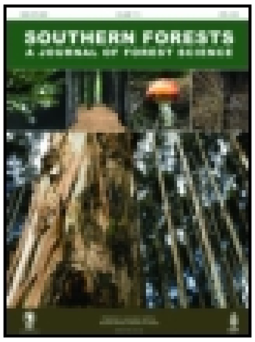

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Growing common plantation tree species in Kenya for sale of carbon and wood supply: what is the best bet?

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The introduction of carbon finance as an incentive in forestry farming has a potential of increasing the amount of carbon sequestered. However, this has created a daunting task among investors in forestry to optimise the joint production of wood and carbon sequestration. For instance, investors might find it profitable to give up some timber returns in exchange for carbon credits. This study evaluated expected income from growing *Cupressus lusitanica* Mill., *Pinus patula* Schiede ex Schltdl. & Cham., *Eucalyptus saligna* Sm. and *Juniperus procera* Hochst. ex Endl. for wood and/or the carbon market in central Kenya. The global average unit price of carbon and stumpage royalty were used to estimate expected returns from sale of carbon credits and wood, respectively. There were significant differences ($p < 0.01$) in the expected amount of income from sale of carbon and wood among the four species. Specifically, at economic rotation of 30 years with stand density of 532 trees ha^{-1} *P. patula* and *C. lusitanica* yielded US\$28 050 and US\$23 650, respectively, from sale of carbon compared with US\$59 000 and US\$51 000, respectively, from sale of wood. This was twice the value investors receive from clear-felling as compared with sales from carbon. Similarly, at economic rotation of 33 years with stand density of 150 trees ha^{-1}, a forest investor in *E. saligna* would earn US\$15 400 from sale of carbon compared with US\$33 000 from sale of wood. Overall, the amount expected to be realised from sale of carbon was lower compared with that from sale of wood. This demonstrates that the price dynamics of carbon offsets in the voluntary and the compliance markets need to remain competitive and attractive for the forest owners to give up some timber returns in exchange for carbon income or to modify forest management regulation in order to increase carbon sequestration.

Keywords: carbon credits, carbon sequestration, *Cupressus lusitanica*, *Eucalyptus saligna*, *Juniperus procera*, *Pinus patula*, sale of wood

Introduction

The introduction of forest carbon trading as an incentive to forestry farming has gained momentum in the recent past. This is because forests, and trees outside forests, remain important as carbon sinks in industrial countries depending on fossil fuels as the main source of energy. However, the demand for forest wood products is globally high and creates a competitive edge for other sources of energy such as fossil fuels. Investment in forestry in this scenario might therefore remain lucrative because of their involvement in carbon sequestration that can tap into some of the investment programmes from multinational oil companies with emission caps. Evaluation of the returns expected by tree investors against the pegged product at time of harvesting and taking advantage of climate change to extend the rotation age if carbon returns will be higher remain important. In this business, carbon is given an economic value allowing people, companies or nations to trade, creating a compliance market or voluntary carbon market to facilitate buying and selling of the rights to emit greenhouse gases (GHGs). This offers the opportunity to industrialised nations, for which reducing emissions is a daunting task, to buy the emission rights from other nations whose industries do not produce as much as of these gases, resulting in amelioration of climate change.

Hamrick and Goldstein (2016) reported a voluntary carbon market total volume of 0.994 billion tonnes of carbon dioxide equivalent (tCO_2e) from pre-2005 to 2015 with a value of US\$4.6 billion. This is a significant achievement from the forest sector over the reporting period. However, in 2015, 92% of the buyers were repeat customers, meaning that the entrance of new buyers remained low reflecting a significant decline in the carbon price from US\$7.30 in 2008 to US \$3.30 in 2015. This may complicate matters among the forest investors who banked on greater investment in the carbon market compared with supply of wood or capitalisation of returns from both frontiers of investment, that is, carbon and supply of wood.

