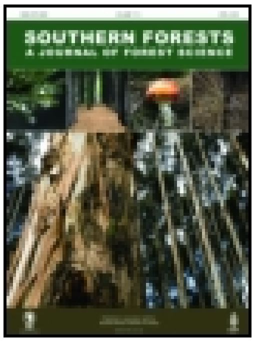

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The economics of the carbon sequestration potential of plantation forestry in south-western Uganda

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This study assessed the amount of carbon stored and the economic viability of the small-scale Clean Development Mechanism (CDM) carbon offsets in *Pinus caribaea* and *Eucalyptus grandis* plantations under varying rotations. Volume equations were used to estimate carbon stocks and merchantable wood volume in the plantations, while net present value (NPV) and annual equivalent value (AEV) were used as measures of profitability at the optimum economic rotation age as well as at the CDM-defined crediting period of 20 years. The findings show that over a 20-year rotation, *E. grandis* and *P. caribaea* plantations sequestered 638 and 418 t CO_2-e ha^{-1}, respectively. The NPVs of *E. grandis* and *P. caribaea* with carbon credits over the CDM carbon-crediting period of 20 years were US\$2 540 ha^{-1} and US\$1 814 ha^{-1}, respectively. This is higher than the NPVs without carbon credits of US\$1 543 ha^{-1} and US\$1 390 ha^{-1} for *E. grandis* and *P. caribaea*, respectively. The AEV of *E. grandis* harvested at its optimal economic rotation of 10 years was US\$316 ha^{-1}. This is slightly higher than the AEV of US\$298 ha^{-1}, utilising the CDM carbon-crediting period of 20 years. In contrast, the AEV of *P. caribaea* under the 20-year CDM carbon-crediting period was higher than harvesting at the optimal economic rotation of 16 years without carbon credits. When the average CDM contract establishment costs exceed US\$500 ha^{-1} and US\$1 000 ha^{-1} for *P. caribaea* and *E. grandis* woodlots, respectively, it is not economically viable for one to participate in the CDM forest carbon offsets programme. In conclusion, the study results indicate that whereas *E. grandis* has a higher biological potential to sequester carbon than *P. caribaea*, it is currently not economically viable for participation in the CDM forest carbon offset scheme. In contrast, it is economically viable for *P. caribaea* plantations to participate in the CDM, if the CDM contract establishment costs are low.

Keywords: carbon offsets, Clean Development Mechanism, *Eucalyptus grandis*, *Pinus caribaea*

Introduction

In response to concerns over the impact of climate change, the Kyoto Protocol set binding emission targets for Annex I countries for a number of potent greenhouse gases (IPCC 2003). Under the Kyoto Protocol, Annex I countries were allowed to meet emissions reductions targets during the first commitment period using flexible mechanisms such as the Clean Development Mechanism (CDM; UNFCCC 1997; Wise and Cacho 2005; BioCarbon Fund 2011). The CDM allows for the purchase of Certified Emission Reductions (CERs) by Annex I countries from non-Annex I countries as a means of complying with binding emission reduction targets (Pagiola and Platais 2007). The projects generating the carbon credits can be carried out in a number of technology sectors, including the land use, land-use change and forestry sector (LULUCF). Under the LULUCF sector, the scope of activities eligible for the CDM in the first commitment period of the Kyoto Protocol were limited to afforestation and reforestation (AR) projects. The CDM makes it possible for AR project owners in developing countries to receive payments for certified emission reductions (CERs) (Chomitz et al. 1999; Asquith et al. 2002; Nelson and de Jong 2003; Nabuurs et al. 2003).

The small-scale AR-CDM category offers a better opportunity for small-scale tree farmers to participate in the CDM carbon market (BioCarbon Fund 2011). The aim of the small-scale AR category is to reduce transaction costs per unit in order to promote small-scale projects (UNFCCC 2007). There are two eligibility requirements AR projects have to fulfill to be considered small scale: (1) they must be developed or implemented by low-income communities and individuals; and (2) they must result in greenhouse gas removals of less than 16 000 t CO_2-e y^{-1} (UNFCCC 2008). In addition, the United Nations Framework Convention on Climate Change (UNFCCC) allows project developers to bundle small-scale projects as a way to further reduce transaction costs. The tree farmers are paid for CERs over a 20-year contract period (UNFCCC 2007).

The Uganda Nile Basin Reforestation Project developed by the National Forest Authority is the first AR-CDM project in Africa that was successfully validated against the UNFCCC standard. The project applied the small-scale AR-CDM methodology and a portfolio of five projects has been established. The potential of forest carbon trade in Uganda is largely a consequence of the excellent conditions for tree growth (Kaboggoza 2011). Substantial land areas could be used for carbon sequestration through plantation forestry (MWLE 2002).

