., Funke, J., Weisbrod, M. and Kaiser, S., 2013. Planning impairments in schizophrenia: Specificity, task independence and functional relevance. *Schizophrenia Research*, 149(1–3), pp.174–179.

Houghton, R.A. and Hackler, J.L., 2006. Emissions of carbon from land use change in sub-Saharan Africa. *Journal of Geophysical Research: Biogeosciences*, [online] 111(G2). https://doi.org/10.1029/2005JG000076.

Iiyama, M., Neufeldt, H., Dobie, P., Njenga, M., Ndegwa, G. and Jamnadass, R., 2014. The potential of agroforestry in the provision of sustainable woodfuel in sub-Saharan Africa. *Current Opinion in Environmental Sustainability*, 6, pp.138–147.

Kanyi, B., Kung'u, J.B., Ofafa, G.A. and Kibas, P., 2015. Entrepreneurial Personality Traits of Tree Farmers in Lari District Who Have Planted Improved Varieties of Eucalyptus Varieties. *International Journal of Research*, 34.

Kawawa, R.C., Obiri, J.F., Muyekho, F.N., Omayio, D.O., Agevi, H., Mwaura, A., Obiet, L., Kimutai, D.K. and Sifuna, A.W., 2016. Allellopathic potential of invasive Psidium guajava L., against selected native tree species in Kakamega Tropical Forest, Western Kenya. IOSR Journal of Pharmacy and Biological Sciences, 11(5), pp. 80-86. http://doi.org/10.9790/3008-1105028086

Keleş, S. and Başkent, E.Z., 2007. Modelling and analyzing timber production and carbon sequestration values of forest ecosystems: A case study. *Polish Journal of Environmental Studies*, 16(3), pp. 473-479.

Kindt, R., Van Damme, P., Simons, A.J. and Beeckman, H., 2006. Planning tree species diversification in Kenya based on differences in tree species composition between farms. I. Analysis of tree uses. *Agroforestry Systems*, 67(3), p.215.

Krull, K. and Craft, C., 2009. Ecosystem development of a sandbar emergent tidal marsh, Altamaha River Estuary, Georgia, USA. *Wetlands*, 29(1), pp.314–322.

Kuehl, R.O., 2000. *Designs of experiments: statistical principles of research design and analysis*. Pacific Grove, CA:Duxbury press.

Kumar, L. and Mutanga, O., 2017. Remote Sensing of Above-Ground Biomass. *Remote Sensing*, [online] 9(9), p.935. https://doi.org/10.3390/rs9090935.

Kuyah, S., Dietz, J., Muthuri, C., Jamnadass, R., Mwangi, P., Coe, R. and Neufeldt, H., 2012a. Allometric equations for estimating biomass in agricultural landscapes: II. Belowground biomass. *Agriculture, Ecosystems & Environment*, 158, pp.225–234.

Kuyah, S., Dietz, J., Muthuri, C., van Noordwijk, M. and Neufeldt, H., 2013. Allometry and partitioning of above-and below-ground biomass in farmed eucalyptus species dominant in Western Kenyan agricultural landscapes. *Biomass and Bioenergy*, 55, pp.276–284.

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, pp.267–277.

Kuyah, S. and Rosenstock, T.S., 2015. Optimal measurement strategies for aboveground tree biomass in agricultural landscapes. *Agroforestry systems*, 89, pp.125–133.

Kuyah, S., Sileshi, G.W., Njoloma, J., Mng'omba, S. and Neufeldt, H., 2014. Estimating aboveground tree biomass in three different miombo woodlands and associated land use systems in Malawi. *Biomass and Bioenergy*, 66, pp.214–222.

Leech, N.L. and Onwuegbuzie, A.J., 2007. An array of qualitative data analysis tools: A call for data analysis triangulation. *School Psychology Quarterly*, 22(4), p.557.

Lexerød, N.L. and Eid, T., 2006. An evaluation of different diameter diversity indices based on criteria related to forest management planning. *Forest Ecology and Management*, [online] 222(1), pp.17–28. https://doi.org/10.1016/j.foreco.2005.10.046.

Li, Z.-H., Wang, Q., Ruan, X., Pan, C.-D. and Jiang, D.-A., 2010. Phenolics and Plant Allelopathy. *Molecules*, [online] 15(12), pp.8933–8952. https://doi.org/10.3390/molecules15128933.

Luedeling, E., Sileshi, G. and Dietz, J., 2011. Advances in agroforestry. *Advances in*

Agroforestry; Kumar, BM, Nair, PKR, Eds.; Springer Science and Business Media: New York, NY, USA, pp.61–83.

