



Soil Carbon Sequestration Differentials among Key Forest Plantation Species in Kenya: Promising Opportunities for Sustainable Development Mechanism

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Abstract: Soil organic carbon (SOC) contributes to the productivity of forests and enhances carbon sink in forest ecosystem. However, the available data on forest based carbon projects among African countries that have ratified Kyoto Protocol and are party to United Nations Framework Convention on Climate Change (UNFCCC) shows little emphasis on SOC, deadwood and litter. Kenya, for example, has piloted five afforestation and reforestation Clean Development Mechanism (AR-CDM) activities in government forests of which none addresses SOC, and yet studies elsewhere have shown that forest soils consist about 73 % of global carbon storage. This study therefore, sought to determine soil carbon sequestration differentials among selected key forest plantations in Kenya and their future implications on sustainable development mechanism. Soils were sampled at 0-20, 20-50 and 50-80 cm depth from *Pinus patula*, *Cupressus lusitanica*, *Juniperus procera* and *Eucalyptus saligna/grandis* plantations in Central Kenya for analysis of carbon, soil pH, nitrogen, phosphorous and potassium. The litter-fall collected from each of these forest plantations were analysed for nitrogen and carbon. The *Pinus patula* plantations had significantly ($p < 0.01$) higher amount of soil carbon ($132.2 \pm 12.55 \text{ MgC ha}^{-1}$) as compared with *Cupressus lusitanica* ($114.4 \pm 12.55 \text{ MgC ha}^{-1}$) and *Eucalyptus saligna* ($85.0 \pm 12.55 \text{ MgC ha}^{-1}$) plantations. Specifically, *Pinus patula* plantation had sequestered almost twice of soil carbon as compared to above and below-ground carbon pools whereas that of *Cupressus lusitanica* and *Eucalyptus saligna /grandis* were about 1.2 and 1.3 times higher, respectively. The levels of acidity varied among species, between and within sites from very strongly acidic to very slightly acidic. The amount of soil nitrogen, phosphorous and potassium between sites, tree species and soil depths differed significantly. This study therefore reveals soil carbon potentials in forest plantations that need to be considered in the development and implementation of afforestation and reforestation activities under Clean/Sustainable Development Mechanism (SDM). Equally, differences on soil carbon sequestered among species need to be taken into account when evaluating carbon stocks under certified and voluntary carbon offset markets in order to promote trees with high potential of carbon sequestration for sustainable development. This is important because, introduction of Reducing Emissions from Deforestation and forest Degradation (REDD+) and forest based Clean Development Mechanisms (CDM) have provided impetus to African governments in implementing afforestation and reforestation (AR) programmes to enhance carbon stock and improve resilience of biophysical and social systems against impacts of climate of change.

Keywords: Soil Carbon Sequestration, Forest Plantations, Soil Organic Carbon, Sustainable Development Mechanism

1. Introduction

Soil organic carbon (SOC) is among of the five carbon pools that are reported under United Nations Framework Convention on Climate Change (UNFCCC). However, the estimation of these carbon pools, namely; above-ground biomass, below-ground biomass, litter, deadwood and soil organic carbon, have largely concentrated on above and below-ground biomass in different forest types. This has resulted to little attention on other carbon pools such as soil organic carbon that has significant potential in climate change mitigation and improving resilience of forest ecosystem for enhanced productivity. For example, studies carried out on estimation of SOC have shown that forest soils consists about 73 per cent of global soil carbon storage, which is the largest active terrestrial carbon reservoir for both a sink and atmospheric carbon. Specifically, estimation of SOC in temperate forest ecosystems have shown that carbon pool in forest soil is almost as twice as large as the pool in the forest vegetation [1-2]. This demonstrates the significance of SOC in the forest ecosystem that remains instrumental not only as a carbon sink but also on determining the productivity of the forest and tree resources. Forests with high levels of SOC directly influence the above and belowground biomass. Equally, exposed soils due to land degradation, deforestation and other poor land management practices results to emission of carbon back to the atmosphere resulting to global warming. For example studies conducted by [3] revealed that litter decomposition as influenced by various climatic factors such as temperature, moisture and other non-climatic factors have resulted to enormous amount of carbon emitted to the atmosphere. This underscores the need for investing both financial and human resources to estimate and report on SOC from different forest types globally. It also signals for the need to monitor shifts on land uses in the context of Agriculture, Forestry and Other Land Use (AFOLU) as well as Land Use, Land-use change and Forestry (LULUCF).

The global shifts on AFOLU and LULUCF provides valuable information on SOC lost and gained depending on the land use patterns that are essential, especially when reporting on agriculture and forest based Nationally Determined Contributions (NDCs). It's estimated that about 20% of the global anthropogenic carbon dioxide is associated with land use changes, either from forestry to agriculture, deforestation, human settlement, infrastructure, and food-fibre-fuel nexus among other determinants including extractive industries. In this regard, countries have embarked on national inventories to estimate the forest and tree resources in order to determine the coverage as well as approximating value of forests in provisioning of good and services at national, regional and international levels in the face of climate change. The global statistics shows that Africa's total forest cover is about 624 million ha of which 16 million ha are forest plantations established for production of industrial round wood, afforestation of degraded land,

protection of environment among others [4, 5]. These forest statistics shows that African forests have a significant potential in carbon sinks thus playing a vital role in the overall carbon cycle [6].