Several studies have demonstrated the substantial amount of carbon that can be stored by plantation forestry projects (Aune et al. 2004; de Jong et al. 2005; Wong et al. 2005; Shuifa et al. 2010; Glomsrød et al. 2011; Vonada et al. 2011). Other studies have also investigated the economic viability of including payments for carbon offsets (Palmer and Silber 2009; Soto-Pinto et al. 2009; Schmitt-Harsh et al. 2012). However, most profitability studies assume equal rotation for plantations with and without carbon credits (Wise and Cacho 2005; Olschewski and Benitez 2005; Palmer and Silber 2009), yet in reality plantations without carbon credits may be harvested before the crediting period of 20 years under CDM. Few studies have compared the profitability of forest carbon payments under alternative rotation length (Köthke and Dieter 2010). In addition, previous studies have provided mixed results, thus perpetuating the ambivalence about the economic viability of forest carbon offsets (Perez et al. 2007; Pfaff et al. 2007). In particular, there are concerns about the possible effect of high transaction costs of small-scale AR-CDM projects, increasing timber prices and low carbon prices on the profitability of forest carbon trade (Montagnini and Nair 2004; de Jong et al. 2000).

Following the expiry of the Kyoto Protocol in 2012, the international community adopted the COP21 agreement in December 2015. The COP21 agreement established a new mechanism, which will succeed the CDM in 2020. However, the rules for the new mechanism have not yet been adopted. Therefore, it is important that the economic viability of forest carbon offsets is assessed in order to inform the design of future carbon projects.

Therefore, this study assessed the effect of including carbon offsets on the profitability of two common plantation forestry species. The study assessed the economic viability of carbon offsets in *Pinus caribaea* and *Eucalyptus grandis* plantations under CDM. The study also tests the effect of variations in transaction costs, timber prices and rotation length on relative profitability of the carbon offsets. *Pinus caribaea* and *E. grandis* are two of the most widely planted exotic plantation species in south-western Uganda. Both have been widely adopted by tree farmers because they are silviculturally robust and adaptable within a range of sites.

Materials and methods

Data collection

Tree inventory data were collected from tree farmers in Rubirizi and Mitooma districts in south-western Uganda. Inventory data included tree height (metres), diameter at breast height (dbh; centimetres), plantation area (hectares), species and age of trees. The data was collected from 94 and 106 plots of *P. caribaea* and *E. grandis*, respectively. Plot size was 20 m × 20 m. The number of plots established on each farm depended on the farm size. The data were collected from plantations of 5, 10, 15 and 20 years of age. District forest department staff, NGO staff and farmers in the study area provided information about the location of plantations.

Focus group discussions were conducted with tree farmers to collect data on the quantity, price and flow of plantation forest products such as timber, thinnings and firewood. The focus group discussions also provided information about the transaction costs associated with on-farm plantation forestry and the typical management regimes. Key informant interviews provided information about technical specifications for small-scale AR-CDM, carbon prices and carbon transaction costs.

Estimation of carbon stocks in woodlots

In order to estimate the temporal sequence of benefits received by farmers from the sale of carbon credits, we estimated carbon accumulation over the 20-year crediting period. The carbon stocks in *P. caribaea* and *E. grandis* plantations at 5, 10, 15 and 20 years were estimated using Ugandan and species-specific volume equations (Alder et al. 2003). The volume equations (Table 1) predict overbark volumes to 5 cm top diameter and underbark volumes up to 10 cm top diameter. Overback volume to a 5 cm top diameter normally approximates stem volume (Alders et al. 2003), whereas underbark volumes up to 10 cm top diameter approximate merchantable volume. The stem volume is converted to above-ground tree biomass using the respective basic wood density and biomass expansion factor, represented as:

$$B_{\mathrm{uh}.t} = V_{\mathrm{h},t} \times D \times \mathrm{BEF} \tag{1}$$

The above-ground biomass was converted to total tree biomass using the root:shoot ratio:

$$B_{\mathrm{h},t} = V_{\mathrm{h},t} \times D \times \mathrm{BEF} \times (1 + R) \tag{2}$$

Table 1: Regression equations used to estimate stem volume and biomass for *Pinus caribaea* and *Eucalyptus grandis*

Species	Volume equation[a]	n	R^2	References
Pinus caribaea	$V = (0.5046\ln(\sqrt{[10\,000/N]})\cdot\exp[-7.2328 + 2.1619\ln(H_d) + \ln(N)]$	867	90.9	Alders et al. (2003)
Pinus caribaea	$V_{10ub} = 0.23232 D_g^{0.30142} \cdot V^{1.02238}$	867	99.8	Alders et al. (2003)
Eucalyptus grandis	$V = 0.008429(H_d - 2.5)2.148 \cdot N^{0.4933}$	346	95.9	Alders et al. (2003)
Eucalyptus grandis	$V_{10ub}/V = 1 - \exp(-0.4327(D_{g1} - 9.5)^{0.762})$	346	99.5	Alders et al. (2003), Shiver and Brister (1992)

