Estimation Of Aboveground And Belowground Carbon Sequestration Of *Cupressus Lusitanica*, *Pinus Patula* And *Eucalyptus Saligna* Plantation Species In Kenya

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ABSTRACT

Carbon sequestration has become a crucial service forests provide for regulation and mitigation of climate change through reduction of greenhouse gas emissions. In Kenya, *Cupressus lusitanica, Pinus patula* and *Eucalyptus saligna* are common exotic plantation species grown in high potential areas. They are characteristerised by fast growth resulting to removal of more carbon dioxide from the atmosphere. However, little has been done in estimating aboveground and belowground carbon of these species. Therefore, this study sought to: estimate carbon sequestered by these species across ages and sites; and determine relationship between tree growth parameters and carbon biomass. The study was carried at Kiambu and Nyeri Counties in Central Kenya. A total of 99 plots measuring 20 by 50 m were established in government managed forest plantations of selected species stratified according to age and species in different forest compartments. Diameters at breast height, total height, crown diameter and crown depth were measured. CO_2FIX V3.1 modelling framework was used in estimating carbon sequestered and linear mixed model used in the analysis of the data. There were significant differences (p=0.006) in the amount of carbon sequestered among species across sites. *Eucalyptus saligna* had the highest amount of carbon (247.9 ± 44.4 MgC ha^{-1}) sequestered in Nyeri South followed by *Pinus patula* (145.6 ± 44.4 MgC ha^{-1}) in Nyeri North and *Cupressus lusitanica* (98.4 ± 44.4 MgC ha^{-1}) in Kiambu. Significant differences (p<0.01) were evident across ages of three species and sites. Age accounted for 70% of the total variability in the amount of carbon sequestered. Growth parameters, aboveground and belowground biomass among three species across ages and sites were significantly correlated (p<0.01). In conclusion, estimates of carbon sequestered from selected tree species in Central Kenya, demonstrated a significant contribution towards emission reduction of harmful gases, specifically carbon dioxide.

Key words: carbon estimation, tree species, sites, age, Kenya

1. INTRODUCTION

Carbon sequestration has become one of the crucial services forests provide for regulation and mitigation of climate change through reduction of greenhouse gas emissions, particularly carbon dioxide. In this process, trees combine carbon dioxide with light and energy to form sugar which is converted into complex compounds that increases dry solid plant substance for continued growth to maturity. Carbon sequestered is then stored in tree tissue at different rates and quantities (Stoffberg et al. 2010). The Intergovernmental Panel on Climate Change (IPCC) defines five broad pools of carbon in forest ecosystem, namely; aboveground biomass, belowground biomass, dead wood litter, litter and soil carbon (Woodall et al. 2008). Under the Kyoto Protocol, which was adopted in 1997 and enforced on 16th February 2005, signatory countries were allowed to credit forest carbon sinks against greenhouse gas (GHG) emissions in order to fulfill their emissions reduction commitments (Sasaki and Kim 2009; Pohjola and Valsta 2007). This necessitated a series of studies in estimating biomass carbon sinks of various forest types with a special emphasis on the first commitment period of Kyoto Protocol between 2008 and 2012.

Studies have shown that carbon sequestered in forest plantations at different periods is significantly higher than that in natural forests (Sasaki and Kim 2009). They reported that carbon stock in plantation forests increased about five fold within the same period from 24.3 MgC ha^{-1} to 101.6 MgC ha^{-1} representing average increase of 1.7 MgC ha^{-1} and about 1.2 MgC ha^{-1} between 2008 and 2012. This was high compared to carbon stock (aboveground and root carbon) in natural forests which increased from 48.7MgC ha^{-1} in 1966 to 76.0 MgC ha^{-1} in 2012 representing annual increase of approximately 0.6 MgC ha^{-1}. These findings correlate with other studies (Fukuda et al. 2003 Fang et al. 2005) where aboveground carbon stocks was higher in plantations than in natural forests. In essence, forest plantations with fast growing species accumulates more biomass resulting to high capacity of sequestering CO_2 in wood, foliage, forest floor, roots and soils.