Marques, F.F., Buckland, S.T., Goffin, D., Dixon, C.E., Borchers, D.L., Mayle, B.A. and Peace, A.J., 2001. Estimating deer abundance from line transect surveys of dung: sika deer in southern Scotland. *Journal of Applied Ecology*, pp.349–363.

Matocha, J., Schroth, G., Hills, T. and Hole, D., 2012. Integrating climate change adaptation and mitigation through agroforestry and ecosystem conservation. *Agroforestry-the future of global land use*, pp.105–126.

Mattsson, E., Ostwald, M., Nissanka, S.P. and Pushpakumara, D.K.N.G., 2015. Quantification of carbon stock and tree diversity of homegardens in a dry zone area of Moneragala district, Sri Lanka. *Agroforestry Systems*, [online] 89(3), pp.435–445. https://doi.org/10.1007/s10457-014-9780-8.

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

McMahon, D.E., Vergütz, L., Valadares, S.V., da Silva, I.R. and Jackson, R.B., 2019. Soil nutrient stocks are maintained over multiple rotations in Brazilian Eucalyptus plantations. *Forest Ecology and Management*, 448, pp.364–375.

Mekonnen, E.L., Asfaw, Z. and Zewudie, S., 2014. Plant species diversity of homegarden agroforestry in Jabithenan District, North-Western Ethiopia. *Int J Biodivers Conserv*, 6, pp.301–307.

Mensah, S., Veldtman, R., Assogbadjo, A.E., Glèlè Kakaï, R. and Seifert, T., 2016. Tree species diversity promotes aboveground carbon storage through functional diversity and functional dominance. *Ecology and Evolution*, [online] 6(20), pp.7546–7557. https://doi.org/10.1002/ece3.2525.

Meunpong, P., Wachrinrat, C., Thaiutsa, B., Kanzaki, M. and Meekaew, K., 2010. Carbon Pools of Indigenous and Exotic Trees Species in a Forest Plantation, Prachuap Khiri Khan, Thailand. *Agriculture and Natural Resources*, [online] 44(6), pp.1044–1057. Available at: <https://li01.tci-thaijo.org/index.php/anres/article/view/245104> [Accessed 20 June 2023].

Mugo, J.M., Mwangi, J.K. and Omamo, A.O., 2018. Allometric Equations for Estimating Silk Oak (Grevillea robusta) Biomass in Agricultural Landscapes of Maragua Subcounty, Kenya.

Neelo, J., Teketay, D., Kashe, K. and Masamba, W., 2015. Stand Structure, Diversity and Regeneration Status of Woody Species in Open and Exclosed Dry Woodland Sites around *Molapo* Farming Areas of the Okavango Delta, Northeastern Botswana. *Open Journal of Forestry*, [online] 05(04), p.313. https://doi.org/10.4236/ojf.2015.54027.

Neilson, E.T., MacLean, D.A., Arp, P.A., Meng, F.-R., Bourque, C.P. and Bhatti, J.S., 2006. Modeling carbon sequestration with CO2Fix and a timber supply model for use in forest management planning. *Canadian journal of soil science*, 86(Special Issue), pp.219–233.

Newell, R.G. and Stavins, R.N., 2000. Climate change and forest sinks: factors affecting the costs of carbon sequestration. *Journal of environmental economics and management*, 40(3), pp.211–235.

Njuguna, J., 2019. Progress in sanitation among poor households in Kenya: evidence from demographic and health surveys. *BMC public health*, 19, pp.1–8.

Njunge, J.T. and Mugo, J.M., 2011. Composition and succession of the woody flora of South Nandi Forest, Kenya. *Research Journal of Botany*, 6(3), p.112.

Nkem, J., Santoso, H., Murdiyarso, D., Brockhaus, M. and Kanninen, M., 2007. Using tropical forest ecosystem goods and services for planning climate change adaptation with implications for food security and poverty reduction.

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 & Environment*, 212, pp.106–118.

Obiri, J.F., 2011. Invasive plant species and their disaster-effects in dry tropical forests and rangelands of Kenya and Tanzania.

Jamba : Journal of Disaster Risk Studies, [online] 3(2), pp.417–428. https://doi.org/10.10520/EJC51186.

Oloo, J.O., Makenzi, D.P.M., Mwangi, J.G. and Abdulrazack, A.S., 2013. Dominant Tree Species for Increasing Ground Cover and their Distribution in Siaya County, Kenya. 2(3).