[a] H_d is dominant height (in m), N is stocking (in trees ha^{-1}), V is total stem volume (overbark to 5 cm top, in m^3 ha^{-1}), V_{10ub} is volume underbark to a 10 cm top diameter (merchantable volume; in m^3 ha^{-1}), D_g is the stand mean basal area diameter (in cm) (*P. caribaea*), and D_{g1} is the stand mean diameter (*E. grandis*)

where $B_{h,t}$ is the total tree biomass per hectare in year t (tonnes of dry matter per hectare; t dm ha^{-1}); $B_{uh,t}$ is the above-ground tree biomass per hectare in year t (t dm ha^{-1}); $V_{h,t}$ represents stem volume per hectare (overbark to 5 cm top) in year t (m^3 ha^{-1}); D is the basic wood density of the species (tonnes of dry matter per m^3; t dm m^{-3}); BEF is the biomass expansion factor for conversion of stem biomass to above-ground tree biomass; and R is the root:shoot ratio for the species.

Carbon stock (CO_2 equivalent; CO_2-e) in tree biomass per hectare in year t is estimated as:

$$C_{h,t} = \frac{44}{12} \times B_{h,t} \times \mathrm{CF} \tag{3}$$

where $C_{h,t}$ represents carbon stock in tree biomass per hectare in year t (t CO_2-e), $B_{h,t}$ is the total tree biomass per hectare in year t (t dm ha^{-1}) and CF is the carbon fraction of tree biomass, a default value of 0.5 is used (Brown 1997; IPCC 2003; McGroddy et al. 2004).

The economic model

In the base-case model, the net benefits of the woodlots with and without carbon credits over the crediting period of 20 years were estimated using the net present value (NPV). To make the alternatives comparable over time, the costs and benefits were discounted into a present value using a real discount rate of 10% and 2015 constant prices (Gittinger 1982; Graves 2007).

This study adopted the 'ideal' carbon payment method proposed by Cacho and Wise (2005), for evaluating certified emission reductions (CERs) under CDM. Under this method, payments for the amount of carbon sequestered are made at the end of the year (Cacho et al. 2003a). The profit function faced by the tree farmer over the project period of T years is:

$$\mathrm{NPV}(T,X,S) = \sum_{t=0}^{T}\left[\left(H_t(S).P_h + A_t(S).P_a\right) - C_t^h(S)\right].\delta^{-t} - C_E + \mathrm{CER}(T,S) \tag{4}$$

where NPV is the net present value of the stream of net revenues (US\$ ha^{-1}) obtained from merchantable volume/stumpage volume (H_t), firewood (A_t) and carbon payments (CER_t) sales from the woodlot, using the discount factor δ for the discount rate r. S represents the particular species and T is time. In this study, wood harvested included stumpage volume at the end of the rotation and firewood (from thinnings and tree tops after harvesting). P_h is the stumpage, P_a is price of firewood harvested and C_t^h represents the variable costs over the rotation. CE represents the establishment costs per hectare (land preparation, planting and establishing carbon contract). The last term in Equation (4) is the present value of the stream of net revenues obtained from the sale of carbon payments (CERs) for CDM. It is defined as:

$$\mathrm{CER}(T,X,S) = \sum_{t=0}^{T}\left[\left(\Delta C_t(S)\right).P_c - C_m\right].\delta^{-t} \tag{5}$$

where ΔC_t represents annual changes in carbon stock in tree biomass per hectare in year t (t CO_2-e); P_c is the price of carbon and C_m is the annual cost of measuring carbon.

The annual change in carbon stock in tree biomass was calculated by dividing carbon stock accumulated in any five-year interval (5, 10, 15 and 20 years) by 5:

$$\Delta C_t = (C_t + 1 - C_t)/5 \tag{6}$$

Similarly, the annual change in merchantable wood volume was assumed to be uniform in any five-year interval. The value of the merchantable wood volume was estimated from underbark volumes up to 10 cm top diameter, using the stumpage value approach. The volume of tree tops after final harvest was estimated as the difference between volume overbark up to 5 cm top diameter (total tree volume) and underbark volumes up to 10 cm top diameter (merchantable volume).

Costs

Carbon transaction costs under the small-scale AR-CDM include contract establishment costs and carbon monitoring costs. The CDM contract establishment is a fixed cost. This implies that the CDM contract establishment cost per hectare will reduce with increasing acreage due to economies of scale. Due to absence of reliable data on transaction costs, estimates from similar carbon projects were used. In this study, CDM contract establishment cost for 100 ha of plantation forest of US\$100 ha^{-1} was adopted in the base-case model (Cacho et al. 2003a). The annual carbon monitoring cost adopted for this study was US\$5 ha^{-1} y^{-1} (Cacho et al. 2004; BioCarbon Fund 2011). Other costs are outlined in Table 2.