Further studies have revealed quantities of carbon sequestered in plantation or natural forests or woodlands or farmlands are attributed to various factors such as growth rate, tree species, size at maturity, life span, study sites, climatic factors, stand age and management practices including harvest cycles, thinning, pruning, fertilizer application, control of pests among others (Rautiainen 2010 Horner et al. 2010 Navar et al. 2009 Seidl et al. 2008 Watermoth and Richards 2008 Williams et al. 2008 Glenday 2008a Glenday 2008b Paul et al. 2008 Hu and Wang 2008 Glenday 2006 Miller et al. 2004 Jiang et al. 2002 Banfield et al. 2002). In particular, species substitution and short-rotation woody crop species plantations grow faster and are likely to sequester more carbon over short period of time frame than hard wood species. On contrast, hardwood species have other desirable characteristics that make them to store carbon for long period of time and enhance diversity (Jacobs, et al. 2009 Vallet et al. 2009 Stoffberg et al. 2010 Nabuurs et al. 2008). Carbon sequestration potential of major plantation species such as *Pinus armandi, Pinus yunnanensis, Pinus kesiya var. langbianensis, Platycladus orientalis, Cunninghamia laceolata* and *Eucalyptus spp* among others accounted for an increase of carbon stock from 12.474 Tg C in 2010 to 56.621 Tg C in 2050 (Chen et al. 2009). Similarly, in Swaziland, plantation forests which mainly constituted with eucalypts, pine and wattle plants were reported to have a higher carbon storage capacity than indigenous species and grasslands (Hassan and Ngwenya 2006).

In Kenya, *Cupressus lusitanica, Pinus patula* and *Eucalyptus saligna* are among common exotic plantation species grown in gazzeted and private forests in different agro-ecological zones. These species have multiple uses and widely used by different actors in primary and secondary forest production. They are also targeted in afforestation and reforestation programmes for compliance and voluntary carbon markets under Clean Development Mechanism (CDM) and Reducing Emissions from Deforestation and forest Degradation (REDD+), respectively. However, little has been done in estimating carbon aboveground and belowground of these major forest plantation species in Kenya. Therefore, this study sought to address: estimation of carbon sequestered by commonly grown plantation species across different ages and sites in Central Kenya; relationship between tree growth parameters and carbon biomass; and the need of generating baseline data on monitoring, reporting and verification systems on carbon accounting.

2. MATERIAL AND METHODS

2.1. DESCRIPTION OF STUDY SITES

This study was carried at Kiambu and Nyeri Counties in the Central highlands conservancy of Kenya. Kiambu County is comprised of six forest stations. Of these, Muguga, Kinale and Uplands forest stations were used in this study. Kinale and Uplands forest stations are on the upper highland (UH 1) at the altitude of 2591 m. a.s.l and 2415 m a.s.l, respectively. They receive mean annual rainfall of 1150 to 1276 mm and 1210 to 1414 mm, respectively. Muguga lies on the lower highland two (LH 2) at the altitude of 2067 m. a.s.l receiving mean annual rainfall of 1000 mm. Nyeri County comprises of three forest stations in Aberdare range (Nyeri South), three in leeward side of Mt. Kenya and four in the windward side of Mt. Kenya (Nyeri North). Kabage and Naromoru forest stations in Aberdare range and leeward side of Mt. Kenya were used in this research. Kabage forest station lies on the easterly exposed edge of the Aberdare Range on the UH 1 on the altitude of 2286 m .a.s.l receiving mean annual rainfall of 1424 mm. Naromoru forest station lies on the drier western leeward side of Mt. Kenya along lower highland agro-ecological zone three (LH 3) at an altitude of 2134 m a.s.l. It receives mean annual rainfall of 855 mm (Jaetzold et al. 2006).

Kiambu County covers an area of 1,323.9 Km^2 and is the smallest County in Central Kenya. It borders Nairobi City and Kajiado County to the south, Nakuru County to the west, Nyandarua County to the northwest and Thika to the east. The County lies between latitudes 0°75′ and 1° 20′ south of Equator and longitudes 36° 54′ and 36° 85′ east. It is an agro-ecological zone (AEZ) that extends in a typical pattern along the eastern slopes of the Nyandarua (Aberdare) Range parallel to the isohypses (Kenya National Bureau of Statistics [KNBS] 2010 Jaetzold et al. 2006; Republic of Kenya 2005a).