The declining trend of the carbon price may affect decisions by actors interested in investing in projects such as those dealing with Reducing Emissions from Deforestation and Forest Degradation (REDD+) and promoting efficient cooking stoves to reduce pressure on deforestation, among other projects. This creates a challenge among forest managers in balancing between optimising the joint production of timber and carbon sequestration, and possibly other non-timber benefits (Liu et al 2002; Chladna 2007; Gené 2007; Pohjola and Valsta 2007; Bigsby 2009; Olschewski and Benítez 2010). These authors reported that if the carbon price is high, forest owners might find it profitable to give up some timber returns in exchange for CO_2 returns or modify forest management regulations in order to increase carbon sequestration. In addition, Olschewski and Benítez (2010) determined the optimal combination of thinnings and final harvest age for joint production of timber and carbon sequestration, when carbon uptake was subsidised and carbon release was taxed. They found different quantities of carbon and growth from Scots pine and Norway spruce where the changes in optimal silviculture for Scots pine increased carbon storage by 42 t CO_2 ha^{-1} with a carbon price of €10 t CO_2 and by 81 t CO_2 ha^{-1} with a carbon price of €20 t CO_2. In addition, a carbon tax/subsidy programme was found to increase income to forest owners considerably. Consequently, real option models developed have demonstrated certainties in the future wood and CO_2 price behaviour and found that optimal rotation periods varied considerably with the type of price process, the method by which carbon income was defined and selection of discount rates. Furthermore, potential impacts of carbon taxes on carbon flux have also led to reduced harvests and increased carbon stock in standing trees and understory biomass where average age increased varying in extent across ownership and sites (Im et al. 2007; Lippke and Perez-Garcia 2008).

Overall, carbon pricing remains an important planning tool among many companies in developed countries aimed at reducing GHG emissions. This is because mainstream business finds the use of carbon pricing more realistic, prudent and useful. Specifically, in Canada, GHG reduction projects are assessed against a carbon price of C$15–68 per tCO_2e projected to increase to C$48–68 per tCO_2e in 2020 and up to 2040. In the United Kingdom, investment in clean energy projects puts a minimum price on carbon of US$7.95 per tCO_2e and is expected to rise to US$29.10 per tCO_2e by 2016. In North America, companies plan for about US$20 per tCO_2e and US$40 per tCO_2e among international oil companies (CDP 2013; Parry et al. 2014). The authors indicated that this compares well with an average of US$25 per tCO_2e used by the International Monetary Fund in the context of promising domestic fiscal instruments for climate change. This creates a good avenue for governments to undertake in-depth analysis of carbon pricing and restructure initiatives to link carbon pricing to social development, environmental conservation and provision of ecosystem services. The end result is that countries would be strategically placed to tap into business investment by multinational companies to support payment of ecosystem services and create a balance of neutrality on GHG emission and effective management of climate change.

In Kenya and other eastern African countries, little or no comparative information is available on carbon and timber investment in major plantation tree species that are commercially grown to supply forest wood products. This study therefore sought to evaluate the economic returns from sale of carbon and wood among commonly grown plantation species in Kenya. The selected tree species, namely *Cupressus lusitanica* Mill., *Pinus patula* Schiede ex Schltdl. & Cham., *Eucalyptus saligna* Sm. and *Juniperus procera* Hochst. ex Endl., are widely grown in Uganda, Tanzania, Rwanda and Ethiopia, which share almost similar agro-ecological zones with Kenya and stand to benefit from the findings and recommendations of this study.

Materials and methods

Description of study sites

This study was carried out in gazetted plantation forests in Kiambu and Nyeri Counties of the Central Highland Conservancy in Kenya. Specifically, data were collected from six forest stations: Muguga, Kinale and Uplands in the Kiambu Forest Ecosystem; and Kabage, Kabaru and Naro Moru in the Nyeri Forest Ecosystem. Kinale and Uplands forest stations lie on the upper highland (UH 1) at an altitude of 2 591 m above sea level (asl) and 2 415 m asl, respectively. The sites receive mean annual rainfall of 1 150–1 276 mm and 1 210–1 414 mm, respectively. Muguga lies on the lower highland two (LH 2) at an altitude of 2 067 m asl and receives mean annual rainfall of 1 000 mm. Kabage forest station lies on the easterly exposed edge of the Aberdare Range on the UH 1 at an altitude of 2 286 m asl and receives mean annual rainfall of 1 424 mm. Naromoru forest station lies on the drier western leeward side of Mt Kenya on the lower highland agro-ecological zone three (LH 3) at an altitude of 2 134 m asl and receives mean annual rainfall of 855 mm (Jaetzold et al. 2006).