Varying rotation approach

In the second approach, we assessed the profitability of plantations with and without carbon offsets under varying rotations. Whereas the base-case model assumed equal rotation for plantations with and without carbon credits, in reality plantations without carbon credits may be harvested before the crediting period of 20 years under CDM. This implies that the non-carbon farmers do not need to wait for the crediting period because they are not under any contract. Instead they can harvest at the optimal economic rotation, which may be different from the crediting period for CDM. Therefore, the economic profitability of plantations without carbon credits at shorter rotations, including the economically optimal rotation of each species, was estimated and compared with carbon offsets. Apart from varying the rotations, the other base-case assumptions remained the same.

The optimal economic rotation age of the forest stand is reached when the land expectation value (LEV) reaches its maximum (Köthke and Dieter 2010). The maximum value of LEV for a sequence of rotations is defined by the Faustmann formula as:

$$\mathrm{LEV} = \frac{\mathrm{Rh}_T + \sum_{a=0}^{T}\left(\mathrm{Rs}_a \times (1+i)^{T-a}\right) - K \times (1+i)^T}{(1+i)^T - 1} \rightarrow \mathrm{Max!} \tag{7}$$

where LEV is the land expectation value (US\$ ha^{-1}), T is the rotation age (years), a is the year of revenue or cost (years), Rh is the stumpage value (US\$ ha^{-1}), Rs is the net

Table 2: Base-case assumptions and parameter values for *Pinus caribaea* and *Eucalyptus grandis*. CDM = Clean Development Mechanism

Parameter	*Eucalyptus grandis*		*Pinus caribaea*		Source
	Value	Unit	Value	Unit	
CDM carbon price	4.15	US\$ t^{-1} CO_2-e	4.15	US\$ t^{-1} CO_2-e	Tennigkeit and Windhorst (2007)
Stumpage price	30	US\$ m^{-3}	50	US\$ m^{-3}	Field data collection (this study)
Price of firewood	5	US\$ m^{-3}	5	US\$ m^{-3}	Field data collection (this study)
Discount rate	10	%	10	%	Gittinger (1982), Wise and Cacho (2005)
Baseline carbon	9	t CO_2-e	9	t CO_2-e	Rainfall Alliance (2009)
Establishment costs	356	US\$ ha^{-1}	467	US\$ ha^{-1}	Field data collection (this study)
Maintenance costs					
Slashing cost	40	US\$ ha^{-1}	40	US\$ ha^{-1}	Field data collection (this study)
First thinning cost	33	US\$ ha^{-1}	33	US\$ ha^{-1}	Field data collection (this study)
Second thinning cost	40	US\$ ha^{-1}	40	US\$ ha^{-1}	Field data collection (this study)
CDM annual monitoring costs	5	US\$ ha^{-1}	5	US\$ ha^{-1}	Cacho et al. (2004), BioCarbon Fund (2011)
CDM contract establishment cost	100	US\$	100	US\$	BioCarbon Fund (2011)
Wood density	0.52	t dm m^{-3}	0.48	t dm m^{-3}	IPCC (2003); Orwa et al. (2009)
Wood carbon content	0.5	–	0.5	–	IPCC (2003)
Root:shoot ratio	0.45–0.2	–	0.46–0.23	–	IPCC (2003)
Biomass expansion factor	1.39	–	1.3	–	IPCC (2003), Rawat et al. (2015)

revenue from thinning (US\$ ha^{-1}), K is the replanting cost (US\$ ha^{-1}), and i is the interest rate.

Given the difference in the rotations, the annual equivalent value (AEV) was derived from the NPV and used to compare profitability. It was adopted because NPV is not appropriate for comparisons of economic feasibility of projects with different lifetimes (Gittinger 1982; Hseu and Buongiorno 1997; Gutiérrez et al. 2006). The AEV approach calculates the constant annual cash flow generated by an investment over its lifespan as an annuity. The present value of the constant annual cash flows is exactly equal to the project's NPV. The AEV is defined as:

$$\mathrm{AEV} = \frac{\mathrm{NPV} \times i}{1-(1+i)^{-n}} \tag{8}$$

where n is the lifetime of the project and i is the discount rate.