2.2. SAMPLING DESIGN

A list of all forest stations managed by Kenya Forest Service (KFS) in five Counties in Central highland Conservancy was drawn. Kiambu and Nyeri Counties were randomly selected. The forest stations in each of these Counties were stratified and clustered on the basis of their agro-ecological zone (AEZ) and composition of plantation species. This resulted to formation of four and three clusters in Kiambu and Nyeri Counties, respectively. The first and second clusters of the forest stations in Kiambu County were randomly selected of which Muguga, Uplands and Kinale forest stations constituting Lari forest block were sampled. In Nyeri County, there were three distinct clusters, one in Aberdare range, the second one on windward side of Mt.

Kenya (Nyeri North) and the third one on the leeward side of Mt. Kenya (Nyeri North). Kabage in Aberdare range and Naromoru in the leeward side of Mt. Kenya were selected.

2.2.1. SPECIES TYPE SAMPLING AND MEASUREMENTS

A forest compartment register was used in selecting the plantation blocks depending on the age of the species, accessibility, secure from wild animals and previous management of the forest. Rectangular plots measuring 20 m by 50 m of *Eucalyptus saligna, Cupressus lusitanica* and *Pinus patula* were established at Lari forest block, Kabage and Naromoru forest stations replicated three times in each age category. The rationale for plot measurements was based on other similar studies (Sierra et al., 2007; Williams et al., 2008; Paul et al., 2008; Alberti et al., 2008; Wang et al., 1996) which corroborated well with Kenya's national inventory plots measuring 0.04 ha for large trees and 0.02 ha for small trees of high densities. The number of plots for each tree species studied varied depending on the total area planted, heterogeneity and homogeneity of the plantation compartments. A total of 36, 33 and 30 plots were established for different stand age of *Cupressus lusitanica*, *Eucalyptus saligna* and *Pinus patula,* respectively in all study sites. In the cases where total area planted was large (> 10 ha) and fairly homogenous, distance between plots ranged between 100 m and 120 m apart as compared to medium and small areas (<10 ha) where distance between plots ranged between 80 and100 m apart. This was first surveyed to avoid any bias in establishing plots for assessing tree growth at different ages and total area planted. Within each plot, total trees were counted and marked for measurements. Actual tree density per hectare was obtained from forest station records. Tree height, diameter at breast height (DBH cm) at 1.3 m above the level ground, crown diameter and crown depth were measured. The crown diameter was measured in four cardinal points and averaged out. The initial planting espacement of *Eucalyptus saligna, Cupressus lusitanica* and *Pinus patula* was 2.5 m by 2.5 m.

2.3. DATA ANALYSIS

2.3.1 ABOVEGROUND AND BELOWGROUND CARBON

The data analysis was carried out using CO_2FIX V3.1 modelling framework as outlined by Masera et al. (2003). Specifically the model considers the total carbon stored in most of the forest stand at any time (CT_i) to be,

$$CT_i = Cb_t + Cs_t + Cp_t (tC/ha) \quad \text{……………………………………………………………….(1)}$$

where Cb_t is the total carbon stored in living (aboveground and belowground) biomass at any time *t,* in metric tones per ha;

Cs_t is the carbon stored in soil organic matter per ha, (this was not presented) and

Cp_t the carbon stored in wood products in tones per ha, however the wood products were not considered in this analysis but implied in discussion of results.

In order to simulate aboveground biomass ($Gb_{it)}$) the model uses input growth rate of stem volumes, which was derived from conventional yield tables. From the growth rate of stem volumes, growth rates of foliage, branches and roots were calculated using time-dependent allocation coefficients and actual crown measurements.

Basically the model used stem volume growth in m^3 per ha per year as the main input, and allometric approach to derive net annual increment of the main biomass components from stem volume growth. Mathematically,

$$Gb_{it} = K_v Y_{ist}(1+\sum(F_{ijt}))Mg_{it}(t/ha/yr) \ldots\ldots(2)$$

where

K_v is a constant to convert volume yields into dry biomass (basic density, in kg dry biomass per m^3 of fresh stem wood volume). In this case K_v was our biomass expansion factor (BEF) of 1.3; basic densities of each tree species were obtained from Kenya Forestry Research Institute (*Pinus patula* = 472 kg/m^3, *Cupressus lusitanica* = 414 kg/m^3 and *Eucalyptus saligna* = for 498 kg/m^3). These basic densities were measured at the bottom, middle and top of the tree stem of different ages, sites and averaged out.

