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Full Length Research Paper

Simulation of the impacts of three management regimes on carbon sinks in rubber and oil palm plantation ecosystems of South- Western Cameroon

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The impacts of managed, extended and complete rotation on carbon sequestration in rubber and oil palm plantations were simulated using the CO2FIX V.2 model, using degraded farmland carbon stocks as a baseline. Results showed that the extended rotation resulted in higher C-sequestration in rubber (264 Mg C/ha), and the complete rotation (88 Mg C/ha) for the oil palm plantation. There was better soil carbon recovery in rubber under the extended rotation, and better recovery in palms under a complete rotation. With respect to soil carbon fractions, fine litter had the highest value in rubber (19 Mg C/ha) and coarse litter in palms (63 Mg C/ha) all under complete rotation. Humus was the most permanently increasing soil carbon component, with the best sinks at 9 and 12 Mg C/ha in rubber and palm under the extended rotation respectively. Inclusion of such systems into post Kyoto Treaties, with incentives from carbon credits could be indispensable in alleviating rural poverty and expanding on forestry projects that mitigate climate change.

Key words: Carbon stock, rotation length, CO2FIXV.2 model, simulation length, carbon credits.

INTRODUCTION

Global warming is a major environmental concern, more so in developing countries where dependence on, and extension of agricultural land results in massive deforestation of existing pristine forest and emission of greenhouse gases (Houghton, 2005; Donald, 2004; ECCM, 2002). Forest and plantation ecosystems management practices can play a significant role in climate change mitigation by sequestering carbon through photosynthesis (Strassburg et al., 2009; Guariguata et al., 2008; Watson et al., 2000; Brown et al., 1996). According to the FAO (2005) global forests ecosystems store more than 638 Gt of carbon. Adaptation to climate change effects is gaining ground as actors realise that climate change cannot be totally avoided and mitigation will take some time to be effective (Malhi et al., 2008; Fischlin et al., 2007; Hansen et al., 2003). Slash and burn agriculture is the predominant method of farming in Central Africa (Zhang et al., 2002) and this means there is potential for carbon sinks in above and below ground biomass in the woody perennials of this type of farming system. It should be noted that more often, local investment choices are determined by the value of agricultural production. Smallholders as well as governments are increasing investments in plantation agriculture and reforestation of logged forest concessions. This is the case with the Cameroon Development Corporation (CDC) with respect to rubber and oil palm plantations in Fako division, Southwest Region of Cameroon. The land area under plantation cultivation is consequently bound to increase, hence the need for projects to be environmentally friendly. Besides significant economic benefits of such plantation systems, carbon credit- or payment for ecological services (PES) incentives could motivate carbon sequestration enhancement methods in project design and implementation (Montagnini et al., 2005). It has been stressed by several authors (Egbe and Tabot, 2011; Shin et al., 2007; Houghton, 2005; Vieira, 2005) that forest plantation ecosystems can be

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Abbreviations: CDC, Cameroon development corporation; **CDM,** clean development mechanism; **REDD,** reducing emissions from deforestation and degradation; **CAI,** current annual increment.

significant carbon sinks and so utilization of land deforested prior to 1990 for such smallholder expansion would reduce forest degradation in addition to creating new sinks of carbon (Garrity et al., 2006; Serigne et al., 2006). This would go a long way towards not only mitigating carbon dioxide emissions but also ensuring sustainable development of rural communities in the process. Carbon credits would mainly be an added incentives for more sustainable and greener forestry/agricultural practices.

With a total land concession of 98,000 ha of which rubber (*Hevea brasilensis* Linn.) and oil palm (*Elaeis guineensis* Jacq.) were planted on 18,610 and 15,482 ha respectively as of 2003 (Odilius Mbuyeh, Pers. Com), the CDC represents an ideal case for monotypic stands studies. By using data from these plantations it would be possible to predict carbon sequestration and sustainability trends in smallholder rubber and palm plantations under different management scenarios, with baseline set at conditions typical of degraded land in the region. The study thus aimed at determining carbon sinks under different management systems in rubber and palms and options for a viable REDD plus. The hypothesis was that different plantation management practices would significantly affect carbon sinks in such perennial monocultures.

