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ORIGINAL ARTICLE

The carbon sequestration potential of tree crop plantations

Rico Kongsager · Jonas Napier · Ole Mertz

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Abstract Carbon (C) conservation and sequestration in many developing countries needs to be accompanied by socio-economic improvements. Tree crop plantations can be a potential path for coupling climate change mitigation and economic development by providing C sequestration and supplying wood and non-wood products to meet domestic and international market requirements at the same time. Financial compensation for such plantations could potentially be covered by the Clean Development Mechanism under the United Nations Framework Convention on Climate Change (FCCC) Kyoto Protocol, but its suitability has also been suggested for integration into REDD+(reducing emissions from deforestation, forest degradation and enhancement of forest C stocks) currently being negotiated under the United Nations FCCC. We assess the aboveground C sequestration potential of four major plantation crops – cocoa (*Theobroma cacao*), oil palm (*Elaeis guineensis*), rubber (*Hevea brasiliensis*), and orange (*Citrus sinesis*) – cultivated in the tropics. Measurements were conducted in Ghana and allometric equations were applied to estimate biomass. The largest C potential was found in the rubber plantations (214 tC/ha). Cocoa (65 tC/ha) and orange (76 tC/ha) plantations have a much lower C content, and oil palm (45 tC/ha) has the lowest C potential, assuming that the yield is not used as biofuel. There is considerable C sequestration potential in plantations if they are established on land with modest C content such as degraded forest or agricultural land, and not on land with old-growth forest. We also show that simple C assessment methods can give reliable results, which makes it easier for developing countries to partake in REDD+ or other payment schemes.

Keywords Aboveground biomass · Allometric equations · Carbon estimations · Carbon sequestration · Ghana · Kade · Land-use change · Tree crop plantation

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R. Kongsager (✉)
UNEP Risoe Centre on Energy, Environment and Sustainable Development, Technical University of Denmark, Risoe Campus, Frederiksborgvej 399, Bldg. 142, P.O. Box 49, 4000 Roskilde, Denmark
e-mail: rick@dtu.dk

J. Napier · O. Mertz
Department of Geography & Geology, University of Copenhagen, Øster Voldgade 10, Copenhagen 1350, Denmark

1 Introduction

Increasing greenhouse gas (GHG) concentrations, mainly carbon (C), in the atmosphere is one of the most pressing global environmental problems, as it will result in a change in the energy balance and consequently the climate. Most emissions come from fossil fuels, but tropical ecosystems store 340 billion tons of C (Gibbs et al. 2007), corresponding to more than forty times total annual anthropogenic emissions from fossil fuels (Canadell et al. 2007). A large part of this C is released when forests and grasslands are cleared, burned and converted to agricultural systems (IPCC 2006). Land-use and land-cover change has contributed about 33 % of global C emissions over the past 150 years, and although the current relative contribution has declined to 10-13 % annually (Houghton et al. 2012), tropical deforestation is still estimated to release about 2.9 billion tons of C each year. Tropical deforestation is largely driven by agricultural expansion, which is already releasing ~1.5 billion tons of C each year (IPCC 2007).