Sampling design

A list of the forest stations managed by the Kenya Forest Service in Central Highland Conservancy was compiled. Kiambu and Nyeri Forest Ecosystems were randomly selected. The forest stations at each of these sites were stratified and clustered on the basis of their agro-ecological zone and composition of plantation species. This resulted in four and three clusters in Kiambu and Nyeri Forest Ecosystems, respectively. The first and second clusters of forest stations in Kiambu were randomly selected, resulting in selection of Muguga, Uplands and Kinale forest stations constituting the Lari forest block. Kabage, Naromoru and Kabaru forest stations in the Nyeri Forest Ecosystem were selected.

Tree species sampling and measurements

A forest compartment register was used in selecting the plantation blocks depending on the age of the species, accessibility, security from wild animals and previous management of the block. Rectangular plots measuring 20 m × 50 m of *E. saligna*, *C. lusitanica* and *P. patula* were established at Lari, Kabage and Naromoru forest stations and replicated three times in each age category. The rationale for plot measurements was based on other similar studies that 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 (Wang et al. 1996; Sierra et al. 2007; Alberti et al. 2008; Paul et al. 2008; Williams et al. 2008). 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, 30 and 14 plots were established for different stand ages of *C. lusitanica*, *E. saligna*, *P. patula* and *J. procera*, respectively, at the selected study sites. The number of plots varied because of the different sizes of the forest plantations selected at the study sites. At the sites where the total area planted was large (>10 ha) and fairly homogenous, the distance between plots ranged from 100 to 120 m, whereas for medium and small areas (<10 ha) the distance between plots ranged from 80 to 100 m apart. The sites were first surveyed to avoid any bias in establishment of 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 in order to estimate total biomass and carbon for a given stand. Tree height, diameter at breast height (DBH; cm) at 1.3 m above ground level, crown diameter and crown depth were measured in four directions and averaged.

Data analysis

Aboveground and belowground carbon measurement

The data analysis was carried out using the CO2FIX 3.1 modelling framework (Masera et al. 2003). Specifically, the model considers the total carbon stored in the forest stand at any time to be:

$$\mathrm{CT}_i\ (\mathrm{t\ C\ ha^{-1}}) = \mathrm{Cb}_t + \mathrm{Cs}_t + \mathrm{Cp}_t \quad (1)$$

where CT_i is the total carbon stored in the forest stand at any time, where $i = 1,2,...k$; Cb_t is the total carbon stored in living (aboveground and belowground) biomass at time t (in t ha^{-1}); Cs_t is the carbon stored in soil organic matter (in t ha^{-1}); and Cp_t is the carbon stored in wood products (in t ha^{-1}). However, the wood products were not considered in this analysis but are implied in discussion of the 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. The model used stem volume growth (in m^3 ha^{-1} y^{-1}) as the main input, and an allometric approach to derive net annual increment of the main biomass components from stem volume growth. Mathematically,

$$\mathrm{Gb}_{it}\ (\mathrm{t\ ha^{-1}\ y^{-1}}) = K_{\mathrm{v}} Y_{ist}(1 + \sum(F_{ijt}))\mathrm{Mg}_{it} \quad (2)$$

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 a biomass expansion factor of 1.3 (Hu and Wang 2008). Basic densities of each tree species were obtained from the Kenya Forestry Research Institute (*P. patula* = 472 kg m^{-3}, *C. lusitanica* = 414 kg m^{-3} and *E. saligna* = for 498 kg m^{-3}). These basic densities were measured at the bottom, middle and top of the tree stem of different ages and sites and averaged. These densities were used to compute the expected tree biomass after obtaining the tree volume as calculated using the local allometric volume equations.