Sensitivity analysis

The base-case results are affected by stumpage price, discount rate, carbon price and carbon transaction costs. Therefore, these variables were subjected to sensitivity analysis. Sensitivity analysis was conducted by changing the variable of interest while keeping all other variables at their base-case values. The base-case assumed a carbon price of US\$4.15 t^{-1} CO_2-e under CDM, which was reported in the Uganda Nile Basin Reforestation Project. Other studies have reported the carbon price to range between US\$5 to US\$25 t^{-1} CO_2-e (Cacho et al. 2005). Therefore, we tested this range within the sensitivity analysis.

The base-case stumpage price was US\$50 m^{-3} for *P. caribaea* and US\$30 m^{-3} for *E. grandis*. However, stumpage prices have been steadily rising throughout the last decade due to the increased demand for timber and they are expected to continue rising (Kaboggoza 2011). Annual price increments of up to 20% have been reported in Uganda. Stumpage prices ranging from US\$50 to US\$70 m^{-3} were evaluated for *P. caribaea* and US\$30 to US\$50 m^{-3} for *E. grandis*. Carbon contract establishment costs ranging from US\$100 to US\$2 000 ha^{-1} were included in the sensitivity analysis. Comparable studies showed a wide range of discount rates, ranging from 5% to 25% (de Jong et al. 2000; Tomich et al. 2002; Aune et al. 2004; Cacho et al. 2003b). Therefore, we tested this range within the sensitivity analysis.

Results

The results indicated that *P. caribaea* and *E. grandis* plantations sequestered 418 and 638 t CO_2-e ha^{-1}, respectively, over a 20-year rotation (Figure 1). The average merchantable wood volume accumulated in *P. caribaea* and *E. grandis* plantations over the same period was 279 and 448 m^3 ha^{-1}, respectively. In this study, the merchantable wood volume refers to tree volume underbark up to 10 cm top diameter (in m^3 ha^{-1}) (Alders et al. 2003).

Base-case results under equal rotation assumption

The results indicated that the NPV of *E. grandis* woodlots with CDM carbon credits of US\$2 540 ha^{-1} was positive and higher than without carbon credits of US\$1 543 ha^{-1}, assuming an equal rotation of 20 years. Similarly, the NPV for *P. caribaea* with carbon credits of US\$1 814 ha^{-1} was higher than without carbon credits of US\$1 390 ha^{-1}. This implies that it is worth investing in carbon forestry under CDM assuming that woodlots with and without carbon credits have equal rotations of 20 years and given the other base-case assumptions. Under these assumptions, carbon payments under CDM increased NPV of *E. grandis* and *P. caribaea* by 65% and 31%, respectively.

Sensitivity analysis

The results of the sensitivity analysis indicated that the NPVs of plantations with carbon credits increased with the price of carbon and stumpage (Figure 2b and d). However, *E. grandis* was more sensitive to change in carbon and stumpage price than P. caribea, as shown by the higher rate of NPV increment. This can be attributed to the higher stocks of merchantable wood (m^3 ha^{-1}) and carbon (t CO_2-e ha^{-1}) (Figure 1). As expected, the NPVs of plantations decreased with increasing discount rates. Similarly, the NPVs of plantations with carbon credits decreased with increasing CDM contract establishment costs (Figure 2a and c). As the carbon contract establishment costs increased, the NPV of woodlots with carbon credits fell below that without carbon credits at US\$500 ha^{-1}

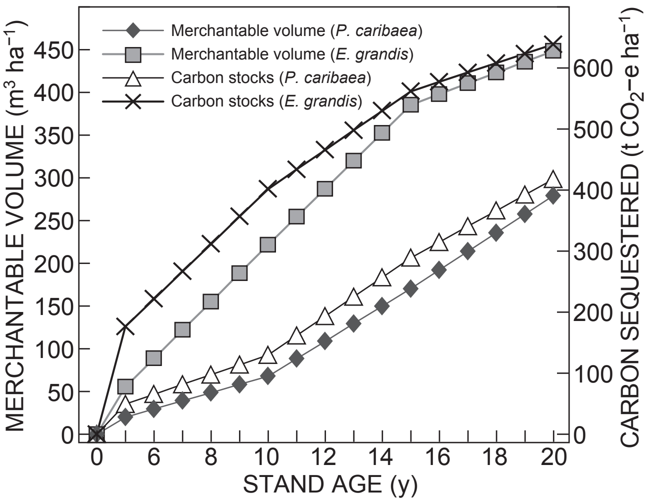

Figure 1: Time trajectory of merchantable wood volume (m^3 ha^{-1}) and carbon stocks in standing tree biomass (t CO_2-e ha^{-1}) for thinned *Pinus caribaea* and *Eucalyptus grandis* plantations

and US\$1 000 ha^{-1} for *P. caribaea* and *E. grandis*, respectively. This suggests that if the average contract establishment costs exceed US\$500 ha^{-1} and US\$1 000 ha^{-1} for *P. caribaea* and *E. grandis* plantations, respectively, then it is not economically viable for one to participate in CDM forest carbon offsets.