However, Africa has not invested much on understanding the carbon dynamics in the forest sector, especially considering the SOC among the total carbon pools. This is an important aspect because a number of African countries are implementing afforestation and reforestation programmes to enhance their forest cover that is below the FAO recommendations of at least 10% forest cover. The efforts to improve forest and tree cover has attracted various incentive programmes at national, regional and international levels. The Kyoto Protocol (KP) under UNFCCC, for example, that is coming to an end in 2020, embraced afforestation and reforestation (AR) in the Clean Development Mechanism is expected to be replaced by Sustainable Development Mechanism (SDM) by 2021. Under the CDM, there exist compliance carbon offset markets for trading certified emission reductions (CERs) from AR programmes among other sector based activities. The available data shows that African countries that ratified the Kyoto Protocol have made very little progress in developing forest based carbon projects to tap these global opportunities in the investment of forest sector. The countries that have embraced AR-CDM have majorly dealt with above and below-ground carbon pools with little emphasis on SOC, deadwood and litter. This demands step wise approaches in estimating SOC in different forest types in order to optimize on the carbon offset returns and provide the total value of forest in the regulation of climate change. The introduction of Reducing Emissions from Deforestation and forest Degradation (REDD+) and voluntary carbon offset markets has also provided impetus to the African governments in implementing AR programmes.

Kenya that is known to be low forest and tree cover country is currently thriving to achieve 10% forest cover by 2030 through different strategic interventions. The country has piloted five AR-CDM activities in government forests, namely; Mau Forest Complex, Mt Kenya and Aberdare Range. The country has also piloted seven forestry sector voluntary projects including Rukinga REDD+ phase I and II, which is the first world project to have issued verified carbon unit certificates. These efforts are expected to enhance carbon stock and improve forest cover. In spite of these notable progress that has profiled Kenya as the most successful African country in tapping the forestry segment of the global certified and voluntary carbon offset markets, none of the AR-CDM activities addresses the soil carbon estimation. There are various reasons advanced based on the literature for neglecting soil organic carbon based on the type of soils and other considerations. This has continued to indicate less interest on SOC that might result to the overlooking of the available potential of SOC in different forest types and tree species that are currently used in AR activities. This study therefore sought to determine soil carbon sequestration differentials among selected key species in forest plantations

in Kenya and their future implications on sustainable development mechanism.

2. Materials and Methods

2.1. Description of Study Sites

This study was carried at Kiambu and Nyeri Counties in the Central Highland Conservancy. Kiambu County covers an area of 1,323.9 Km² lies between latitudes 0°75' and 1° 20' south of Equator and longitudes 36° 54' and 36° 85' east. Its agro-ecological zone (AEZs) extend in a typical pattern along the eastern slopes of the Nyandarua (Aberdare) Range. It has great potential for tea growing in Githunguri and Limuru, coffee, dairy farming and pyrethrum, among others. It is the most densely populated area with a density of 562 persons per km² compared to 280 persons per km² in 1979, with a population growth rate of 8.4% (Kenya National Bureau of Statistics [7-9]).

Nyeri County forms part of Kenya's eastern highlands. It is the most expansive covering an area of 3,266 km² and is situated between Longitudes 36° and 38° east and between the equator and Latitude 0° 38' south. The population densities at Nyeri North and Nyeri South were 142 and 351 persons per km², respectively (Kenya National Bureau of Statistics [KNBS], 2010; Republic of Kenya, 2005b). The main physical features of Nyeri County are Mt. Kenya (5199 m. a.s.l.) to the east and the Aberdare range (3999 m. a.s.l.) to the west. These mountains are of volcanic origin. They determine relief, climate and soils, and consequently, the agricultural potential of the County (Republic of Kenya, 2005b). The average annual rainfall ranges from 2200 mm on the most easterly exposed edge of the Aberdare range to 700 mm on the Laikipia Plateau. The economic livelihood of people in this County is dependent on agriculture as over 67% of the total area is arable land with main agro-ecological zones (AEZ) UM 2 (main coffee zone 2), LH 4 (Cattle-sheep-Barley Zone) and LH 5 (Ranching zone).

2.2. Study Design

A list of all forest stations managed by Kenya Forest

Service in Kiambu, Kirinyaga, Murang'a, Nyandarua and Nyeri Counties in Central highland Conservancy was obtained. Kiambu and Nyeri Counties were randomly selected out of the five Counties. The forest stations in each of these Counties were stratified and clustered on the basis of their AEZ and composition of plantation species, resulting to four and three clusters in Kiambu and Nyeri Counties respectively. The first cluster of Kiambu County comprised of Thogoto and Muguga. The second one comprised of Uplands, Kerita and Kinale. The third cluster comprised of Ragia, Kamae and Kieni while the fourth one comprised of Kimakia. The first cluster of Nyeri County comprised of Kabage, Kiandongoro and Zaina. The second cluster comprised of Chehe, Hombe, Gathiuru and Kabaru while the third one comprised of Naromoru and Nanyuki.

The first and second clusters of forest stations in Kiambu County were randomly selected resulting to sampling of Muguga, Uplands and Kinale forest stations. Stratification and simple random sampling were used among three clusters (Aberdare range, Windward and leeward sides of Mt. Kenya) at Nyeri County, resulting to random selection of Kabage, Kabaru and Naromoru forest stations.