MATERIALS AND METHODS

Study sites

Data was collected in Fako Division in the Mount Cameroon region, South-western Cameroon. Fako Division is defined by latitude 4°28´30″N and 3°54´26″N, and longitude 8°57´10″E and 9°30´49″ E. The land area is approximately 203,071 ha. The climate is typically equatorial. There is a short dry season from December to February and a rainy season from March to November. The rainfall pattern varies through the region; with Debunscha recording 10,617 mm while other areas have 2,500 to 3,000 mm mean annual rainfall. The relative humidity ranges between 75 to 87% with a mean temperature range of 17 to 35^oC at sea level. Vegetation varies with altitude, ranging from low evergreen forests, through submontane to alpine forests. The soils are ancient ferralitic, volcanic, nutrient-rich andosols (Bele et al., 2011).

Brief description of the CO2FIXV.2 Model and baseline data

Carbon stocks were predicted for all species as a function of above ground biomass, using the CO2FIXV.2 model. A descriptive manual for the CO2FIX V 2.0 by Nabuurs et al. (2001) is in-built into the model. The model simulates carbon stocks and fluxes in trees, soil, and wood products of tree ecosystems per hectare, in time steps of one year. It consists of the biomass, soil and products modules. Carbon stock in biomass can be modeled for stands of varying age and species on the basis of age according to the equation:

$$a = \frac{A}{1 + e^{-[\frac{b+kt}{v}]}}$$

value of the attribute (the maximum stand biomass) attained, t = time, and, k is a growth rate constant while v is a variable which positions the curve relative to the x-axis.

For stands with unknown age, modeling is on the basis of diameter-increment functions:

$$Bi = A(B_{max} - B)B^k$$

where Bi = biomass increment, B = actual biomass, Bmax = the maximum attainable biomass in the stand, and, A is a linear regression function and k is the rate of biomass increment.

The growth of biomass in branches, foliage, and roots is then calculated as an additional fraction to the growth rate of the stem biomass, as follows:

Total biomass Bt = Bs + Bf + Bb+ Br

where Bt = Growth of total tree biomass, Bs = Growth of stem biomass, Bf = Growth of foliage biomass, Bb = Growth of branch biomass, and Br = Growth of root biomass; all of which are derived through a set of sub-equations (Masera et al., 2003; Nabuurs et al., 2001).

The input data for biomass simulation include current annual increment (CAI) of the stem wood volume (m^3 /ha/yr), biomass turnover rates, initial biomass, growth and mortality of each functional group relative to standing biomass, and interactions within and between the functional groups (Masera et al., 2003; Nabuurs et al., 2001).

Parametization of the soil carbon requires litter input (Mg C/ha/yr) from foliage, fine roots, branches, coarse roots and stems, quantified from turnover rates, natural mortality, management mortality, and logging slash provided by the simulator in other modules of the model. Mean temperature and rainfall for the region is required for calculation of potential evapotranspiration for the region, important in determining rates of decomposition. The size of non-woody litter, finer and coarse litter pools is determined by inputs from various sources of litter, minus the fractionation rate per pool. The proportion allocated to soluble compounds, holocellulose, and lignin-like compounds is in turn determined by fractionation rates and litter quality classes (Nabuurs et al., 2001).

In addition, for managed forests and plantations the products module tracks the carbon from harvesting to final decay. Carbon is released to the atmosphere through manufacturing by-products, firewood, or decomposition in landfills (Masera et al., 2003; Nabuurs et al., 2001). The balance of carbon in the different processes of sequestration and emissions thus determines whether an ecosystem is a net source or sink of carbon.

The baseline situation for simulation in the current study was deforested tropical lands under shifting cultivation, in which carbon stocks in plant biomass is ephemeral, and the most stable compartment is soil carbon. Ringius (2002) reported 13.5 Mg /ha as mean stock for continuously cultivated, low input systems with a maximum of five years fallow period in sub-Saharan Africa, and we assume this as the baseline. This is important as it implies there would be no significant loss (Strassburg et al., 2009) of carbon during the establishment and duration of the plantations, and low-carbon land uses have a higher potential for sequestration (Silver et al., 2000).