The variable Y_{ist} is the volume yield of stem wood for each cohort i (in m^3 ha^{-1} y^{-1}). F_{ijt} is 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). Mg_{it} is the dimensionless growth modifier due to interactions among and within cohorts. This was not factored into estimation of total biomass in this study. A root:shoot ratio of 0.3 and carbon content of 50% for estimation of carbon in aboveground and belowground biomass were used in this study (Hu and Wang 2008; Jacobs et al. 2009).

Local volume equations

The local formulas for computing the stem volume of *C. lusitanica*, *J. procera*, *E. saligna* and *P. patula* (Valkonen et al. 2000) used were as follows:

Cupressus lusitanica and *Pinus patula*:

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

Juniperus procera:

$$\mathrm{Log}V = -4.2224 + 0.9673\log D^2H \quad (4)$$

Eucalyptus saligna:

$$V = 0.0368162 + 0.0000310D^2H \quad (5)$$

Unit cost of carbon and wood

The unit cost of wood was based on the minimum DBH (cm) for clear-felling and thinning for each of the commonly grown plantation species. The stumpage royalty (price) for *C. lusitanica*, *E. saligna*, *P. patula* and *J. procera* were estimated in KSh m^{-3} converted to US$ m^{-3} (US$1 = KSh100) within the threshold of the DBH as per the Kenya Forest Service price list (Table 1). The stumpage royalty was exclusive of felling, loading and related harvesting costs transferred to the buyer. The carbon pricing was estimated at an average of US$5.50 based on trend analysis from pre-2008 to 2015 (Figure 1) for the voluntary carbon market on reducing emissions from deforestation and forest degradation (Peters-Stanley and Gonzalez 2014; Hamrick and Goldstein 2015). The data were analysed using a linear mixed model and analysis of variance (ANOVA) with GenStat® 15th Edition (VSN International, Hemel Hempstead, UK). Significant differences were declared at the 5% and 1% significance levels unless stated otherwise.

Results

Income estimation from sale of carbon credits and wood of selected tree species

The average carbon sale and expected amount of income to be realised from aboveground and belowground biomass (AGB) and clear-felling among commonly grown plantation species across ages and sites differed significantly ($F_{2,208} = 83.81$, $p < 0.01$; Table 2). Overall, the amount likely to be realised from sale of carbon from AGB was lower compared with sale of wood, which was twice the value from carbon sale. Age was a significant factor ($F_{1,208} = 17.90$; $p < 0.01$) in variation of the amount of income likely to be realised from the sale of carbon and clear-felling. For instance, expected income to be realised

Table 1: Price list for stumpage royalty of selected tree species in Kenya. Source: Kenya Forest Service, 2014/15 financial year

Tree species	Minimum DBH (cm)		Maximum DBH (cm)		Minimum stumpage royalty (KSh m^{-3})		Maximum stumpage royalty (KSh m^{-3})	
	Thinning	Clear-felling	Thinning	Clear-felling	Thinning	Clear felling	Thinning	Clear felling
Cupressus lusitanica	15	15	55	100	1 972 (US$19.7)	2 375 (US$23.8)	2 423 (US$24.3)	3 108 (US$31.1)
Pinus patula	20	20	55	100	1 844 (US$18.4)	2 222 (US$22.2)	2 180	2 797 (US$28)
Eucalyptus saligna	–	20	–	100	–	1 975 (US$19.7)	–	2 490 (US$24.9)
Juniperus procera	<24	<24	>56	>56	4 136 (US$41.4)	5 043 (US$50.4)	8 433 (US$84.3)	10 234 (US$102.3)

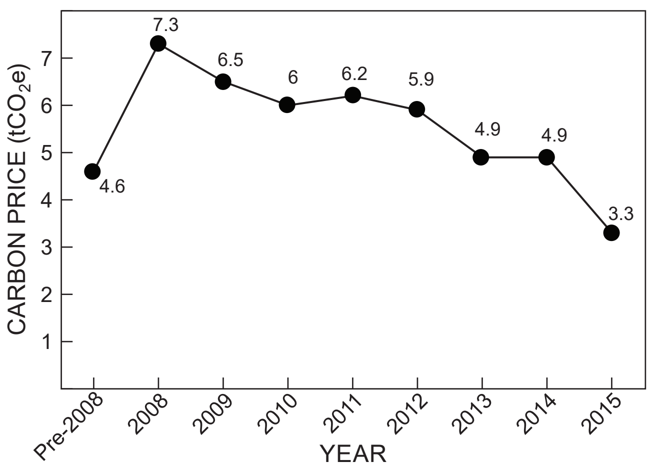

Figure 1: Trends on carbon price from forest-based carbon market. Source of data: Hamrick and Goldstein (2015, 2016)