2.3. Soil Sampling from Selected Forest Plantations

Soil was sampled from six subplots of 4 m by 5 m established at the four edges and middle of the main plot of 20 m by 50 m (Figure 1) for all the selected tree species and age categories at different study sites. In each of the six subplots, a central point was chosen where soil samples were collected at 0-20, 20-50 and 50-80 cm depth using soil augur. Any surface vegetation material was removed before soil augering was done. The collected soil samples from the six subplots of the same depth were thoroughly mixed and a composite sample of about one kilogram was packed into polythene bags for laboratory analysis of carbon, soil pH, nitrogen, phosphorous and potassium. Litter fall was collected from the same area of the soil sampling subplots, thoroughly mixed and about 300-500 g was packed into polythene bags for analysis of N and C.

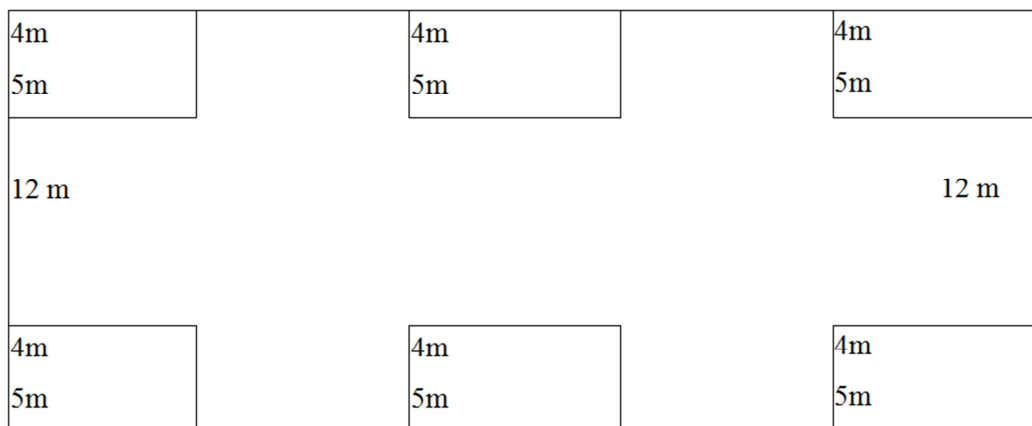


Figure 1. Layout of temporal forest plantation plots for soil sampling and tree measurements of various tree species at different ages.

2.4. Analysis of Soil Samples, Litter Fall and Above-Belowground Biomass

Soil samples were analysed for carbon (C), nitrogen (N), phosphorous (P), potassium (K) and soil pH. Litterfall was analysed for C and N. All analytical methods were conducted using the procedures as described by [10]. Statistical comparisons were done for C, N, P, K and pH under different soil depths and species using ANOVA and analysis of covariance. Pairwise comparisons were done using orthogonal contrasts. Total soil carbon estimated per ha was based on soil bulk density and percentage of carbon analyzed from soil samples. This was given by

$$\text{Total soil carbon (ha)} = (\text{Bulk density (kg/m}^3\text{)} * \text{soil depth * \%C}) * 100 \quad (1)$$

where the soil bulk density was determined using procedures as outlined by [10]. Mean comparisons of carbon sequestered were done using least significant difference (LSD), which

Table 1. Estimation of soil and above & below ground carbon sequestered by commonly grown plantation species at Kiambu, Nyeri North and Nyeri South.

| Site | Tree species | Mean soil carbon (MgC ha ⁻¹) | Above and below ground biomass (MgC ha ⁻¹) |
|-------------|-----------------------------|--|--|
| Kiambu | <i>Cupressus lusitanica</i> | 169.3 | 98.4 |
| | <i>Eucalyptus saligna</i> | 109.7 | 79.9 |
| | <i>Pinus patula</i> | 191.1 | 87.2 |
| Nyeri North | <i>Cupressus lusitanica</i> | 70.1 | 62.5 |
| | <i>Eucalyptus saligna</i> | 83.2 | 55.5 |
| | <i>Pinus patula</i> | 70.2 | 145.6 |
| Nyeri South | <i>Cupressus lusitanica</i> | 104.4 | 91.8 |
| | <i>Eucalyptus saligna</i> | 62.3 | 247.9 |
| | <i>Pinus patula</i> | 135.4 | 72.7 |
| s.e.d | | 12.55 | 44.4 |

Moreover, mean comparisons in the amount of soil carbon sequestered by the species among sites showed a significant difference ($p < 0.05$) in the quantity of carbon sequestered by *Cupressus lusitanica* and *Pinus patula* in Kiambu, Nyeri North and Nyeri South. Similarly, there were significant differences ($p < 0.05$) in the amount of soil carbon sequestered by *Eucalyptus saligna* among the sites except for Nyeri North and Nyeri South. *Eucalyptus saligna* had generally lower amount of soil carbon sequestered among the sites as compared to *Pinus patula* and *Cupressus lusitanica* except in

was obtained by multiplying twice the standard error of difference (s.e.d) based on linear mixed model approach.