Modelling and data analyses

Study plots of rubber were established in the CDC Tiko rubber plantations and those of palms in the oil palm plantations in Limbe and Moliwe of the South West Region of Cameroon. Six age series of rubber plantations (2, 6, 9, 11, 13 and 16 years) were selected for measurement, while the age series of palm plantations were 3, 7, 9, 13 and 44 years. One hundred and eighty plants per hectare per age series and 90 plants per hectare per age series were randomly evaluated for rubber and oil palm respectively. For rubber, stem diameters were measured

Table 1. Some inputs for carbon stock simulation generated from field data.

Species	Cohorts	DBH* (cm)	Height (m)	CAI ($m^3/hayr^{-1}$)	Plant density/ha
Rubber	1	4.7±0.1d*	-	1.5	510
	2	12.3±0.2e	-	6.4	510
	3	18.1±0.2d	-	9.4	510
	4	22.3±0.3c	-	12.5	510
	5	23.2±0.3b	-	11.8	510
	6	24.6±0.3a	-	11.0	510
Palm	1	-	3.8±0.1e	7.0	204
	2	-	5.5±0.1d	4.6	204
	3	-	6.3±0.1c	2.9	204
	4	-	11.5±0.1b	2.3	204
	5	-	13.7±0.2a	1.8	204

HSD (<0.05). *Means with the same letter within the column for each species are not significantly different. DBH= diameter at breast, CIA = current annual increment.

at breast height (DBH) using diameter tapes, while for palms, total heights were measured. It was necessary to select methods that best simulate natural growth of each species. In consequence, for palms, although both DBH and height were measured in the field, height was used in the simulation as opposed to DBH, as it was found to correlate better with palm biomass growth. This is consistent with the FAO (1997) recommendations. One way ANOVA on all data sets following positive tests for normality and homogeneity of variance showed significant differences between the different age series (Table 1) and it was appropriate to consider them separate cohorts. The volume (V) of rubber plants were determined using the equation

$V=8.872(DBH)^{2.270}$ (Eba a' Atyi, 2000).

where DBH = diameter at breast height.

A biomass conversion factor of 0.45 kg/m^3 (conservative estimate) was applied to these volumes to get the biomass.

For the oil palm, the biomass was estimated from the heights according to the equation:

Y (biomass, kg) = 10.0 + 6.4 * total height (m) (FAO, 1997).

The current annual increment (CAI) for the different rubber and palm cohorts were estimated by dividing the total biomass by the age of each cohort. The maximum biomass per cohort was estimated by multiplying the biomass per plant by the plant density (510 and 204 for rubber and oil palm respectively) (Table 1).

Wood densities (dry) of rubber (0.53 Mg/m^3) were obtained from Gisel et al. (1992) and those of palms (0.25 Mg/m^3) from FAO (1997). Climate data was obtained from the meteorological station in Ekona. The mean temperature and rainfall were used to calculate potential evapotranspiration (PET) for the region, using an in-built PET module in the CO2FIXV.2 model. Three management regimes were evaluated, including:

1. Complete rotation for 30 years which entails clear-felling and replanting the entire plantation every 30 years;
2. Managed rotation in which the harvesting is spanned over five years, with 33% of the plants cut at age 26 and 28 years, and the final fraction at the end of the cycle at 30 years with simultaneous replanting, and
3. Extended rotation in which half of the plantation was cut down and replanted at 30 years, and the other half 10 years later. We term this intervening 10 years the 'shunt gap' [the time shift between the initial cut when the rotation was normally supposed to end, and the eventual cut of the remaining half of the plantation].

Carbon stocks were parametized for plant biomass, soil and product compartments of the model. For the product module in rubber, cut plants were mainly allocated to energy, while for palms they were allocated to soil/landfilled, as per the dominant practice in the region. Turnover rates were approximated from field observations, and the management pattern in the region was used to estimate allocation of the cut fraction to different biomass compartments (Table 2). Commercial produce such as the harvested fruits and latex were not considered due to difficulty in ascertaining the fluxes in the different production processes and shelve life, while annual weeds were also not considered because of rapid turnover and low residence times. The parameters generated (initial carbon stocks, plant and wood densities, simulation length, rotation length, CAI, initial soil carbon and other parameters in Table 2) were used in the CO2FIXV.2 software as input data for carbon stock simulations. The simulation length which is the total duration of continuous cultivation at the same site was 180 years, while the rotation length which is the economic lifespan of the plants, was 30 years and 40 years for the extended rotation.