This has led to a growing interest in lowering the emissions rate of GHG from different types of land-use, and it has been argued that an increased focus on forestry and agroforestry systems as C sinks will be necessary to achieve a significant long-term reduction in atmospheric GHG levels (C and methane), particularly from tropical areas (Soto-Pinto et al. 2010; Verchot et al. 2007). Compared to normal tropical agricultural crops, tree crop plantations have a significantly larger sequestration potential and are able to sequester C for longer periods with smaller annual fluctuations. Many annual crops such as maize can fix more C than forestry systems in any given year, but their biomass usually decomposes rapidly, and the rate and return of sequestered C to the atmosphere are very fast (Liguori et al. 2009). This knowledge is important as tree crop plantations could be a more feasible mitigation solution in many parts of developing countries compared to pure afforestation and reforestation projects, since tree crop plantations also provide work, income and food, especially when established in smallholder systems where local people have control over production. As such, plantations may also be an important element in increasing adaptive capacity in the sense of adapting to climate change and other pressures that local communities in developing countries are facing. Large-scale plantations operated by larger companies may also provide economic development, but they are often associated with major environmental and social problems, especially those related to non-compliance with environmental management regulations and de facto land alienation, when plantations obtain long-term leases on community lands (Fitzherbert et al. 2008; Fox et al. 2009; Koh and Wilcove 2008; Ngidang 2002; Sheil et al. 2009). To use tree crop plantation to sequester C and at the same time increase sustainable development would link climate change mitigation and adaptation, and an enhancement of this link has been called for by several authors (Ayers and Huq 2009; Halsnæs and Verhagen 2007; Klein et al. 2007; Klein et al. 2005; Tol 2005; Verchot et al. 2007)

Information on C sequestration in forest plantations, agroforestry and natural forests is plentiful. Conversely, information on tree-crop plantation monoculture systems is incomplete. Some studies have been conducted, mainly in Southeast and East Asia, on the C content of oil palm (e.g. Chase and Henson 2010; Foong-Kheong et al. 2010; Germer and Sauerborn 2008; Khalid et al. 1999) and rubber plantations (e.g. Cheng et al. 2007; Song and Zhang 2010; Yang et al. 2005). With regard to Africa, only a very few studies have been conducted on tree-crop plantation monoculture systems, for example, Wauters et al. (2008) on rubber and Duguma et al. (2001) on cocoa in an agroforestry system.

The present study differs from these studies by using a much simplified methodology which can be useful in less developed countries with more limited resources. It also differs by measuring a much older rubber plantation (compared to Wauters et al. 2008), and by doing so in West Africa and not in Central Africa (compared to Duguma et al. 2001), where growing conditions are different, especially with regard to precipitation. It has also not been possible to locate any articles on the C content of oil palm and orange plantations in Africa. Moreover, our study focuses on Ghana, which is currently experiencing a change from a period in which where deforestation was the main source of C emissions to one in which emissions from the degradation of forests and agroforests will be the main source of GHG emissions. Most of the forest has been converted to plantations, mainly for the production of cocoa (Sandker et al. 2010). Therefore, the window of opportunity for avoided deforestation projects in Ghana is closing quickly, and the focus now has to be directed to afforestation and reforestation projects. However, another way to enhance C sequestration in Ghana could be high-accumulation plantation crops that, besides sequestration, provide Ghanaians with products and work opportunities, which can raise living standards in general. This is reflected in the Nationally Appropriate Mitigation Action Plan submitted by Ghana (UNFCCC 2010), in which commercial plantations on degraded land are identified as a mitigation action for the country.

The main objective of this study is therefore to estimate the C sequestration potential of mature tree-crop plantations in the tropics, specifically in Ghana. Seven plantations of four different plantation crops – cocoa (*Theobroma cacao*), oil palm (*Elaeis guineensis*), rubber (*Hevea brasiliensis*), and orange (*Citrus sinesis*) – at different ages were selected to investigate C sequestration in the aboveground living biomass after establishment. The measurements were non-destructive, and tree biomass was computed using allometric equations. The objective was also to compare the results of simple methods to the results of more in-depth studies using more costly and time-consuming methods that may not be affordable for researchers in developing countries with limited resources.

2 Methods and study area

2.1 Study site

This study was carried out in 2011 at the Agricultural Research Centre in Kade (ARC-Kade), which is located 123 km NW of Accra, near Kade in the Kwaebibirem District of the Eastern Region of Ghana (Fig. 1). ARC-Kade and its surroundings were chosen as the study area because of their proximity to plantations of several types and ages, which makes them comparable as they are being grown under similar environmental conditions and with the same methods of cultivation. ARC-Kade is located in the high forest zone, and the area is described as an ecotone between the moist semi-deciduous and the moist evergreen forest (Nye 1961).