Above and below-ground biomass was estimated using CO2FIX 3.1 modelling framework [11-13]

3. Results

3.1. Estimation of Soil Carbon Sequestration Among Selected Species in Different Sites

There were significant differences ($F_{(4,271)} = 8.08$; $p < 0.01$) in the amount of soil carbon sequestered by commonly grown plantation species adjusted for age at Kiambu, Nyeri South and Nyeri North. *Pinus patula* had the highest amount of soil carbon (191.1 ± 12.55 MgC ha⁻¹) followed by *Cupressus lusitanica* (169.3 ± 12.55 MgC ha⁻¹) at Lari sub county, Kiambu. *Eucalyptus saligna* had the least amount of soil carbon at Kiambu and Nyeri South except in Nyeri North (Table 1).

Nyeri North. Subsequently, mean comparisons of soil carbon sequestered among species within each site, differed significantly ($p < 0.05$) in Kiambu and Nyeri South.

3.2. Estimation of % C and Selected Soil Elements Across Depths Among Different Species

There were significant differences ($F_{(8, 271)} = 3.91$; $p < 0.01$) in the amount of soil carbon across study sites and soil depths among tree species (Table 2).

Table 2. Mean soil carbon sequestered (MgC ha⁻¹) at different soil depths by among species in Kiambu, Nyeri North and Nyeri South.

| Site | Tree species | Mean soil carbon sequestered (MgC ha ⁻¹) at different soil depths | | |
|-------------|-----------------------------|---|----------|----------|
| | | 0-20 cm | 20-50 cm | 50-80 cm |
| Kiambu | <i>Cupressus lusitanica</i> | 84.8 | 180.2 | 245.4 |
| | <i>Eucalyptus saligna</i> | 69.1 | 125 | 136.4 |
| | <i>Pinus patula</i> | 96.9 | 193.8 | 285.4 |
| Nyeri North | <i>Cupressus lusitanica</i> | 60.2 | 74.7 | 75.9 |
| | <i>Eucalyptus saligna</i> | 53.3 | 79.2 | 117.9 |
| | <i>Pinus patula</i> | 57 | 100.3 | 54 |
| Nyeri South | <i>Juniperus procera</i> | 29.4 | 48.1 | 74.4 |
| | <i>Cupressus lusitanica</i> | 78.3 | 91.5 | 143.9 |
| | <i>Eucalyptus saligna</i> | 29.4 | 56 | 102.4 |
| | <i>Pinus patula</i> | 56.1 | 141.5 | 211 |
| s.e.d | | 21.55 (14.22) | | |

* In parenthesis is the s.e.d for *Juniperus procera*

There also were significant differences ($F_{(2, 224)} = 79.22$; $p < 0.01$) in the levels of soil pH among the sites (Table 3). Kiambu soils were slightly acidic (6.11) as compared to Nyeri North (5.14) and Nyeri South (5.15), which were strongly acidic with a standard error difference of 0.093. Overall, the soil pH in all the study areas was mainly acidic. The levels of acidity varied among species, between and within sites from

very strongly acidic to very slightly acidic. The soil under *Cupressus lusitanica* plantations exhibited almost same soil pH at Kiambu, Nyeri North and Nyeri South similar to *Eucalyptus saligna* plantations. However, the soil under *Pinus patula* plantations, which is known to grow well in acidic conditions, had low amount of acidity in the soil in Kiambu as compared to Nyeri North and Nyeri South.

Table 3. Mean estimates of C and major soil elements across soil depths among different species in the study sites.