At the end of the simulation, the carbon stocks at the end of each cycle for all species were analysed via one way ANOVA, following positive Kolmogorov-Smirnov tests for normality and Levine's test for homogeneity of variance. For non-parametric data as in the case of the rubber plantation, Johnson transformation was conducted prior to Analysis of variance. Soil carbon stocks were analysed before and after each cycle. The Tukey post hoc Honestly Significant Difference (HSD) test was used to compare means. All analyses were done at α=0.05 using the MINITAB V.15 statistical package (Minitab Statistical Software, MINITAB Inc. USA).

Mean carbon stocks per rotation were calculated according to the equation

$$Cm(Mg/cycle) = \frac{C1 + \ldots + Cn}{n}.$$

where Cm is the mean carbon stock (Mg/ha) per rotation, and C1 ... Cn are the carbon stocks at the end of the different rotations and n is the number of rotations on the same site.

RESULTS

Carbon stocks

Table 1 presents initial modelling parameters determined from field data while Table 2 shows some

Table 2. Some parameters for the simulations.

Turnover rates(1/yr)				PET mm	Allocation of biomass (Fractions)						
Species	**Foliage**	**Branches**	**Roots**		**Stem logwood**	**Stem slash**	**Branches logwood**	**Branches slash**	**Foliage slash**	**Slash firewood**	**Slash soil**
Rubber	0.50	0.50	0.50	616	0.95	0.05	0.75	0.25	1.00	0.05	0.95
Palms	0.50	—	0.10	616	0.00	1.0	—	—	1.00	0.00	1.00

Initial carbon estimates Mg C/ha (YASSO model parameters unchanged (Nabuurs et al., 2001))							
Species	**NWL**	**FWL**	**CL**	**SOL**	**HCL**	**LC**	**Humus**
Rubber	1.25	0.87	3.06	0.49	1.12	2.18	4.00
Palms	1.25	0.87	3.06	0.49	1.12	2.18	4.00

Parametized end products (Fractions)						
Species	**Long term**	**Medium term**	**Short term**	**Recycling**	**Energy**	**Landfill**
Rubber	0	0	1	0	0.95	0.05
Palms	0	0	1	0	0	1

Where; PET= Potential Evapo-transpiration, NWL= Non Woody Litter, FWL= Fine Woody Litter, CL= Coarse Litter, SOL= Soluble Components, HCL= Holocellulose and LC= Lignin-like Components. YASSO is the model on which the CO2FIXV.2 soil module is based (Nabuurs et al., 2001).

Table 3. Carbon stock for rubber and palm plantations under complete, managed and extended rotation regimes.

Species	Management regimes	Total biomass (Mg DM/ha)	Total carbon** (Mg /ha)	Stock‡ (Mg /ha)
Rubber	Complete rotation	272.7a	181.9±3.5b	168.3±3.5b
	Managed rotation	154.8b	162 ±3.2c	148.4±3.2c
	Extended rotation	387.8c	278.16±4.5 a	264.6±4.5a
Oil Palm	Complete rotation	137.5a	89.40±1.3a	88.1±1.3a
	Managed rotation	71.9c	86.63±1.2b	73.0±1.2b
	Extended rotation	116.2b	80.03±1.4c	66.4±1.4c

HSD (<0.05). *Means with the same letter within the column for each species are not significantly different. **Carbon sink plus baseline carbon; ‡Total carbon minus baseline carbon stocks.

estimated parameters for carbon stock simulation. Results at the end of the simulation period indicated that carbon stocks varied in all species and the management systems. Carbon stocks for the different management regimes per species are shown in Table 3. For the rubber plantation, CO_2 sequestered differed significantly across all management regimes with the highest (264 Mg C/ha) in the extended rotation and least (148 Mg C/ha) in the managed rotation. In the oil palm, the highest carbon stocks (88 Mg C/ha) were observed in the complete rotation and the least (66 Mg C/ha) in the extended rotation.