from sale of carbon and clear-felling of *C. lusitanica* at age 24, almost at economic age rotation of about 30 years, was significantly higher ($p < 0.05$) at Kiambu compared with Nyeri North and Nyeri South forest ecosystems. Similar evidence was observed for *P. patula* at the economic rotation age of about 30 years among sites. In addition, there were significant differences in the expected amount of income to be realised from sale of carbon credits and wood among the environmental sites ($F_{2,208} = 13.80$; $p < 0.01$), interaction between sites and tree species ($F_{4,208} = 23.26$; $p < 0.01$), and interaction between environmental sites and levels of sales ($F_{4,208} = 6.15$; $p < 0.01$; Table 2).

There were significant differences ($F_{1,20} = 92.08$; $p < 0.01$) between the amount of income to be realised from clear-felling and sale of carbon credits for *J. procera* at Nyeri North forest ecosystem. Clear-felling and sale of carbon credits contributed 58% of the total variation in the expected amount to be realised, followed by age (21%) and interaction between age and sources of sale (8%), leaving 13% unexplained.

Projection of mean annual increment and income from sale of carbon and wood

For projections based on the mean annual increment (MAI) assuming the same density, site quality and other environmental factors remained constant, a tree investor in *C. lusitanica* at Kiambu would be expected to realise an income of US$22 000 ha^{-1} from sale of carbon credits and US$47 500 ha^{-1} from clear-felling at economic rotation age of 30 years. Similarly, the expected income to be realised from *P. patula* at economic rotation age of 30 years at the same site through sale of carbon credits would be about US$26 125 ha^{-1} and US$55 000 ha^{-1} from clear-felling. Overall, the projected income from clear-felling was higher for both tree species followed by income from sale of carbon AGB (Figure 2).

Furthermore, at economic rotation age of 30 years at Nyeri North forest ecosystem, a tree investor would realise about US$12 375 ha^{-1} from sale of carbon and US$26 250 ha^{-1} from clear-felling of *C. lusitanica*. Similarly, the same tree investor would fetch US$19 250 from sale of carbon and US$41 250 from clear-felling of *P. patula* in the same forest ecosystem. Similarly, an investor in *E. saligna* would realise US$14 437 ha^{-1} from sale of carbon credits and US$31 250 ha^{-1} from clear-felling (Figures 3 and 4). Consequently, an investor in a *J. procera* plantation, with a stand density of 150 stems ha^{-1} at 70 years old, would realise US$56 250 from sale of wood compared with US$8 250 from sale of carbon (Table 3).

Discussion

The comparisons between carbon and wood income expected to be realised from *C. lusitanica*, *P. patula*, *E. saligna* and *J. procera* indicated tree investors were more likely to be encouraged to invest on wood production because of high returns assuming the cost of production remains constant or significantly less. This may create a challenge to promoting the growing of trees for the carbon market and will ultimately widen the gap between income from wood and carbon sales at a given economic rotation, resulting in less interest in carbon. This suggested that unstable and fluctuating carbon prices, as evident currently, would hamper investment plans based on carbon trading. The price stability in carbon credits that reflects in the trends of wood income would persuade tree investors to engage in both investments for wood and carbon.