| Site | Tree species | Soil depth (cm) | pH | % C | % N | P_ppm | K_ppm | Bulk density (g/cm ³) |
|-------------|----------------------|-----------------|-------|-------|-------|-------|-------|-----------------------------------|
| Kiambu | <i>C. lusitanica</i> | 0-20 | 6.08 | 4.52 | 0.74 | 7.29 | 407.4 | 0.94 |
| | | 20-50 | 6.23 | 3.67 | 0.62 | 1.68 | 406.5 | 0.97 |
| | | 50-80 | 6.14 | 3.12 | 0.49 | 3.02 | 435.7 | 0.98 |
| | <i>E. saligna</i> | 0-20 | 5.87 | 3.4 | 0.59 | 3.23 | 605.5 | 1.05 |
| | | 20-50 | 5.91 | 2.18 | 0.45 | 2.39 | 597.7 | 1.16 |
| | | 50-80 | 5.88 | 1.48 | 0.31 | 0.51 | 563.9 | 1.14 |
| | <i>P. patula</i> | 0-20 | 6.27 | 5.12 | 0.83 | 8.90 | 397.4 | 0.94 |
| | | 20-50 | 6.30 | 3.81 | 0.60 | 4.42 | 317.4 | 1.03 |
| | | 50-80 | 6.28 | 3.49 | 0.50 | 4.08 | 313.9 | 1.02 |
| Nyeri North | <i>C. lusitanica</i> | 0-20 | 5.59 | 3.11 | 0.58 | 18.90 | 326.2 | 0.99 |
| | | 20-50 | 5.42 | 1.52 | 0.41 | 9.18 | 376.0 | 1.00 |
| | | 50-80 | 5.42 | 0.91 | 0.27 | 8.27 | 363.4 | 1.02 |
| | <i>E. saligna</i> | 0-20 | 4.51 | 2.93 | 0.62 | 14.04 | 214.7 | 0.90 |
| | | 20-50 | 5.00 | 2.31 | 0.36 | 9.16 | 167.6 | 0.96 |
| | | 50-80 | 5.02 | 1.77 | 0.39 | 7.94 | 137.1 | 0.92 |
| | <i>P. patula</i> | 0-20 | 4.85 | 2.92 | 0.42 | 9.73 | 288.3 | 0.96 |
| | | 20-50 | 4.85 | 1.98 | 0.34 | 8.06 | 323.0 | 1.04 |
| | | 50-80 | 5.34 | 0.67 | 0.24 | 4.79 | 265.3 | 1.06 |
| | <i>J. procera</i> | 0-20 | 6.07 | 1.46 | 0.52 | 7.85 | 457.6 | 1.04 |
| | | 20-50 | 5.74 | 0.94 | 0.45 | 8.41 | 346.4 | 1.03 |
| | | 50-80 | 5.63 | 0.93 | 0.28 | 11.04 | 317.2 | 1.00 |
| Nyeri South | <i>C. lusitanica</i> | 0-20 | 5.35 | 4.38 | 0.57 | 6.65 | 544.9 | 0.89 |
| | | 20-50 | 5.21 | 2.05 | 0.44 | 7.48 | 557.5 | 0.89 |
| | | 50-80 | 5.03 | 2.08 | 0.43 | 5.75 | 475.5 | 0.86 |
| | <i>E. saligna</i> | 0-20 | 5.74 | 1.76 | 0.43 | 3.10 | 357.0 | 0.85 |
| | | 20-50 | 5.15 | 1.22 | 0.35 | 4.76 | 308.0 | 0.91 |
| | | 50-80 | 5.03 | 1.38 | 0.74 | 7.10 | 303.2 | 0.91 |
| | <i>P. patula</i> | 0-20 | 4.89 | 3.44 | 0.75 | 5.58 | 254.1 | 0.83 |
| | | 20-50 | 4.98 | 3.28 | 0.65 | 4.70 | 254.7 | 0.88 |
| | | 50-80 | 4.93 | 3.30 | 0.49 | 5.22 | 262.9 | 0.83 |
| s.e.d | | | 0.274 | 0.456 | 0.098 | 2.46 | 93.79 | 0.058 |

On the other hand, the interaction effects between sites and species were significant ($F_{(4, 271)} = 12.62$; $p < 0.01$) with respect to C. Also there were significant interaction effect in C ($F_{(8, 271)} = 2.08$; $p = 0.037$) between environmental sites, tree species and soil depths. This was however different for *Juniperus procera* whose interaction effect was only between age and depth albeit non-significant ($F_{(4, 48)} = 0.23$; $p = 0.918$).

The amount of soil nitrogen between sites, tree species and soil depths differed significantly ($F_{(8, 221)} = 2.00$; $p = 0.047$). This was different for *Juniperus procera* whose significant interaction effect was only between age and depth ($F_{(4, 24)} = 4.86$; $p = 0.005$). Similarly, the amount of soil nitrogen differed significantly ($F_{(2, 221)} = 13.66$; $p < 0.01$) among sites with Kiambu having the highest at 0.57% followed by Nyeri South (0.54%) and Nyeri North (0.41%) with a standard error difference of 0.470. Equally, there were significant differences ($F_{(2, 221)} = 3.52$; $p = 0.031$) in the amount of nitrogen among the tree species with *Pinus patula* having

highest amount (0.55%) followed with *Cupressus lusitanica* (0.52%) and *Eucalyptus saligna* (0.47%) with a standard difference of 0.033.

Consequently, amount of nitrogen varied significantly ($F_{(2, 221)} = 22.80$; $p < 0.01$) across soil depths. The highest (0.63%) was observed at 0-20 cm followed by 20-50 cm (0.48%) and 50-80 cm (0.43%) with a standard error difference of 0.032. There were also significant differences on the interaction ($F_{(4, 221)} = 6.05$; $p < 0.01$) of N between environmental sites, tree species and soil depths (Table 3).

The amount of P significantly varied ($F_{(2, 219)} = 3.50$; $p = 0.032$) among the species with *Cupressus lusitanica* having the highest P (7.16 ppm) followed by *Pinus patula* (6.13) and *Eucalyptus saligna* (5.34 ppm) with a standard error difference of 0.819. There were also significant differences ($F_{(2, 219)} = 12.83$; $p < 0.01$) in amount of P across soil depths, which reduced with increase in depth, 0-20 cm (8.51 ppm), 20-50 cm (5.40 ppm) and 50-80 cm (4.90 ppm)

with a standard error difference of 0.800. The significant differences ($F_{(2, 259)} = 13.39$; $p < 0.01$; s.e.d = 31.44) with respect to K (ppm) among sites were observed with Kiambu having the highest (447.4 ppm) followed by Nyeri South (385.8 ppm) and Nyeri North (281.6 ppm). Equally, significant differences ($F_{(2, 259)} = 10.01$; $p < 0.01$; s.e.d 31.24) in K were found in *Cupressus lusitanica* (412.3 ppm), *Eucalyptus saligna* (368.8 ppm) and *Pinus patula* (302.8 ppm) plantations. The bulk density significantly differed ($F_{(2, 271)} = 35.71$; $p < 0.01$; s.e.d = 0.019) across sites with Kiambu having the highest (1.01 g/cm³) followed by Nyeri North (0.98 g/cm³) and Nyeri South (0.87 g/cm³) with a standard error difference of 0.019. Bulk density also significantly differed across soil depths, 0-20 cm (0.94 g/cm³), 20-50 cm (0.99 g/cm³) and 50-80 cm (0.98 g/cm³).