Results for soil carbon before and after harvest are shown in Table 4. In the rubber plantation, soil carbon stocks before harvest were similar to the extended

Table 4. Soil carbon sinks of rubber and palm plantations under complete, managed and extended rotation regimes.

Species	Management regimes	Soil carbon just before harvest (Mg /ha)	Soil carbon just after harvest (Mg /ha)
Rubber	Complete rotation	13.7±0.5a*	45.1±0.5b
	Managed rotation	18.6±0.5b	34.80±5.0c
	Extended rotation	18.5±1.0b	63.20±1.0a
Oil Palm	Complete rotation	18.0±1.3a	89.40±1.3a
	Managed rotation	37.2±1.2b	86.63±1.2b
	Extended rotation	19.6±1.4a	80.03±1.4c

HSD (<0.05). *Means with the same letter within the column for each species are not significantly different.

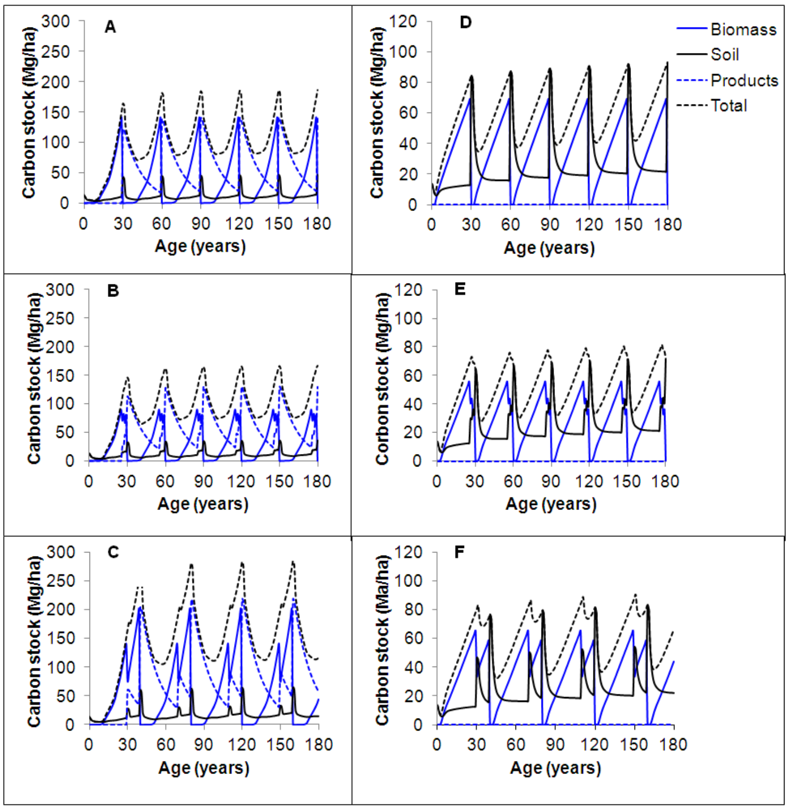

Figure 1. Dynamics of carbon stocks in rubber (A- C) and palm (D-F) plantations under complete, managed and extended rotations respectively.

and managed rotations but differed from those of the complete rotation. After harvest, soil carbon was highest in the extended rotation (63.20±0.99 Mg C/ha) and least in the managed rotation (34.80±4.99 Mg C/ha). In the oil palm plantation ecosystem, the managed rotation had significantly higher soil carbon stocks than the other two management regimes before harvest, and after harvest soil carbon stocks were highest in the complete rotation regime (89.40±1.29 Mg C/ha) and least in the extended rotation regime (80.03±1.43 Mg C/ha) (Table 4).