The carbon market is currently a global concern where the carbon prices significantly vary from a group of nations to individual nations and the voluntary market. Currently,

Table 2: Expected income from sale of carbon and clear-felling of selected tree species

Tree species	Stand density (stems ha^{-1})	Age (y)	Expected income (US$) from AGB tCO_2e ha^{-1}	Expected income (US$) from clear-felling m^3 ha^{-1}
Kiambu				
Cupressus lusitanica	800	8	1 849	4 046
	590	14	4 148	9 697
	532	24	9 204	22 773
Eucalyptus saligna	1 238	7	5 077	11 847
	250	10	1 051	2 319
	150	12	3 846	7 266
Pinus patula	550	6	2 638	5 254
	200	10	2 421	4 475
	506	13	6 515	12 076
	60	32	3 854	7 953
Nyeri North				
Cupressus lusitanica	1 050	8	2 542	5 728
	1 000	13	3 433	7 672
	525	24	3 594	8 367
Eucalyptus saligna	780	8	2 823	5 625
	525	19	2 969	5 609
	150	33	4 267	8 282
Pinus patula	600	8	2 724	5 777
	640	17	6 716	12 264
	425	30	10 701	20 607
Nyeri South				
Cupressus lusitanica	1 100	8	2 956	6 459
	1 000	14	7 272	17 012
	235	24	3 986	9 921
Eucalyptus saligna	700	7	4 853	8 606
	840	8	13 233	24 159
	390	14	9 853	18 604
Pinus patula	750	10	4 010	7 215
	200	26	3 003	5 780

the carbon market is dominated by the European Union, where companies that emit GHGs are required to cut their emissions or buy pollution allowances or carbon credits from the market, under the European Union Emission Trading Scheme (EU-ETS). Europe has experienced volatile carbon prices due to fluctuations in energy prices and supply and demand, and will continue to dominate the global carbon market for another few years as the United States and China, the world's top polluters, have yet to establish mandatory emission-reduction policies. The US market remains primarily a voluntary market, but multiple cap and trade regimes are either fully implemented or near imminent at the regional level. The first mandatory, market-based cap-and-trade programme to cut CO_2 in the US, called the Regional Greenhouse Gas initiative (RGGI), kicked into gear in north-eastern states in 2009, growing nearly ten-fold to US$2.5 billion, according to Point Carbon (Hamrick and Goldstein 2016).

Since the approval and operationalisation of voluntary carbon markets about 1 billion tCO_2e have been offset, worth US$4.5 billion, of which 50% are for forest-based projects (Hamrick and Goldstein 2015). It's further estimated that by 2100, REDD+ will contribute to an emission reduction of between 13 and 50 billion tCO_2e. This has catalysed the investment in afforestation and reforestation programmes under Clean Development Mechanisms and REDD+ schemes to incentivise forest investment. It has also resulted in establishment of carbon finance to fund climate change mitigation and adaptation in developing countries. In this regard, carbon trading has become the policy instrument of choice among governments aiming at reducing GHG emissions.

However, the threats created by variation in carbon price might remain a deterrent to achieving the global target of reducing increasing temperature below 2 °C. This requires stabilisation of carbon prices in both voluntary and compliance markets in order to enhance forest investment for mitigation and adaptation to climate change. For example, Hamrick and Goldstein (2016) reported that buyers expressed fears on the voluntary market due to low prices. The correct price of carbon credits can be underscored if it is matched with the market value of wood and ability of different tree species to sequester carbon. This would provide a competitive edge for carbon credits as a commodity to promote the global objective of reducing emissions from anthropogenic activities. Specifically, taking this approach in trading forest carbon would enable tree growers and other investors in forests to develop a market similar to other economic sectors.

The findings from this study revealed a huge gap in expected returns from sale of carbon and wood of selected major commercial trees species grown in forest plantations in Kenya. Specifically, a stand density of 150 stems ha^{-1} of *J. procera* at a growth age of 70 years had an average

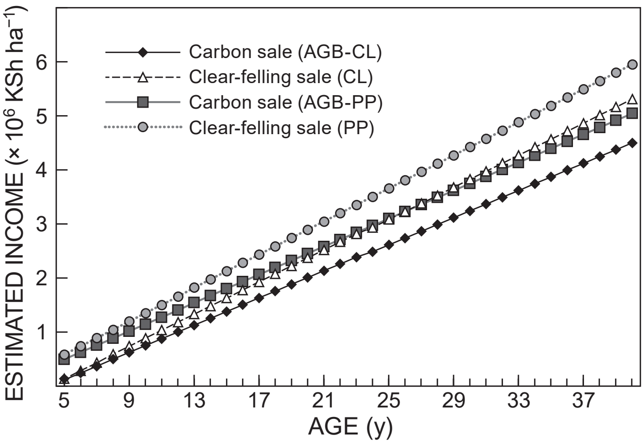

Figure 2: Projected income based on mean annual increment from sale of carbon (AGB) and clear-felling of *Cupressus lusitanica* (CL) and *Pinus patula* (PP) in the Kiambu forest ecosystem