3.3. Comparisons of the Amount of Carbon Dioxide Equivalent Above and Below Ground (AGB) and Soil Among Forest Species Across Ages and Sites

The amount of carbon dioxide equivalent (CO₂e) removed from the atmosphere by selected forest plantation species at below-ground, above-ground and soil significantly ($F_{(4,86)} = 6.03$; $p < 0.01$) varied across ages and sites (Table 4). Age as a covariate was highly significant ($F_{(1,86)} = 17.55$; $p < 0.01$) in the amount of CO₂e among tree species. Similarly, amount of CO₂e significantly differed ($F_{(2,86)} = 14.73$; $p < 0.01$) among the sites where Kiambu recorded highest amount followed by Nyeri South and Nyeri North. There were also significant interaction effect between age and sites for CO₂e among species above-ground and below-ground as well in soil.

Table 4. Comparison in the amount of CO₂e in the AGB and soil among species across sites.

| Site | Tree species | Stand density | Age in years | CO ₂ e t ha ⁻¹ (AGB) | CO ₂ e t ha ⁻¹ (soil) | CO ₂ e t ha ⁻¹ (total) | |
|-------------------|----------------------|----------------------|--------------|--|---|--|---------|
| Kiambu | <i>C. lusitanica</i> | 960 | 5 | 38.1 | 459.3 | 497.3 | |
| | | 800 | 8 | 168.0 | 560.5 | 728.5 | |
| | | 590 | 14 | 377.1 | 750.7 | 1,127.8 | |
| | | 532 | 24 | 836.7 | 793.5 | 1,630.2 | |
| | <i>E. saligna</i> | 671 | 2 | 41.6 | 479.4 | 521.1 | |
| | | 758 | 5 | 77.2 | 376.5 | 453.8 | |
| | | 1238 | 7 | 461.5 | 419.1 | 880.6 | |
| | | 250 | 10 | 95.6 | 405.8 | 501.4 | |
| | <i>Pinus patula</i> | 150 | 12 | 349.7 | 484.0 | 833.7 | |
| | | 550 | 6 | 239.9 | 574.1 | 814.0 | |
| | | 200 | 10 | 220.0 | 644.7 | 864.7 | |
| | | 506 | 13 | 592.3 | 946.6 | 1,538.9 | |
| | Nyeri North | <i>C. lusitanica</i> | 60 | 32 | 350.4 | 693.5 | 2,247.0 |
| | | | 1100 | 5 | 7.1 | 233.0 | 240.0 |
| 1050 | | | 8 | 231.1 | 342.1 | 573.2 | |
| 1000 | | | 13 | 312.1 | 203.2 | 515.2 | |
| <i>E. saligna</i> | | 525 | 24 | 326.7 | 239.0 | 565.6 | |
| | | 780 | 8 | 256.7 | 315.0 | 571.7 | |
| | | 525 | 19 | 269.9 | 307.6 | 577.5 | |
| | | 150 | 33 | 387.9 | 271.5 | 659.3 | |
| <i>P. patula</i> | | 600 | 8 | 247.7 | 299.3 | 547.0 | |
| | | 640 | 17 | 610.5 | 177.3 | 787.8 | |
| | | 425 | 30 | 972.8 | 170.2 | 1,143.0 | |
| | | 1000 | 5 | 29.9 | 418.4 | 448.3 | |
| Nyeri South | | <i>C. lusitanica</i> | 1100 | 8 | 268.8 | 365.7 | 634.4 |
| | | | 1000 | 14 | 661.1 | 360.8 | 1,021.9 |
| | 235 | | 24 | 362.4 | 421.3 | 783.7 | |
| | 700 | | 7 | 441.2 | 183.1 | 624.3 | |
| | <i>E. saligna</i> | 840 | 8 | 1,203.0 | 216.8 | 1,419.8 | |
| | | 390 | 14 | 895.7 | 290.6 | 1,186.2 | |
| | | 999 | 5 | 184.4 | 363.6 | 548.1 | |
| | | 750 | 10 | 364.6 | 731.5 | 1,096.1 | |
| | <i>Pinus patula</i> | 200 | 26 | 273.0 | 297.7 | 570.7 | |
| | | s.e.d | | | 83.86 | 63.97 | 118.4 |