Carbon dynamics

In the complete rotation the total carbon stock in rubber after 30 years was 165 Mg C/ha, with an increase in soil carbon to 43 Mg C/ha (Figure 1A). Under managed rotation rubber sequestered 112 Mg C/ha after 26 years when the cutting begins, and 141 Mg C/ha for the first rotation at 30 years. The carbon sink in plant biomass was 71 and 80 Mg C/ha respectively while soil carbon was 16 and 17 Mg C/ha, respectively; the corresponding stocks allocated to products (fuel wood) were 25 and 44 Mg C/ha, respectively (Figure 1B). In the extended rotation regime, carbon stock at 30 years was 165 Mg C/ha with soil carbon stocks increasing from 12 to 28 Mg C/ha following inputs from the biomass compartment. Just before cutting of the other half of the plantation at 'shunt gap' of 10 years, total carbon stock in the plantation was 252 Mg C/ha. Of this value, carbon stock in plant biomass was 201 Mg C/ha, soil carbon was 16 and 35 Mg C/ha were allocated to products (fuel wood). The total carbon stock for a

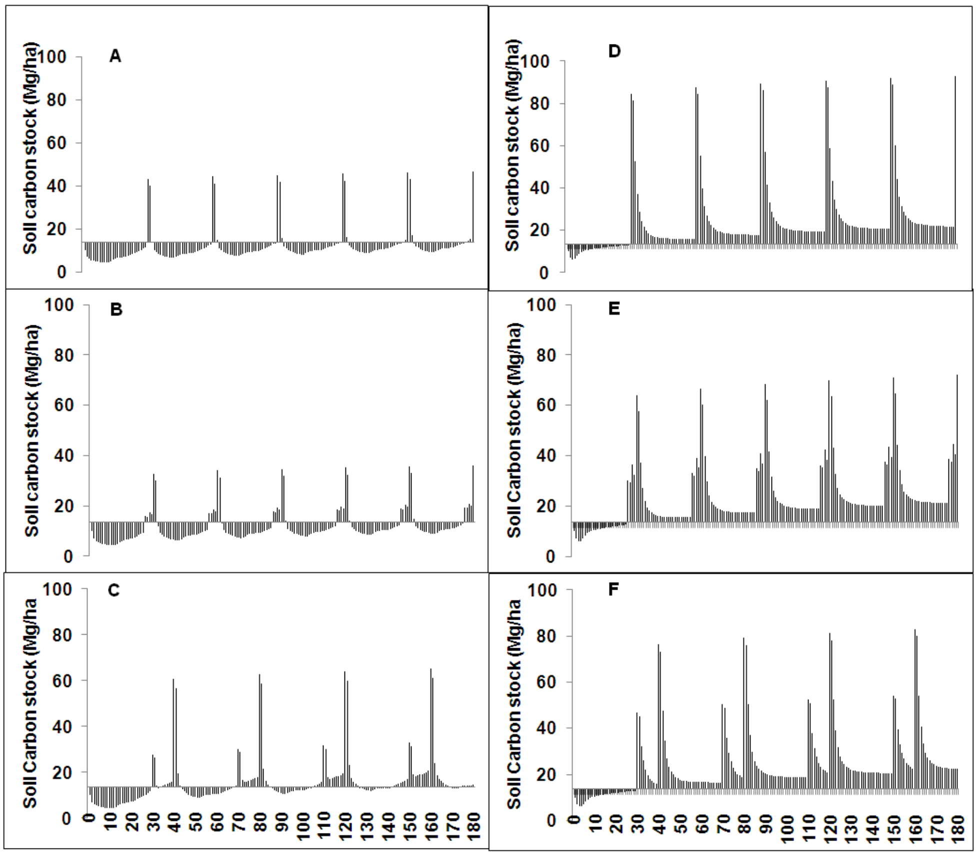

Figure 2. Impact of different management options on soil carbon recovery in rubber (A-C) and oil palm (E-F) plantation systems. A and D = complete rotation, B and E = Managed rotation, C and F = extended rotation. Bars represent net carbon stocks.

Table 5. Mean soil carbon fractions under different management regimes in rubber and oil palm plantation systems.