Y_{ist}, is the volume yield of stem wood for each cohort "*i*" in m^3 ha−1 per year.

The local allometric volume equation used for *Cupressus lusitanica* and *Pinus patula* was;

$$V=0.01722+0.0001937D^2+0.00005069DH+0.00002296\ D^2H \ldots\ldots(3)$$

and that of *Eucalyptus saligna* was;

$$V = 0.0368162+0.0000310D^2H\ldots\ldots(4)$$

F_{ijt}, the biomass allocation coefficient of each living biomass component "*j*" (foliage, branches, and roots) relative to stems, for each cohort "*i*" at time *t* (kg) and Mg_{it} is the dimensionless growth modifier due to interactions among and within cohorts. This was not factored in estimation of total biomass in this study. Local root-shoot ratio of 0.3 and carbon content of 50% of aboveground to belowground biomass was used (Hu and Wang, 2008; Jacobs et al. 2009). Specifically, belowground biomass of local developed allometric equations is a product of aboveground biomass and a factor of 0.24. The crown surface area and volume were computed based on the geometrical shape of the crown as follows,

Conoid shapes, crown area $= \Pi D/2*(\sqrt{(L^2+(D/2)^2)}$ ……(5)

and

volume $= \Pi*(D^2L/12)$ ……(6)

where

D is the crown diameter, L is the crown depth and Π is a constant given by 22/7.

Linear mixed regression model based on unbalanced designs were used to determine statistically significant differences on the amount of carbon sequestered aboveground and belowground across ages and sites. In this analysis, age was used as covariate and random effect when comparing overall amount of carbon sequestered among plantation species at different sites. Regression analysis was used to determine relationship between DBH and biomass; carbon sequestered and plantation stand age. Correlation analysis was also used to determine relationship among tree parameters (DBH, height, crown surface area, crown volume, crown diameter and crown depth). Mean comparisons of amount of carbon sequestered by different species, sites and stand age were based on standard error of difference (s.e.d) and least significant difference (LSD = 2*s.e.d) at 5% significance level. General statistical software (Genstat version 13) was used in data analysis.

3. RESULTS AND DISCUSSIONS

3.1. TOTAL ABOVEGROUND AND BELOWGROUND CARBON SEQUESTRATION

There were significant differences ($F_{(4,23)} = 4.80$; Wald statistic = 19.13; p=0.006) in the amount of carbon sequestered in aboveground and belowground among *Cupressus lusitanica*, *Eucalyptus saligna* and *Pinus patula* in Kiambu, Nyeri North and Nyeri South (Table 1). *Eucalyptus saligna* had the highest total amount of carbon (247.9 ± 44.4 MgC ha^{-1}) sequestered in Nyeri South followed by *Pinus patula* (145.6 ± 44.4 MgC ha^{-1}) in Nyeri North and *Cupressus lusitanica* (98.4 ± 44.4 MgC ha^{-1}) in Kiambu. Multiple mean comparisons of amount of carbon sequestered aboveground and belowground by *Eucalyptus saligna* significantly varied ($p<0.05$) between Nyeri South and Kiambu; Nyeri North and Nyeri South. Similarly, there were significant differences ($p<0.05$) in total carbon sequestered among species within Nyeri South and Nyeri North except in Kiambu.

Further contrasts indicated no significant differences ($p>0.05$) in the amount of aboveground and belowground carbon sequestered by *Eucalyptus saligna* at Kiambu and Nyeri North. Similarly, amount of carbon sequestered by *Cupressus lusitanica* at Kiambu, Nyeri South and Nyeri North did not vary significantly ($p>0.05$). Also comparisons within study sites showed that there were no significant differences ($p>0.05$) among the species on total amount of carbon sequestered at Kiambu.