The elevation is 114 m above sea level, the terrain is relatively flat, and the latitude is 6°09’N and longitude 0°55’W. The mean annual temperature is 26°C, and only minor seasonal variations occur (Fig. 2). Precipitation, which averages 1,425 mm per year, is a bimodal regime with the major rainy season being concentrated from March to July and a further minor season occurring from September to December (Fig. 2). The main economic activity in the area is agriculture based on oil

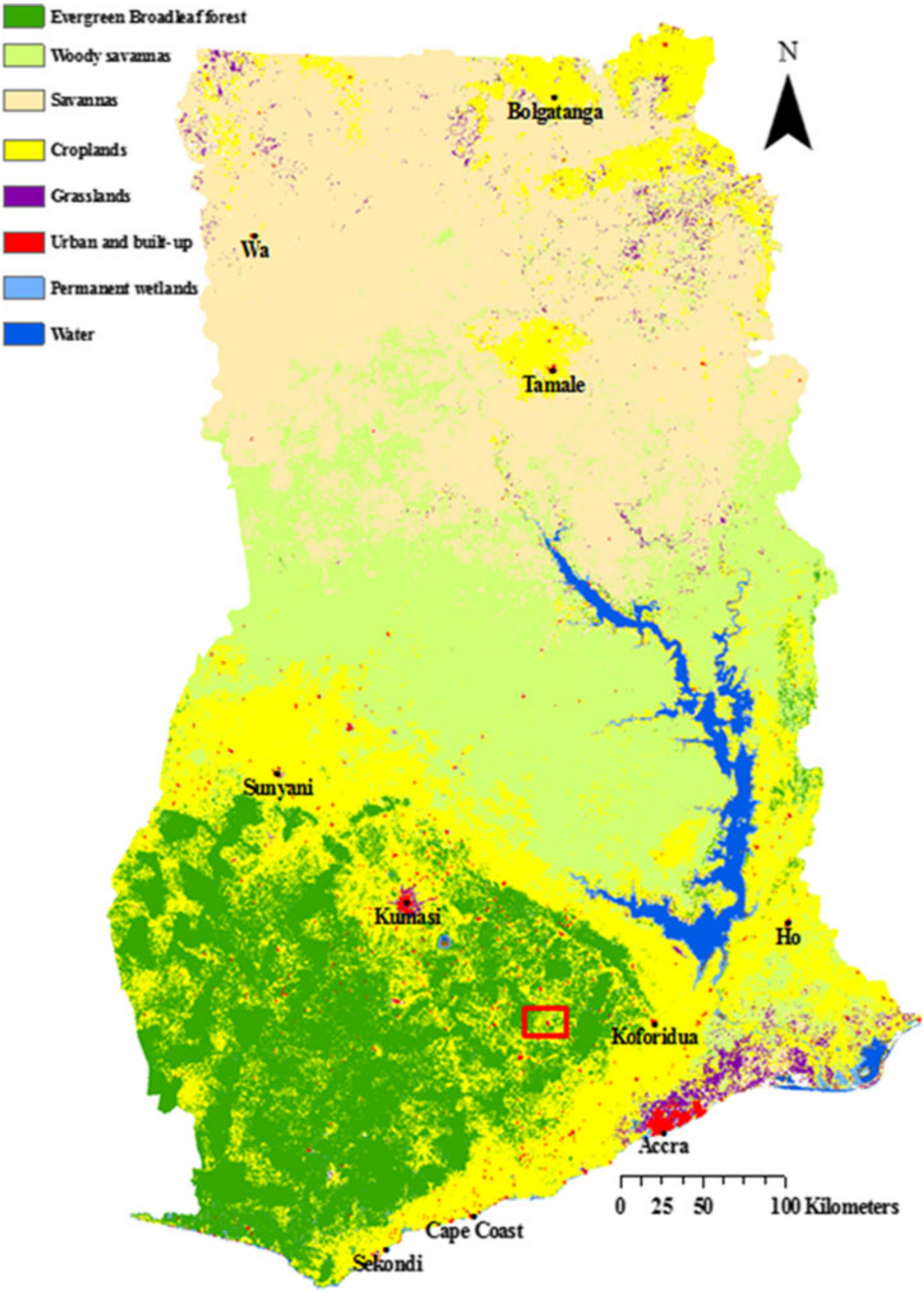

Fig. 1 Land cover types in Ghana in 2008 (Source: NASA Moderate-Resolution Imaging Spectroradiometer) (processed by the authors). The red square indicates the area of interest, which is enlarged in Fig. 3

palm, cocoa, rubber, citrus, plantain, cassava, maize, and cattle- and goat-breeding. In general, the landscape is characterized by a mosaic of secondary forests, agricultural plots, pastures, shaded cocoa and rural settlements.

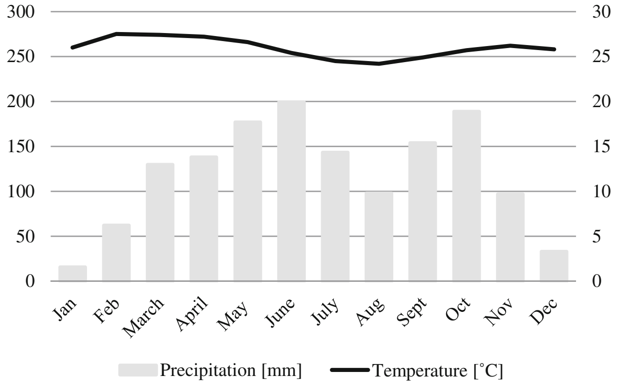

Fig. 2 Climate diagram, ARC-Kade, 1980-2010. Annual averages: precipitation 1,425 mm; temperature 26 °C. Data for 1984, 2005, 2006 and 2007 are incomplete and not included (data provided by Dr S. Adjei-Nsiah 2011)

2.2 Stratification of the project area

In order to facilitate the fieldwork and increase accuracy and precision in measuring and estimating the C, the project area was stratified according to the plantations present in the area. This reduced the sampling effort while maintaining the same level of confidence since there was a smaller variation in C stocks in each stratum than in the whole area. The project area was stratified by land-uses and ages in the four plantation types of interest by applying a