Species	Management regime	Soil carbon fractions (Mg C/ha)						
		NWL	FWL	CWL	SOL	HCL	lignin	humus
Rubber	Complete rotation	9.9	19	5.5	0.9	1.4	1.2	7.1±0.5a‡
Palms		11.3	0.0	63.1	1.1	1.1	1.1	11.8±1.3b*
Rubber	Managed rotation	8.4	12.0	3.8	0.6	1.1	1.5	7.7±0.5a
Palms		9.1	0.0	39.8	0.8	3.8	2.7	9.3±1.0b
Rubber	Extended rotation	4.5	8.2	2.2	0.7	1.0	0.9	12.5±1.2a
Palms		5.6	0.0	18.9	1.1	1.1	1.1	16±1.4b

HSD (<0.05) *Means with the same letter within the column for each management regime are not significantly different at the end of each cycle. ‡Humus was the main variable component at the different cycles. NWL= non woody litter, FWL= fine woody litter, CWL = coarse woody litter, SOL = soluble compounds, HCL = holocelulose.

simulation period of 180 years under extended rotation regime was 168 Mg C/ha while soil carbon recovery was 36 Mg C/ha (Figure 1C).

In the oil palm plantation ecosystem under the complete rotation regime (Figure 1D), the total carbon stock for the first rotation (30 years) was 82 Mg C/ha with the carbon sink in biomass contributing 69 Mg C/ha to this value while soil carbon was 13 Mg C/ha. Under the managed rotation, the total carbon stock at the end of the first rotation was 68 Mg C/ha and from this value the carbon sinks in plant biomass and soil were 36 and 32 Mg C/ha, respectively. The total carbon stock for a simulation period of 180 years was 77 Mg C/ha, with soil carbon accounting for 41 Mg C/ha (Figure 1E). In the extended rotation regime (Figure 1F), carbon stock at 30 years was 81 Mg C/ha with soil carbon stocks increasing from 13 to 47 Mg C/ha following inputs from the biomass compartment. Total carbon stock at 'shunt gap' of 10 years was 74 Mg C/ha, the carbon sink in biomass was 58 Mg C/ha and soil carbon was 16 Mg C/ha. There was no product component in the oil palm plantation ecosystem, as cut plants are not used as fuel wood and are left on-site to decompose and thus it is allocated to the soil compartment.

Relative to baseline conditions, oil palm plantations maintain a positive balance in soil carbon stock under all management regimes, but rubber did not except for the extended regime (Figure 2). In the final rotation for instance, soil carbon stocks drop to below baseline conditions 5 years after harvest in the complete (46 and 11 Mg C/ha at 150 and 155 years respectively) and managed rotation (36 to 12 Mg C/ha at 150 and 155 years respectively) in rubber while in the extended rotation the stocks for the same time interval were 33 and 19 Mg C/ha respectively (Figure 2 A-D). In the oil palm plantations, the respective stocks at 150 and 155 years were 92 and 32 Mg C/ha (complete), 71 and 26 Mg C/ha (managed), and 54 and 27 Mg C/ha (extended) rotation regimes (Figure 2 E-F).

In the soil, carbon is partitioned into non-woody, fine and coarse litter fractions, holocellulose, lignin, soluble compounds and humus components, for all management regimes (Table 5). Fine litter had the highest peak in rubber (19 Mg C/ha), while coarse litter was the highest in oil palm (63 Mg C/ha), all under complete rotation. Humus was the most permanently increasing soil carbon component, with optimum values below 20 Mg C/ha for all species and management regimes. In the rubber plantation ecosystem, the extended rotation resulted in the best humus accumulation (12 Mg C/ha) and in the palm ecosystem both managed and extended rotation resulted in best humus accumulation (16 Mg C/ha) (Table 5).

DISCUSSION

Carbon stocks in the different plantation ecosystems

Total carbon stocks at the end of the simulation period were higher than those at the end of each rotation due the accumulation of biomass and soil carbon with time. Determinants of carbon stocks include plantation age, rate of volume increment and wood density (Egbe and Tabot, 2011; Tschakert et al*.,* 2006). Rubber plantations had highest CAI and wood density than palms, thus the results are consistent with findings of authors who reported higher carbon stocks in stands with higher rates of diameter increments and wood densities (Rahayu et al., 2005; Vieira et al., 2005). Similar results have been found in other systems, for instance 69.9 Mg C/ha for a coffee agroforest (Masera et al., 2003), 152 Mg C/ha for cocoa agroforests in south Cameroon (Duguma et al., 2001), 190 Mg C/ha as the mean for 13 species ranging in age from 6 to 23 years in Bangladesh (Shin et al., 2007). Carbon sequestration potentials in rubber are similar to those reported by Roshetko et al. (2007), but those of oil palm are much less, probably due to the low plant and wood density.