***Table 1**: Estimation of total carbon stock adjusted for age by different type of species in Kiambu, Nyeri North and Nyeri South*

	Mean total carbon (MgC ha^{-1}) sequestered in Kiambu, Nyeri North and Nyeri South		
Species type	Kiambu	Nyeri North	Nyeri South
Cupressus lusitanica	98.4	62.5	91.8
Eucalyptus saligna	79.9	55.5	247.9
Pinus patula	87.2	145.6	72.7
s.e.d	44.4		

The significant difference on the amount of aboveground and belowground carbon sequestered among species and across sites may be explained by the nature of tree species. Eucalypts are generally known to grow fast and accumulate more biomass than *Cupressus lusitanica* and *Pinus patula* resulting to high amount of carbon sequestration within the same period. Eucalypts are also known to be self pruning thus demanding less silvicultural management as compared *Cupressus lusitanica* and *Pinus patula* which, requires such operations at specific time of growth to improve on their stem quality and total biomass. Delays of such operational management are more likely to affect the diameter growth, which is a key parameter on tree volume that has direct relationship on estimation of the total biomass from the stem density. The low amount of carbon sequestered at Nyeri North may be explained by site effect. *Eucalyptus saligna* grows well on high altitude and rainfall. This concurs with Stoffberg et al. (2010) who reported quantity of carbon sequestered depended on factors such as growth rate, tree species, size at maturity and life span. This corroborates further with Paul et al. (2008) who found *Eucalyptus cladocalyx* and *Corymbia maculata* plantations had 37-50% of carbon sequestered in the total tree biomass in stem, 18-27% in both branches and roots and the reminder in foliage or bark.

During data collection it was noted in the forestry office records and personal communications from all forest stations that most plantation under *Cupressus lusitanica* and *Pinus patula* had two to four delays on pruning and thinning as a result of government ban on logging and inadequate sources of funding to support forestry activities in each forest station. It was also observed that some forest stations had started to engage the community on pruning and forest other management activities. Waterworth and Richards (2008) found out that forest management practices like harvests cycles, thinning, pruning, fertilizer application, control of pests and diseases, burn and slash significantly affects amount of carbon sequestration and greenhouse gas emissions. The low stand densities per hectare of *Eucalyptus saligna* as observed in the field during data collection across ages among the sites as compared with other species could explain further high amount of carbon sequestration as there would be less competition among trees resulting to faster growth rate, hence more biomass. Horner et al. (2010) found that moderately thinned stands (560 tree ha-1) of *Eucalyptus camaldulensis* produced highest aboveground carbon stock and storage rate of 4.2 MgC per year as compared to unthinned one at 1.6 MgC per year after 42 years. Glenday (2008) also found that differences in carbon sequestration among levee, evergreen and transitional forests/woodlands were as a result of higher stem densities and large DBH.

Consequently the age effect could as well explain differences on amount of carbon sequestered aboveground and belowground. The minimum ages measured for *Eucalyptus saligna*, *Pinus patula* and *Cupressus lusitanica* were 2, 6 and 5 years and 33, 32 and 24 years at maximum, respectively. This may further give evidence as to why *Pinus patula* was second on total amount of carbon sequestered besides being fast growing tree species as compared to *Cupressus lusitanica*. Other studies on white forests pine have shown that stem wood, which was a major aboveground biomass pool increased with age with variation of canopy biomass at advanced ages (Peichl and Arain 2007). Similarly, Onyekwelu (2004) reported on *Gmelina arborea* plantations stem biomass accounted for 83.6% of the aboveground biomass, which increased from 83.2 t ha^{-1} in 5 years to 394.9 t ha^{-1} in 21 years stand. Equally, Guo et al. (2010) buttressed this on their study where they showed biomass carbon stock varied with forest ages, site quality and stand density.

Environmental site effects like types of soil, rainfall and altitude may also explain differences on aboveground and belowground carbon sequestration among species across the sites. For instance, rainfall differences would significantly affect the growth rate of trees resulting to either low or high biomass as observed in the case of Nyeri North of Naromoru, which is on the leeward side of Mt. Kenya. Paul et al. (2008) reported the rate of accumulation of carbon was dependent on annual rainfall.