4. Discussion

The differences of soil carbon sequestered among species could be associated with various factors such as production of litter, amount of leaf-litter fall, rate of decomposition of leaf-litter, amount of lignin found in leaf-litter, age of the plantation, climatic conditions, plantation management, fire incidences and type of soil among others. Specifically, plant litter decomposition is valuable in the formation of soil organic matter, the mineralization of organic nutrients and the

carbon balance in terrestrial ecosystems where it has been established that 53% of the total carbon is in the organic layer of the soil stored [14-16]. The production of leaf litter and its decomposition is species dependent. For example, a study conducted by [17] showed production of litter under broad-leaved plantation species and natural forest was significantly higher than that under coniferous species. Similarly, the variation of the rate of decay of litter among different tree species may be explained by the amount of lignin in the leaves of the selected species as well as amount of moisture

in the soil. Research has shown that biotic decomposition in mesic ecosystems is usually negatively correlated with the concentration of lignin, a group of complex aromatic polymers present in the plant cell walls that is recalcitrant to enzymatic degradation and serves as structural barrier impeding microbial access to labile carbon compounds [16]. Overall, lignin plays a very important role in the carbon cycle, sequestering of atmospheric carbon into living tissues of woody vegetation. There exists variation on lignin content in the leaves of coniferous and broad leaved trees. A study conducted by [18] established that the lignin content in the litter of *Pinus sylvestris* and *Pinus conotrta Dougl* were 29.3% and 37%, respectively, as compared to broadleaf tree like *Eucalyptus grandis* that was 21.1%.

The higher amount of soil carbon sequestered by *Pinus patula* in this study as compared to other species may be associated with high amount of carbon in the leaf-litter fall catalyzed by rate of decomposition as influenced by environmental factors such as rainfall and temperature. This was well manifested with differentials of the amount of carbon found in the leaf-litter of *Pinus patula* (46%), *Cupressus lusitanica* (41%) and *Eucalyptus saligna* (43%). Sites that were generally receiving low amount of rainfall, had less soil carbon, like the case of the dry part of Nyeri North that had the least soil carbon as compared to other sites. Less amount of soil moisture essentially hinders microbial activities in carbon fixation and mineralization of soil nutrients.

Other studies conducted by [19] have shown differences in the amount of soil carbon sequestered by plantation species such *Cupressus lusitanica*, *Eucalyptus grandis* and *Pinus patula*. In their study, *Cupressus lusitanica* had highest amount of soil C followed with *Pinus patula* and least with *Eucalyptus grandis* due to litter quality input and rate of decomposition. A study by [20] also showed that Scots pine had higher amount of C on decomposing wood and bark as compared to spruce and birch in Finland. Series of studies have also advanced the same understanding following simulation in CENTURY and YASSO models where they have indicated that accumulation of soil organic pools were driven by changes in litter inputs, rate of decomposition, management regimes, root activity, stand growth rates among others. Specifically, plantation management practices like pruning, thinning, liming, drainage, clear felling and timber harvesting among others could also bring the variations on the amount of C as leftovers would decompose differently depending on the site characteristics and on the litter quality of the material [14, 21-24].

The significant variations of the percentage C across soil depths, decreased with, increasing soil depth. This implied that more C is concentrated in the top layer of the soil where there is high organic matter due to high amount litter fall that decomposes within the top layer of the soil. The amount of SOC at the top layer of the soil, about 1 m depth varies depending on the ecosystem and microbial activities as influenced by abiotic and non-abiotic factors. In arid and semi-arid areas, amount of SOC in the upper layer is

estimated to be about 30 tons/ha whereas in organic cold regions is estimated to be about 800 tons/ha [3]. Overall most studies have reported C storage and concentration increased in the upper layers of the soil and decreased with soil depths among hardwood and softwoods tree species in different forest types [25, 26]. In this study, it was also found SOC varied with age of tree where young forest stands had higher soil carbon as compared to middle aged. This may be explained by different rates of decomposition that is characterized by at least two stages, where the first stage is described by leaching of soluble compounds and by decomposition of solubles and non-lignified cellulose and hemicellulose resulting to 0-40% of mass loss as compared to late stage that encompasses the degradation of lignified tissue. This may further be explained by incidences of fire outbreak resulting to increase of ash that is rich in exchangeable bases, which leads to the reduction of soil acidity. A study by [27] reported the effect of lime in shifting the ectomycorrhizas in red pine plantations. Ectomycorrhizas are significant component of the forest floor in red pine plantations and produce high levels of surface acid phosphate activity. Therefore induced lime has the potential to alter the mineralization of organic P and P nutrition of the host. Overall, quantification of soil carbon among different soil depths showed an increasing trend due to multiplier of soil depths and bulk density.

The bulk density increased with increase of soil depths due to low organic matter, poor structure, low moisture and roots penetration as well as pressure exerted by overlying layers [28]. The significant amount of N in *Pinus patula* as compared to *Cupressus lusitanica* and *Eucalyptus saligna* may be explained by effect of forest floor leading to large differences in turnover rates of litter fall and the amount of soil organic matter accumulated in the soils. Studies have revealed that a low C/N ratio of broadleaves led to a better humus layer status [14]. The N quantities may also be influenced by amount of lignin in different species that has a great effects on the nitrogen dynamics of forest ecosystems as well as other ecological processes [18]. For instance, the rate at which forest litter decomposes forms an important aspect of assessing past, current and future carbon and N responses of forests under changing climate conditions. Also the litter decomposition entails physical and chemical processes that reduce litter to carbon dioxide, water and mineral nutrients that is regulated by a number of biotic and abiotic factors [18, 29]. Nitrogen comes mainly from three sources, namely; uptake from the soil, foliar uptake of atmospheric deposition and internal reallocation from one organ to another [30]. Thus increased N deposition causes an increased rate of soil organic matter. Also a study on carbon and nitrogen release from decomposing Scots pine, Norway Spruce and silver birch stumps found that N was released considerably more slowly from the stumps than from the stems and branches [20]. However, [31] reported forests respond to increased N availability by increase in stand leaf area and net photosynthesis and increased stem growth. This concurs with [32] who reported mineral soil N status among

tree species were strongly related to litter fall N status and was significantly higher in 0-30 cm of soil depth.