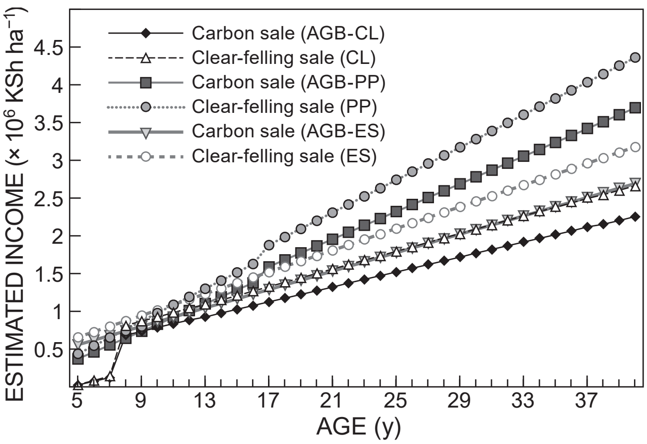

Figure 3: Projected income based on mean annual increment from sale of carbon (AGB) and clear felling of *Cupressus lusitanica* (CL), *Pinus patula* (PP) and *Eucalyptus saligna* (ES) in the Nyeri North forest ecoystem

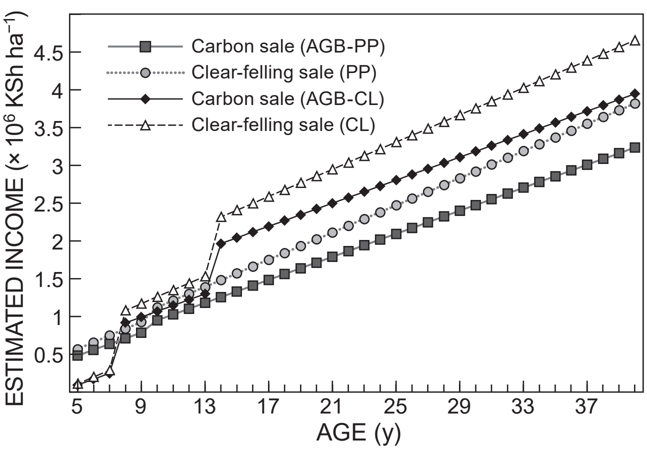

Figure 4: Projected income based on mean annual increment from sell of carbon (AGB) and clear-felling of *Cupressus lusitanica* (CL) and *Pinus patula* (PP) in the Nyeri South forest ecosystem

Table 3: Expected income (US$) from clear-felling and sale of carbon from *Juniperus procera* at Nyeri North forest ecosystem

Age (y)	Income (US$) Clear-felling	Income (US$) AGB tCO_2e ha^{-1}
19	8 750.00	2 063.00
65	52 500.00	8 250.00
70	56 250.00	8 250.00

DBH of 50.3 cm resulting in 3.048 m^3 $tree^{-1}$. If clear-felled, the same tree would fetch US$361.90 for the estimated volume. Comparatively, it would sequester 4.92 tCO_2 based on AGB carbon estimates. This implies that a single stem of *J. procera* absorbed about 70.3 kg CO_2 every year over a lifetime of 70 years. At an average cost of US$5.50 for sale of carbon, a tree investor would fetch US$27.10, far below the clear-fell price of US$361.60 m^{-3}. Therefore, matching the unit of carbon credit as per tree market value shows that at the age of 70 years, *J. procera* should fetch a minimum value of US$74 compared with the current dynamic prices of carbon which have fallen below US$5. If such carbon prices are not corrected, there is every reason for a tree investor to opt for better options that can yield superior returns. *Juniperus procera* is native to Kenya, Tanzania, Uganda, Zimbabwe, Democratic Republic of the Congo, Djibouti, Eritrea, Malawi and Sudan, among others. This species has multiple uses and characteristics that an investor can capitalise on compared with growing for carbon market *per se*. The uses of this species remain advantageous for carbon sequestration that can easily motivate a farmer to alter the economic rotation age to enhance reduction of GHG emissions.