Varying rotation approach

The land expectation values (Figure 3) for *P. caribaea* and *E. grandis* were maximised at 16 and 10 years, respectively. These are the optimal economic rotations for the two types of plantations.

The results indicated that the AEV of *E. grandis* when harvested at its optimal economic rotation of 10 years, without carbon credits, is US\$316 ha^{-1}. This is slightly higher than the AEV of *E. grandis* with carbon credits under base-case assumptions of US\$298 ha^{-1}. This implies that an *E. grandis* stand harvested at 10-years rotation without carbon credits is more profitable than one that receives payments for carbon credits under CDM but has to observe the 20-year credit period. In contrast, the AEV of *P. caribaea* with carbon credits under CDM was US\$213 ha^{-1} and higher than US\$169 ha^{-1} for *P. caribaea* harvested at its optimal economic rotation of 16 years without carbon credits.

Sensitivity analysis using equivalent annual annuity approach

In general, the AEVs of the plantations increased with stumpage price (Figure 4b). However, the AEVs of the

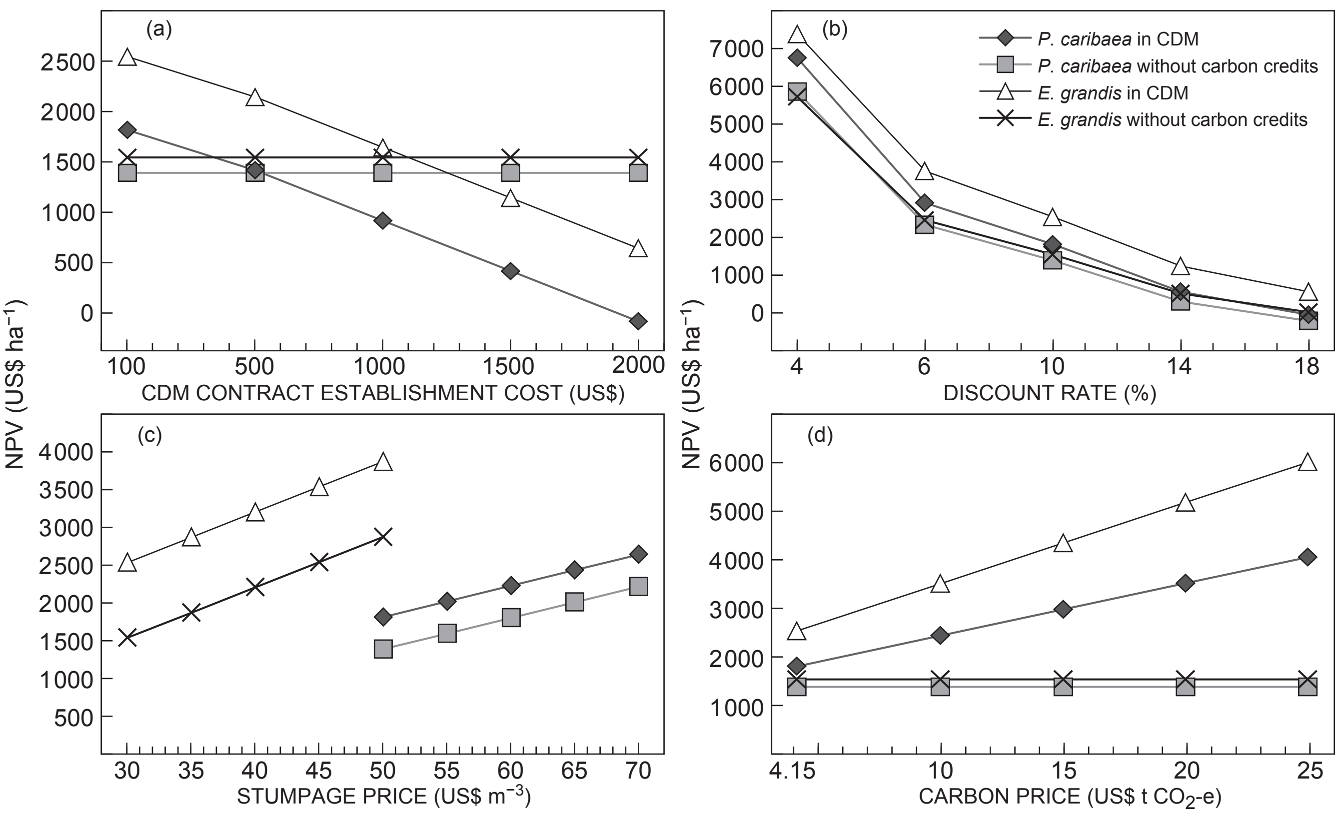

Figure 2: Sensitivity of net present value (NPV) under the Clean Development Mechanism (CDM) to contract establishment cost (a), stumpage price (b), discount rate (c) and carbon price (d)

shorter-rotation plantations increased at a faster rate than the longer rotations. This implies that at a high stumpage price for *E. grandis*, it would pay to adopt shorter rotations without carbon credits rather than wait for the 20-year crediting period under CDM. In contrast, the faster increase of AEVs in the shorter-rotation pine woodlots was not sufficient to exceed the AEV of woodlots with carbon credits in the range tested. Therefore, carbon offsets in *P. caribaea* woodlots are more robust to increase in stumpage price.