The findings on other selected soil parameters concurred with soil classifications within Central Kenya, which are known to be largely nitisols. These are characterized by pH <5.5 due to leaching of soluble bases and high clay content >35% [33]. Therefore the correlation of soil pH with P indicated the levels at which these elements would be available to plants to support the plant growth and accumulation of biomass for enhancement of carbon sequestration. Both sites, C, N, P and K were high. This indicated high amount of precipitation and soil mobilization as influenced by different trees species, thus availability of major nutrients for tree uptake/forest productivity. Soil pH usually has a big influence on the uptake of minerals. Thus soils with high acidity do not provide good conditions for the microorganisms that are very valuable with litter decomposition and other dead wood for nutrient fixation and carbon sinks.

The positive relationship between C and N showed available N could also be used as an indicator of soil carbon sequestration. This is because deposition of N on forests may increase C by increased growth and accumulation of soil organic matter through increased litter production or N-enriched litter. This leads to reduced long term decomposition rates of organic matter. Other studies have shown such relationship between C and N and offered appropriate explanations including large differences in turnover rates of foliar litter fall, forest management, and different tree species among others. Also the increase in nitrogen deposition on forests over a longer period of time may reduce the decomposition of organic matter. In general, this showed that soils in various plantation forests in Central Kenya have a huge potential of soil carbon stocks for mitigation of climate change. For instance, [34] found levels of soil C and N declined during the second rotation of *Pinus radiata* and ratios of C/N in the surface soil increased from 27 to 30 in lower quality sites and from 24 to 26 in higher quality sites.

Overall, the implications of soil carbon differentials on sustainable development mechanism is evident in this study. Specifically, the findings collaborates well with a series of studies demonstrating the potential role of SOC in climate change mitigation through sequestration of atmospheric carbon dioxide, thus providing a long lasting solution on sustainable reduction of greenhouse gases in a less cost effective manner. This calls for strengthening of afforestation of agricultural soils and management of forest plantations to enhance SOC stock through sequestration as influenced by interaction between climate, soil, tree species and management as well as the rate of chemical decomposition of the litter. In order to harness this potential, the inclusion of SOC in the sustainable mitigation mechanisms especially in afforestation and reforestation programmes to tap the forest carbon offset markets under Clean Development Mechanism (CDM) and voluntary mechanism will spur social-economic growth and environmental sustainability. For example, this

study revealed that in most cases amount of CO₂e among species across study sites, were higher in soils than above and below ground biomass. The considerations of SOC in this regard, will resonate well especially with Paris Agreement (PA) where parties agreed to reduce the rising temperature below 2°C above-preindustrial levels. The implementation of this Paris Agreement is based on the understanding that countries confirmed their intention to share reductions according to common but differentiated responsibilities and respective capabilities. This is reflected in the proposed Nationally Determined Contributions (NDCs) that need to be explored opportunistically on the role of SOC in the overall investments on mitigation options fronted by countries that have signed Paris Agreement.

Further, the evidence demonstrated in this study points to landscape-based approach in addressing SOC as an important sink that need to be mainstreamed in the NDCs and utilize the existing global climate financing such as Green Climate Fund and other incentives to spur sustainable development in the context of combating negative effects of climate change. For example, pushing for SOC in the Sustainable Development Mechanisms with well-developed structures can result to significant investments in the forest sector to enhance carbon stock and sustainable management of forests. This will in turn promote other related sectors of the economy such as agriculture, trade, energy among others through various functions of forests and tree-resources in social-economic development of the nation. In this sense, the future of SDM will rely on strengthening its flexibility in addressing various sustainable options of reducing greenhouse gas (GHG) emissions as fronted by various parties to Paris Agreement. This will result to increased incentives based on different schemes that countries can tap to reduce their vulnerability to climate change and improve on mitigation efforts for sustainable development.

5. Conclusion and Recommendations

The role of forest SOC in reducing atmospheric GHG is apparent in many studies. It is also evident that different species sequester different amounts of carbon depending on abiotic and non- abiotic factors. The potential carbon sink by forest plantations as presented in this study cannot be underestimated in their overall contributions to climate change mitigation. The national based initiatives on afforestation and reforestation programmes to improve the forest cover, like the current call by the national and county governments of the republic of Kenya will certainly results to increased carbon sink. This will work well when the governments also continue to promote other alternatives to livelihoods in order to minimize the leakages on carbon footprints. The realization of the contribution of SOC at a global scale will therefore require strengthening of policy and institutional frameworks to support investment in the forest sector. This study therefore recommends setting up reliable baseline emissions scenario from the forest sector that takes into account the contribution of SOC as source and sink. In

this manner, appropriate quantification/measurement, monitoring, reporting and verification will be institutionalized. This will ensure total valuation of the contribution of forest sector in climate change mitigation as reflected in various implementations options of Nationally Determined Contributions. This is important because, soil organic carbon dynamics are usually driven by the changes in climate and land cover or land use, calling for the need to strengthen the integration of LULUCF and AFOLU interventions in various NDCs options.

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