Olorunfemi, I.E., Komolafe, A.A., Fasinmirin, J.T. and Olufayo, A.A., 2019. Biomass carbon stocks of different land use management in the forest vegetative zone of Nigeria. *Acta Oecologica*, [online] 95, pp.45–56. https://doi.org/10.1016/j.actao.2019.01.004.

Omeja, P., Obua, J. and Cunningham, A.B., 2004. Regeneration, density and size class distribution of tree species used for drum making in central Uganda. *African Journal of Ecology*, [online] 42(2), pp.129–136. https://doi.org/10.1111/j.1365-2028.2004.00509.x.

Omeja, P.A., Chapman, C.A., Obua, J., Lwanga, J.S., Jacob, A.L., Wanyama, F. and Mugenyi, R., 2011. Intensive tree planting facilitates tropical forest biodiversity and biomass accumulation in Kibale National Park, Uganda. *Forest Ecology and Management*, [online] 261(3), pp.703–709. https://doi.org/10.1016/j.foreco.2010.11.029

Otuoma, J., Anyango, B., Ouma, G., Okeyo, D., Muturi, G.M. and Oindo, B., 2016. Determinants of aboveground carbon offset additionality in plantation forests in a moist tropical forest in western Kenya. *Forest Ecology and Management*, 365, pp.61–68.

Otuoma, J., Ongugo, P., Kemboi, D., Mairura, F. and Akinyi, F., 2013. To plant or protect: Evaluating forest recovery dynamics under natural and aided regeneration in western Kenya. In: *Book of Proceedings*. p.6.

Pandey, D.K., 2009. Allelochemicals in Parthenium in response to biological activity and the environment. *Indian Journal of Weed Science*, 41(3 & 4), pp.111–123.

Rabha, D., 2014. Aboveground Biomass and Carbon Stocks of an Undisturbed Regenerating Sal (Shorea Robusta Gaertn. F.) Forest Of Goalpara District, Assam, Northeast India. *International Journal of Environment*, [online] 3(4), pp.147–155. https://doi.org/10.3126/ije.v3i4.11743.

Ramachandran Nair, P.K., Nair, V.D., Mohan Kumar, B. and Showalter, J.M., 2010. Chapter Five - Carbon Sequestration in Agroforestry Systems. In: D.L. Sparks, ed. *Advances in Agronomy*. [online] Academic Press. pp.237–307. https://doi.org/10.1016/S0065-2113(10)08005-3.

Reppin, S., Kuyah, S., de Neergaard, A., Oelofse, M. and Rosenstock, T.S., 2020. Contribution of agroforestry to climate change mitigation and livelihoods in Western Kenya. *Agroforestry Systems*, 94, pp.203–220.

Risser, P.G. and Rice, E.L., 1971. Diversity in tree species in Oklahoma upland forests. *Ecology*, 52(5), pp.876–880.

Ruiz-Jaen, M.C. and Potvin, C., 2011. Can we predict carbon stocks in tropical ecosystems from tree diversity? Comparing species and functional diversity in a plantation and a natural forest. *New Phytologist*, [online] 189(4), pp.978–987. https://doi.org/10.1111/j.1469-8137.2010.03501.x.

Seidl, R., Rammer, W., Jäger, D., Currie, W.S. and Lexer, M.J., 2007. Assessing trade-offs between carbon sequestration and timber production within a framework of multi-purpose forestry in Austria. *Forest Ecology and Management*, 248(1–2), pp.64–79.

Senbeta, F. and Denich, M., 2006. Effects of wild coffee management on species diversity in the Afromontane rainforests of Ethiopia. *Forest Ecology and Management*, [online] 232(1), pp.68–74. https://doi.org/10.1016/j.foreco.2006.05.064.

Seta, T. and Demissew, S., n.d. Diversity and standing carbon stocks of Agroforestry trees in Wenago District, Ethiopia.

Shimamoto, M., Ubukata, F. and Seki, Y., 2004. Forest sustainability and the free trade of forest products: cases from Southeast Asia. *Ecological Economics*, 50(1–2), pp.23–34.

Simons, A.J. and Leakey, R.R.B., 2004. Tree domestication in tropical agroforestry. In: *New Vistas in Agroforestry: A Compendium for 1st World Congress of Agroforestry, 2004*. Springer. pp.167–181.

Sokal, R.R. and Rohlf, F.J., 2012. Descriptive statistics. *Biometry, the principles and practice of statistics in biological research 4th edition, Freeman and Co, New York*.