3.2. ESTIMATION OF ABOVEGROUND AND BELOWGROUND CARBON SEQUESTERED ACROSS AGES

There were significant differences ($F_{(15, 62)} = 114.31$; $p<0.01$) in the amount of carbon sequestered across ages of *Cupressus lusitanica*, *Pinus patula* and *Eucalyptus saligna* in Kiambu, Nyeri North and Nyeri South. This accounted for 70% of the total variability in the amount of carbon sequestered. Similarly, significant differences in the amount of carbon sequestered across ages among sites ($F_{(2, 62)} = 34.58$; $p<0.01$) , tree species ($F_{(2, 62)} = 30.01$; $p<0.01$) and interaction between sites and species ($F_{(4, 62)} = 30.93$; $p<0.01$), sites and age ($F_{(8, 62)} = 39.58$; $p<0.01$), tree species and age ($F_{(1, 62)} = 97.86$; $p<0.01$) were evidenced. This accounted for 3%, 3%, 5%, 13% and 4%, of total variability, respectively with only 3% remaining unexplained. The amount of carbon sequestered by *Cupressus lusitanica* in Kiambu increased from 10.4 ± 15.98 MgC ha^{-1} at age 5 to 228.2 ± 15.98 MgC ha^{-1} at age 24 while that of *Pinus patula* in Nyeri North increased from 67.5 ± 15.98 MgC ha^{-1} at age 8 to 265.3 ± 15.98 MgC ha^{-1} at age 30, respectively. Equally, the amount of carbon sequestered by *Cupressus lusitanica* at 24 years among sites was significantly higher ($p<0.05$) at Kiambu as compared to Nyeri North and Nyeri South sites. Other tree species had varied amount of carbon sequestered among sites (Table 2).

Table 2: Estimated above-ground and below-ground carbon sequestered by commonly grown plantation species across ages and sites

Site	Tree species	Age	Stand density per (ha)	MgC ha^{-1}
Kiambu	*Cupressus lusitanica*	5	960	10.4
		8	800	45.8
		14	590	102.8
		24	532	228.2
	Eucalyptus saligna	2	671	11.3
		5	758	21.1
		7	1238	125.9
		10	250	26.1
		12	150	95.4
	Pinus patula	6	550	65.4
		10	200	60.0
		13	506	161.5
		32	60	95.6
Nyeri North	*Cupressus lusitanica*	5	1100	2.2
		8	1050	63.0
		13	1000	85.1
		24	525	89.1
	Eucalyptus saligna	8	780	70.0
		19	525	73.6
		33	150	105.8
	Pinus patula	8	600	67.5
		17	640	166.5
		30	425	265.3
Nyeri South	*Cupressus lusitanica*	5	1000	8.3
		8	1100	73.3
		14	1000	180.3
		24	235	98.8

	Eucalyptus saligna	7	700	120.3
		8	840	337.0
		14	390	244.3
	Pinus patula	5	999	50.3
		10	750	99.4
		26	200	74.5
s.e.d				21.03

Consequently, stepwise analysis across ages in each site showed significant differences in the amount of carbon sequestered. For instance, in Kiambu, there were significant differences ($F_{(10, 26)} = 127.04$; $p<0.01$) in the amount of carbon sequestered by *Cupressus lusitanica*, *Pinus patula* and *Eucalyptus saligna* across ages (Table 2). Of the total variability in the amount of carbon sequestered aboveground and belowground, 88% was accounted by age as compared to 10% by species leaving about 2% unexplained. Similarly, significant differences ($F_{(7, 20)} = 75.07$; $p<0.01$) were also obtained in Nyeri North where age and tree species accounted for 54% and 44%, respectively, of the total variability leaving about 2% unexplained. Equally, significant differences ($F_{(6, 16)} = 28.77$; $p<0.01$) were found in Nyeri South where 44%, 41% and 12% of the total variability were accounted by tree species, age and interaction effect, respectively, leaving 3% unexplained.

This continued to demonstrate the significance of age in biomass accumulation resulting to higher levels of carbon sequestered by different tree species. Other studies on white forests pine reported stem wood as a major aboveground biomass pool increased with age and variation of canopy biomass at advanced ages (Peichl and Arain 2007 Onyekwelu 2004). Equally, Guo et al. (2010) reported biomass carbon stock varied with forest ages, site quality and stand density.