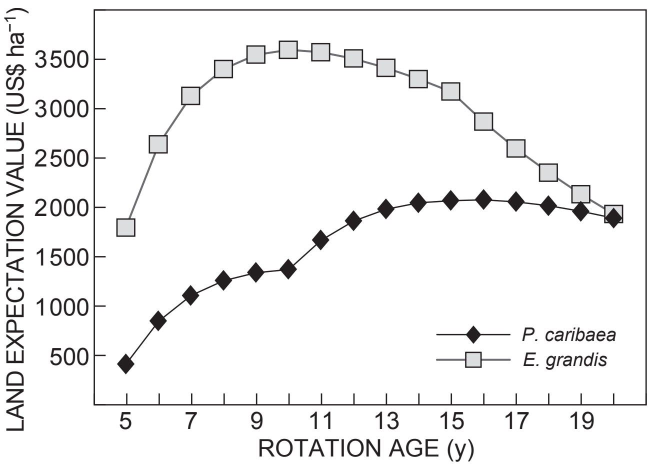

Figure 3: Time trajectory of the land expectation value for *Pinus caribaea* and *Eucalyptus grandis*

As expected, carbon offsets were more profitable with increasing carbon prices (Figure 4c).

Discussion

The findings show that *E. grandis* and *P. caribaea* plantations accumulated substantial amounts of carbon over a 20-year rotation. This suggests that the plantation forestry sector has the potential to significantly contribute to carbon sequestration and climate-change mitigation. The potential of carbon trade in Uganda's plantation forests has been attributed to the relatively fast tree growth. The results also indicated that it is worth investing in carbon forestry under CDM in the equal rotation scenario. However, this changes under the varying rotation approach. The results showed that whereas *E. grandis* has a higher biological potential to sequester carbon than *P. caribaea*, it is not economically viable for participation in the CDM forest carbon offset scheme under the base-case assumptions. The results indicated that at a high stumpage price for *E. grandis*, it would pay to adopt shorter rotations without carbon credits rather than wait for the 20-year crediting period under CDM. This is in agreement with microeconomic theory, which indicates that a rise in timber prices shortens the optimal rotation period (Nicholson and Snyder 2008). This suggests that participation in forest carbon offsets will become even less economically viable as the stumpage price of *E. grandis* increases. In Uganda, stumpage prices have been steadily rising over time and they are expected to