Stape, J.L., Binkley, D. and Ryan, M.G., 2004. Eucalyptus production and the supply, use and efficiency of use of water, light and nitrogen across a geographic gradient in Brazil. *Forest ecology and management*, 193(1–2), pp.17–31.

Tadele, D., Moges, A. and Dananto, M., 2018. Impact evaluation on survival of tree seedling using selected in situ rainwater harvesting methods in Gerduba Watershed, Borana Zone, Ethiopia. *Journal of Horticulture and Forestry*, [online] 10(4), pp.43–51. https://doi.org/10.5897/JHF2018.0531.

Tang, C.Q., Hou, X., Gao, K., Xia, T., Duan, C. and Fu, D., 2007. Man-made Versus Natural Forests in Mid-Yunnan, Southwestern China. *Mountain Research and Development*, [online] 27(3), pp.242–249. https://doi.org/10.1659/mrd.0732.

Tilahun, M., Damnyag, L. and Anglaaere, L.C.N., 2016. The Ankasa Forest Conservation Area of Ghana: Ecosystem service values and on-site REDD+ opportunity cost. *Forest Policy and Economics*, [online] 73, pp.168–176. https://doi.org/10.1016/j.forpol.2016.08.011.

Tsingalia, H.M. and Kassily, F.N., 2009. The origins Kakamega Forest grasslands: A critical review. *Journal of Human Ecology*, 27(2), pp.129–135.

Tumwebaze, S.B., Bevilacqua, E., Briggs, R. and Volk, T., 2013. Allometric biomass equations for tree species used in agroforestry systems in Uganda. *Agroforestry systems*, 87, pp.781–795.

Vilà, M., Espinar, J.L., Hejda, M., Hulme, P.E., Jarošík, V., Maron, J.L., Pergl, J., Schaffner, U., Sun, Y. and Pyšek, P., 2011. Ecological impacts of invasive alien plants: a meta-analysis of their effects on species, communities and ecosystems. *Ecology Letters*, [online] 14(7), pp.702–708. https://doi.org/10.1111/j.1461-0248.2011.01628.x.

Wade, C.M., Austin, K.G., Cajka, J., Lapidus, D., Everett, K.H., Galperin, D., Maynard, R. and Sobel, A., 2020. What Is Threatening Forests in Protected Areas? A Global Assessment of Deforestation in Protected Areas, 2001–2018. *Forests*, [online] 11(5), p.539. https://doi.org/10.3390/f11050539.

Wang, Y., LeMay, V.M. and Baker, T.G., 2007. Modelling and prediction of dominant height and site index of Eucalyptus globulus plantations using a nonlinear mixed-effects model approach. *Canadian Journal of Forest Research*, [online] 37(8), pp.1390–1403. https://doi.org/10.1139/X06-282.

Warner, K., 1997. Patterns of tree growing by farmers in eastern Africa. *Michael Arnold, J. E. & Dewees, PA (eds.). Farms, Trees and Farmers. Responses to Agricultural Intensification. Earthscan Publications Ltd., London*, pp.90–110.

Williams, S.E. and Middleton, J., 2008. Climatic seasonality, resource bottlenecks, and abundance of rainforest birds: implications for global climate change. *Diversity and Distributions*, 14(1), pp.69–77.

Woodbury, P.B., Smith, J.E. and Heath, L.S., 2007. Carbon sequestration in the US forest sector from 1990 to 2010. *Forest Ecology and Management*, 241(1–3), pp.14–27.

Yadav, R., Bisht, J. and Bhatt, J.C., 2017. Biomass, carbon stock under different production systems in the mid hills of Indian Himalaya. *Tropical Ecology*, 58, pp.15–21.

Yakob, G., Asfaw, Z. and Zewdie, S., 2014. Wood production and management of woody species in homegardens agroforestry: the case of smallholder farmers in Gimbo district, south west Ethiopia. *International Journal of Natural Sciences Research*, 2014, pp.165–175.

Zegeye, H., Teketay, D. and Kelbessa, E., 2006. Diversity, regeneration status and socio-economic importance of the vegetation in the islands of Lake Ziway, south-central Ethiopia. *Flora - Morphology, Distribution, Functional Ecology of Plants*, [online] 201(6), pp.483–498. https://doi.org/10.1016/j.flora.2005.10.006.

Zomer, R.J., Neufeldt, H., Xu, J., Ahrends, A., Bossio, D., Trabucco, A., Van Noordwijk, M. and Wang, M., 2016. Global Tree Cover and Biomass Carbon on Agricultural Land: The contribution of agroforestry to global and national carbon budgets. *Scientific reports*, 6(1), p.29987.