The inconsistence of *Eucalyptus saligna* in the amount of carbon sequestered across ages and sites may be explained by the harvesting cycles of the species. Some stands were at first planting and others were 1st, 2nd, 3rd and 4th coppice regimes. For example, the highest amount of carbon was observed at ages 7, 8, 12 and 14 because there were at first planting while at age 5, 10, 19 and 33 were on the third coppice whilst at age 2 was on first coppice. Even though some stands were on the same coppice, they had different amount of carbon sequestered. This may be due to site effect and stand density. It was evident that *Eucalyptus saligna* accumulated more biomass at first planting and if left over a long period of time would significantly sequester significant amount of carbon compared to other tree species.

3.3. RELATIONSHIP AMONG GROWTH PARAMETERS AND CARBON SEQUESTRATION

There were significant positive correlation ($p<0.01$) among DBH, tree height, crown surface area, crown volume and estimated aboveground and belowground biomass for *Eucalyptus saligna*, *Pinus patula* and *Cupressus lusitanica* of different ages in Kiambu, Nyeri North and Nyeri South. Diameter at breast height was the main parameter that had high significant correlation with tree biomass and crown volume (Table 3).

Table 3: Correlation among growth parameters of three tree species types in Kiambu, Nyeri North and Nyeri South

Tree parameters	DBH (cm)	Height (m)	Crown surface area (m^2)	Crown volume (m^3)
Diameter at breast height (cm)	-			
Height (m)	0.79	-		
Crown surface area (m^2)	0.47	0.32	-	
Crown volume (m^3)	0.76	0.59	0.36	-
Total biomass (kg)	0.87	0.72	0.3	0.83

The DBH had a near exponential fit with estimated tree biomass best fitted with polynomial function of degree two (Figure 1).

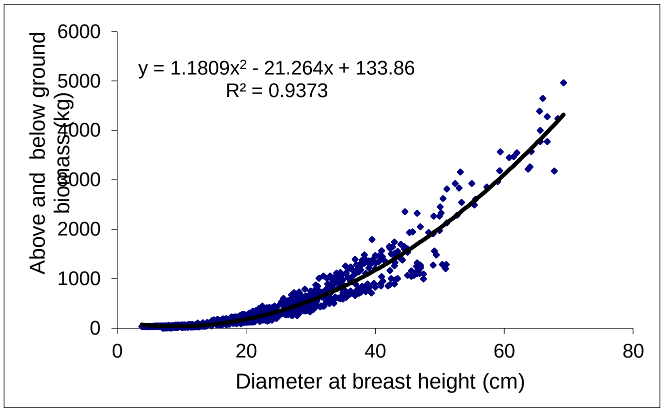

***Figure 1**: Relationship between DBH and tree biomass for three species types at Kiambu, Nyeri North and Nyeri South*

In addition, there were significant differences in crown surface area ($F_{(4, 1087)} = 132.14$; $p<0.01$) and crown volume ($F_{(4, 1088)} = 10.63$; $p<0.01$) among the tree species between and within sites. In each of the tree species within study sites, an increase of the crown surface area resulted to an increase of crown volume leading to an increase on the amount of carbon sequestered. This also varied by age among the sites and tree species as well as tree stand density (Table 4).

***Table 4**: Estimated stand density, area, mean crown area, mean crown volume and carbon sequestered*

Site	Tree species	Age	Density per ha.	Area (ha)	DBH (cm)	Crown area (m^2)	crown volume (m^3)	MgC ha^{-1}
Kiambu	*Cupressus lusitanica*	5	960	7.8	11.2	31.8	22.3	10.4
		8	800	13.8	19.3	65.1	63.8	45.8
		14	590	10.3	28.2	95.0	110.5	102.8
		24	532	2.5	38.9	162.6	268.6	228.2
	Eucalyptus saligna	2	671	3.54	5.9	29.4	14.6	11.3
		5	758	3.56	9.3	33.8	18.9	21.1
		7	1238	5.2	18.5	59.3	44.4	125.9
		10	250	2	20.2	67.3	64.4	26.1
		12	150	9.8	38.0	266.7	464.4	95.4
	Pinus patula	6	550	2.3	19.3	36.0	23.4	65.4