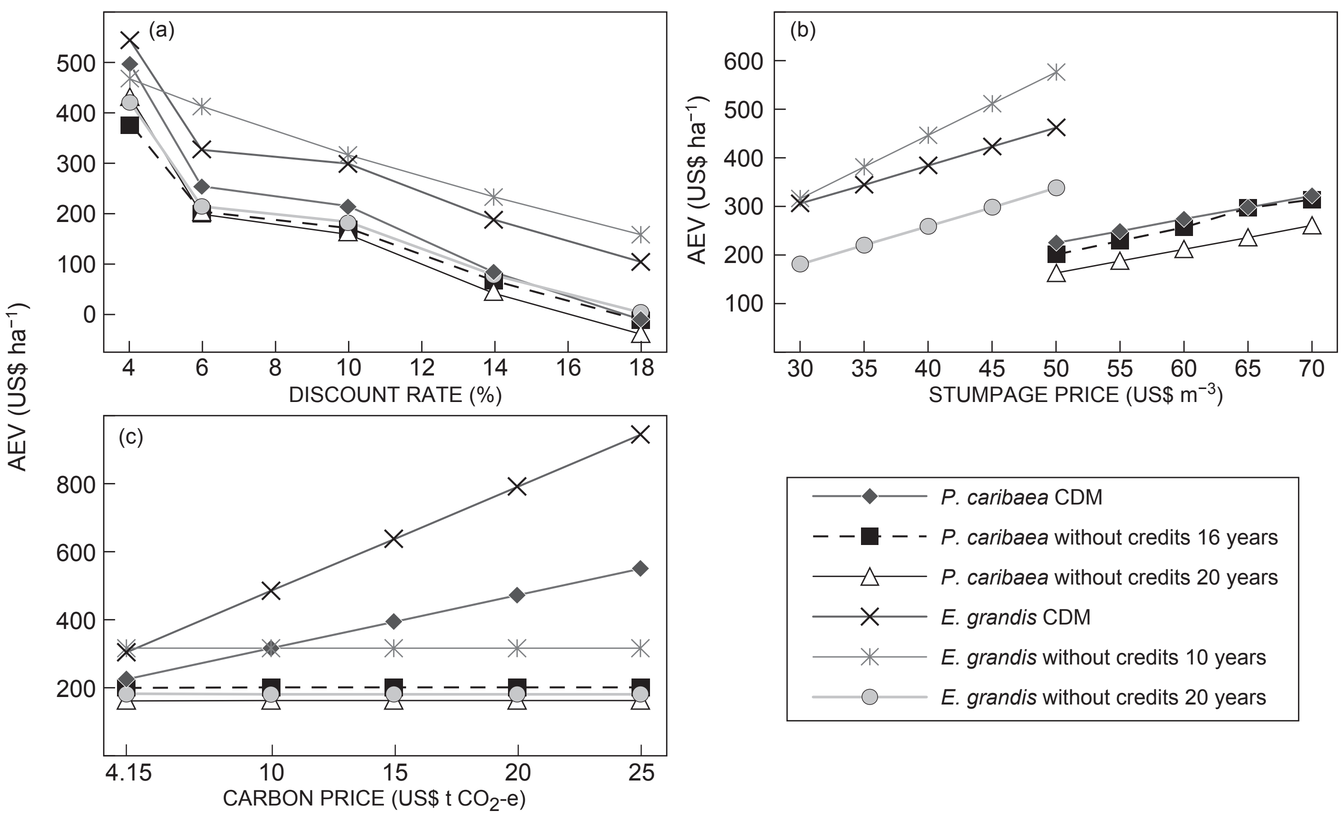

Figure 4: Sensitivity analysis using an equivalent annual annuity approach to discount rate (a), stumpage price (b) and carbon price (c) under different rotations

continue rising (Kaboggoza 2011). Therefore, this requires the price of forest carbon credits to match the increase in the eucalypt stumpage price if forest carbon offsets are to become viable for *E. grandis* plantations.

The results indicated that inclusion of carbon offsets in eucalypt plantations can become viable if the carbon price is raised from the current US\$4.15 t^{-1} CO_2-e. Therefore, the price of forest carbon should be increased beyond US\$4.15 t^{-1} CO_2-e in order to make carbon offsets under CDM economically attractive to eucalypt tree farmers. This is justified by the higher potential of eucalypts to sequester carbon, thus contributing to mitigation of global warming.

In contrast, it is economically viable to include *P. caribaea* plantations in CDM, even at the current carbon prices. Given its slower growth rate, the optimal economic rotation of 16 years is close to the 20-year crediting period under CDM. Therefore, sale of carbon credits may be considered an additional benefit to *P. caribaea* plantation owners.

The results showed that when the average CDM contract establishment costs exceed US\$500 ha^{-1} and US\$1 000 ha^{-1} for *P. caribaea* and *E. grandis* woodlots, respectively, it is not economically viable for one to participate in the CDM forest carbon offsets programme. However, such costs are still unaffordable to the average small-scale forest plantation owners and may continue to be a major hindrance to small-holder farmer participation in CDM under LULUCF. Therefore, modalities for the small-scale AR category need to be simplified further, in order to reduce the transaction costs and promote the participation of small-scale projects in CDM under LULUCF. Given that carbon contract establishment costs are fixed, participation in CDM under LULUCF can be made profitable either by having a large acreage, such that the average cost per hectare is lowered, or by bundling many farmers together to share the costs (BioCarbon Fund 2011). At the national level, government and NGOs should facilitate the process of bundling tree farmers together in sizable groups in order to reduce costs per project.

The soil carbon stock was not accounted for under the assumptions of this paper because the net change in soil carbon is expected to be positive but small. The consensus is that soil carbon should be measured under LULUCF if a decrease is expected or if the financial benefit exceeds the cost of measuring and certifying the soil carbon (Brown 2001; Cacho et al. 2003a).

Conclusion

In conclusion, the carbon price under CDM should be increased in order to make it economically viable for participation of fast-growing species such as *E. grandis*. Similarly, it is economically viable for *P. caribaea* plantations to participate in the CDM, as long as the CDM contract establishment costs are low. Therefore, modalities for the small-scale AR category need to be simplified further, in order to reduce the transaction costs and promote the participation of small-scale projects in CDM under LULUCF. Secondly, government and NGOs should facilitate the process of bundling tree farmers together in sizable groups in order to reduce costs per project. Currently, it is difficult to obtain adequate primary data on CDM carbon contract establishment costs and carbon monitoring costs. Future studies should focus on this aspect of carbon forestry in African countries.

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