This study also demonstrated that a stand density of 60 trees ha^{-1} for *P. patula* at growth age 32 years had an average DBH of 59 cm. This resulted in US$123 $tree^{-1}$ at clear-felling having absorbed about 5.84 tCO_2, an equivalent of 182 kg CO_2 y^{-1}. The minimum value a tree investor would receive from carbon sale would be about US$32.10 compared with US$123 for the same amount of wood. Translating this to carbon price, the minimum cost of a carbon credit would be about US$21 at this age of tree stand and site. This would not only attract a tree grower to invest for the carbon market but also to lengthen the economic age rotation period resulting in effective mitigation of climate change. The advantageous economic rotation age of *P. patula* for plywood, sawn timber and pulpwood at 35, 30 and 18 years, respectively, can be extended beyond the harvesting period if returns from carbon are higher than those from sale of planned wood. Specifically, a tree investor might be willing to extend the rotation age period to a maximum of 50 years, almost two cycles as stipulated by the Kyoto Protocol whereby trees should be left to stand for a period of 25 years before clear-felling.

The interplay of environmental factors and tree species would be advantageous to tree investors in the context of climate change and demand for wood to meet national and international needs. In this study, sites played a significant role in variation of carbon sequestered, translating to different returns from the same and different tree species. Specifically, at Nyeri North and Nyeri South forest ecosystems, *P. patula* stands of age 30 and 26 had stand densities of 425 and 200 stems ha^{-1}, respectively, with an average DBH of 36 cm. This yielded an average cost of US\$46.80 tree^{-1} at clear-felling having absorbed about 2.29 and 1.36 tCO_2, an equivalent of 76.3 and 52.3 kg CO_2 y^{-1}, respectively. Therefore, the minimum cost of carbon credits based on the market value of trees should be US\$21 and US\$34 at Nyeri North and Nyeri South, respectively. Similarly, *C. lusitanica* at age 24 with stand densities of 532, 525 and 235 stems ha^{-1} at Kiambu, Nyeri North and Nyeri South forest ecosystems, respectively, absorbed about 1.57, 0.622 and 1.54 tCO_2 implying each tree absorbed about 65.5, 25 and 164.1 kg CO_2 y^{-1}, respectively. In order to attract the carbon market, the minimum unit cost per carbon credit should be US\$27. This would also lengthen the economic rotation period of pulpwood by 15–20 years and sawn timber by 30 years to a maximum of 40 years. The rotation age may indicate a better opportunity for a tree investor to forgo pulpwood and invest for timber, thus increasing the carbon storage potential in timber products for a longer period. The same trend in carbon differentials and expected cost from sale of carbon credits and wood for *E. saligna* was observed at all study sites. Therefore, the introduction of carbon credits should be sold at a minimum of US\$19 to motivate tree investors to shift to the carbon market under different economic rotations. It is widely known that eucalypts are grown for fuelwood (6–8 years) with four economic rotations, pulpwood/fibreboard (8 years) with three economic rotations, timber (20 years) with two economic rotations and plywood at age of 30 with possibly two economic rotations. This could be extended even up to 100 years depending on the returns that the tree investor would fetch from the carbon sales, thus enhancing carbon sinks for climate change mitigation.

Conclusion and recommendations

The significant variation in income expected to be realised from sale of wood compared with that from sale of carbon may jeopardise national and international efforts to mitigate climate change through forestry. This requires stabilisation of carbon prices and relative control of wood prices in order to create a balance that promotes both economic and environmental benefits. The pricing of carbon should be species-specific to incentivise tree growers to extend the economic rotation age with the purpose of meeting environmental benefits. Global policy on the carbon market and carbon trading need to be developed to guide carbon-based investments in forestry in order to realise the overall goal of sustainable forest management.

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