		10	200	4.2	28.6	63.0	53.8	60.0
		13	506	20.5	28.9	84.3	84.4	161.5
		32	60	11.1	59.0	450.4	963.0	95.6
Nyeri North	*Cupressus lusitanica*	5	1100	5	6.6	102.4	17.1	2.2
		8	1050	5	20.1	319.0	53.2	63.0
		13	1000	19.4	21.9	515.9	86.0	85.1
		24	525	10.1	27.4	769.0	128.2	89.1
	Eucalyptus saligna	8	780	5	19.1	44.0	30.6	70.0
		19	525	25	23.3	124.3	157.1	73.6
		33	150	3.6	42.7	271.2	485.3	105.8
	Pinus patula	8	600	5	18.6	471.1	78.5	67.5
		17	640	5	26.5	794.6	132.4	166.5
		30	425	5.4	36.3	1555.0	259.2	265.3
Nyeri South	*Cupressus lusitanica*	5	1000	5	9.8	137.1	22.9	8.3
		8	1100	3.5	19.6	492.4	82.1	73.3
		14	1000	16.3	27.9	886.7	147.8	180.3
		24	235	30.4	40.1	1801.1	300.2	98.8
	Eucalyptus saligna	7	700	1.5	22.5	264.4	44.1	120.3
		8	840	4.5	30.7	177.9	29.7	337.0
		14	390	4	36.5	850.8	180.9	244.3
	Pinus patula	5	999	4.4	15.7	185.0	30.8	50.3
		10	750	16	22.9	867.1	144.5	99.4
		26	200	12	35.6	1459.7	243.3	74.5
	s.e.d				2.56	37.27	18.49	21.03

The positive correlation between DBH, crown surface area and crown volume showed as the DBH increased, crown surface area over crown volume ratio increased implying more biomass as a result of photosynthesis process, hence more carbon sequestration at different ages of tree growth. The variations in crowns surface area and crown volume among species may be explained by differences in age among species across sites, stand density and silvicultural management operations such as pruning and thinning. Essentially, pruning of the lowest branches regulates branching habit and crown base. Other studies have shown tree height, crown height and crown diameter growth rates were highest in the young trees and decrease with tree age, although the rate of decrease differs among species and among the growth parameters. Relatively larger crown diameter growth compared to tree height and crown height may suggest that older trees may have reached near asymptotic tree height growth levels while still growing laterally in tree crowns (Stoffberg et al. 2008).

Overall, carbon sequestration estimates aboveground and belowground from three common plantation species in Kenya, demonstrated a significant potential in reduction of GHG, specifically carbon dioxide in mitigation of climate change (Figure 2).

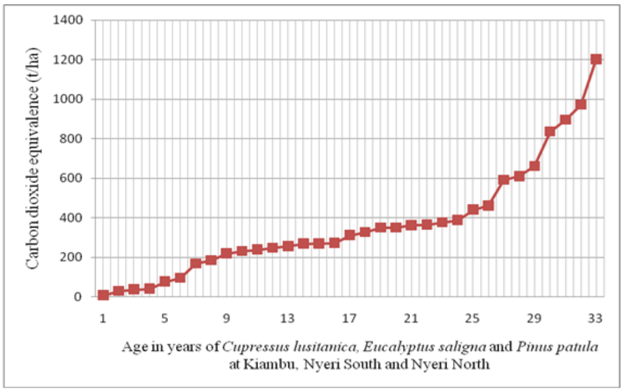

Figure 2.*Estimation of carbon dioxide equivalence removal from the atmosphere by three species across sites*

4. CONCLUSION

The finding on estimation of carbon stocks demonstrated potential of the three selected tree species on reduction of carbon dioxide from atmosphere. The study also provided insight on some of the applicable methodologies on estimating carbon stocks based on available allometric equations. The differences on carbon stocks among selected tree species showed the need for optimal investment in commercial forestry with multiple benefits like taking advantage of carbon markets. Therefore, as the Government of Kenya embarks on REDD+ activities and developing national carbon accounting system in monitoring, reporting and verifications, there is a need of taking into account the contribution of species in total carbon sinks. These demands for more awareness of different potentials each tree species has in carbon sequestration. The relationship found among growth parameters strongly indicated a need to develop local biomass allometric equations for *Cupressus lusitanica, Eucalyptus saligna* and *Pinus patula* as well as other key species in improving accurate reporting of carbon estimates.

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