Because the planting density of the plants was different as per the recommended planting practices in the region, the focus here should thus be on the impact of the management regime on carbon dynamics of each plantation system.

Impact of management regimes on carbon sinks and dynamics

The extended rotation regime allows for higher carbon stocks in all species because the 'shunt gap' ensures that the replanted section reaches productive maturity before the next section is cut, and there is relatively less material available for fuel wood, decomposition and consequent emission of CO_2 per unit time (Egbe and Tabot, 2011). This increase in carbon stock with rotation length is consistent with findings by Kaul et al. (2010) for sal and teak plantations using the same simulation model. In addition, at all times under extended rotation, the plantation would be a net carbon sink. With complete rotation, the plantation becomes a major source of carbon dioxide at the end of each rotation as clear-felling is done. The higher carbon stocks in the oil palm plantation ecosystem could thus be due to higher CAIs of younger replanted sections.

Through litter fall during the growth phase and higher inputs when the plantations are cut at the end of each rotation, soil carbon increases with time (Paul et al., 2002). Such soil sequestration from biomass inputs is determined by the proportion of non-woody-, fine- and coarse litter fractions as well as rates of oxidation, decomposition and leaching. When carbon-rich biomass inputs are high and decompose slowly, the rates of leaching and oxidation are low, resulting in higher sequestration potential (Pretty et al., 2002).

Soil carbon fractions and potential for recovery of soil carbon

In the soil compartment there were high values of lignin, holocellulose, coarse and fine litter components immediately after harvest. These are ephemeral, and would be the most easily leached fractions (Nabuurs et al., 2001). Humus on the other hand was the most stable component of soil carbon. The amount of carbon returned to the soil is thus inherent on the plant's composition (Egbe and Tabot, 2011; Marland et al., 2004). For both species, the extended rotation has the best impact on soil carbon, as carbon is returned to the soil at a rate suitable for retention, and at all times carbon is stored in above-ground biomass. Furthermore, the extended and managed rotations enable the farmer to have a source of income at all times; they are also more ecologically sound comparatively (Egbe and Tabot, 2011).

The results in the context of REDD plus

Carbon stock simulation in the current study satisfies the conditions stipulated by the CDM regulatory board

(UNFCCC/CCNUCC EB, CDM-AR-PDD Report Version 05). The results are significant in the context of a potential REDD-plus scenario which additionally considers conservation of forest carbon stocks, sustainable forest management and enhancement of carbon stocks in predominantly developing countries (Nakakaawa et al., 2011). The use of logs and twigs from the cut plantations as fuel reduces forest deforestation and degradation for energy (Roshetko et al., 2007) and perennial cash crops yield more income, reducing deforestation for cultivation of subsistent food crops. Such plantations, if established on land deforested prior to 1990, represent reforestation (Roshetko et al., 2007) and if in accordance with CDM guidelines (The Kyoto Protocol, 1998), should thus qualify for carbon credits as incentives, in addition to the economic value of the produce. This is especially socio-ecologically important if the rural communities originally farming in those areas are allowed to carry out these projects, as this reduces spatial and people-based leakage (Van Noordwijk and Minang, 2009). Intercropping annual food crops, pineapple, mushroom and other produce types that thrive in these plantations could be enhanced, converting the monocultures into more productive and attractive agricultural mosaics as crop yields would provide food and income to the families (Roshetko et al., 2007). This reduces commodity-based leakage (Van Noordwijk and Minang, 2009), consequently achieving both goals of carbon sequestration and improvement of rural livelihoods.

Conclusion

Extended rotations are best practices for reforestation of degraded lands with rubber while for oil palm complete rotation would yield the best results. Wood from the cut rubber plants would reduce dependence on pristine and secondary forest for fuel wood, while biomass fractions returned to soil would markedly increase soil carbon above baseline conditions. It is thus important that rubber and oil palm be considered by managers for reforestation of deforested land in the Central African sub-region. Carbon credits from potential post Kyoto Treaties would mainly be incentives, as produce from these species have established national and international markets.

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