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]


1Department of Biological Sciences, Masinde Muliro University of Science and Technology (MMUST), P.O Box 190-50100 Kakamega, Kenya. Email: hagevi@mmust.ac.ke
2Kenya Forestry Research Institute (KEFRI), P. O. Box 5199 – 40108, Kisumu, Kenya
3Department of Agriculture and Land-Use system; Masinde Muliro University of Science ad Technology (MMUST), P.O Box 190-50100 Kakamega, Kenya
4Kenya Agricultural and Livestock Research Institute (KALRO), P. O. Box 278 – 50400, Busia, Kenya
*Corresponding author

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 eucaliptus 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 nativas adyacentes (p<0.001). El carbono medio estimado en los tratamientos fue de 2.62 MgC ha⁻¹ en los rodales reduciendo en 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; Finkrat 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 Oiamo, 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, Silesi 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 Mg ha⁻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 advise 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, Kibirí 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, Mahanga and Blukhomme. 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; Otouma 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 0°00’ and 0°15 N and 34°45’and 35°07’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 (Otouma et al., 2013). The increase in altitude causes a gradual change in species characteristics from tropical rainforest to tropical afro-montane forest (Heim and Smirenksi, 2013). The area’s mean annual rainfall ranges from 1,600 to 2,000 mm, while the mean temperature is 19°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 Smirenksi, 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 Smirenksi, 2013). 371 persons per km² 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; Otouma 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 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* (\( AGB = 0.01 \times DBH^{1.8} \)). The equation by Kuyah et al. (2013) for *Eucalyptus* spp (\( AGB = 0.085 \times DBH^{2.72} \)) 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 \( AGB = 0.091 \times DBH^{2.72} \) (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 \( \rho \) 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).

\[
BGB = AGB \times 0.26.
\]

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\(^{-1}\)).

\[
TB = AGB + BGB \times TC = TB \times 0.46
\]

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, \( n \) 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)

\[
I = H'/H_{\text{max}} \times \sum_i^S 1/Pi nPi/ins
\]

Where \( S \) represents the number of species, \( H' \) represents the Shannon diversity indices, and \( Pi \) represents the proportion of individuals found in the \( i \)th 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 \( p \leq 0.05 \). 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 Rohlif, 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 gillettii (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.**

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

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.**

<table>
<thead>
<tr>
<th></th>
<th>EDTS</th>
<th>MTS</th>
<th>ITS</th>
</tr>
</thead>
<tbody>
<tr>
<td>EDTS</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MTS</td>
<td>0.15625</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>ITS</td>
<td>0.1111</td>
<td>0.2222</td>
<td>1</td>
</tr>
</tbody>
</table>
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 (Mg C 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 stand 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 (Mg C ha\(^{-1}\)), 3.09 (Mg C 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 (Mg C 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 stand (MTS) and native trees stand (ITS) in Kakamega Nandi Forest Ecosystem.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>AGB ha⁻¹</th>
<th>BGB ha⁻¹</th>
<th>TC ha⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>EDTS</td>
<td>4.54±0.95b</td>
<td>1.18±0.25b</td>
<td>2.62±0.55b</td>
</tr>
<tr>
<td>MTS</td>
<td>5.34±0.61b</td>
<td>1.39±0.074b</td>
<td>3.09±0.35b</td>
</tr>
<tr>
<td>ITS</td>
<td>32.87±6.76a</td>
<td>8.55±1.76a</td>
<td>19.05±3.92a</td>
</tr>
<tr>
<td>p</td>
<td>1.43e-08***</td>
<td>1.43e-08***</td>
<td>1.43e-08***</td>
</tr>
<tr>
<td>Signif. Codes;</td>
<td>0.001***</td>
<td>0.001***</td>
<td>0.001***</td>
</tr>
</tbody>
</table>

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 C·ha⁻¹) (F₁,₁₅ = 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 Leaky, 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 area (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 Eucalyptus 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](image_url). 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 Zewdie, 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 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; Omega 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. Omega 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 (Gurumess, 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 understory 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 understory 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 (Omefa, 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 C per hectare in live tree biomass, on average (Kuyah et al., 2013), (16 MgC ha$^{-1}$) (Henry et al., 2009), (86.6 MgC ha$^{-1}$) (Dimóbé 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 plant biomass 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. Omefa 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 (Omefa, 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. (Abbe 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@mmust.ac.ke

Author contribution statement (CRediT)

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