Landsat scene from 1986 and a land-use map from 1991 (Fig. 3). The Landsat scene was also used for calibrating the GPS. The land-use map, giving the year of establishment for each plantation, was applied for detailed planning and the definition of boundaries in the measurement plan. Visual inspection of the four plantation types could not justify subjacent stratification, as the areas seemed to be homogenous units in relation to the variable to be measured.

2.3 Carbon pools measured

In general there are six C pools applicable to Land Use, Land-Use Change and Forestry (LULUCF) activities – aboveground trees, aboveground non-tree, belowground roots, litter, dead wood and soil organic matter. The selection of which pools to measure depends on several factors, including expected rate of change, magnitude and direction of change, availability and accuracy of methods to quantify change, and the cost of measuring (Pearson et al. 2005). In this study we focused on the C pool in the aboveground living biomass of trees since this accounts for the largest percentage of the sequestered C within a forest ecosystem (Yang et al. 2005; Alves et al. 2010), and it is therefore the most important pool in the land-use change context (Kotto-Same et al. 1997). Consequently, other C pools, as well as C in harvested material, were not considered. It should be noted that only a very limited amount of aboveground non-tree, litter, and dead wood were found at all sites.

Soil C content, however, is significant, but studies have shown that this changes insignificantly as a consequence of land-use changes. Soto-Pinto et al. (2010) found that soil C was mainly influenced by agro-climatic zone, not by land-use, and Kotto-Same et al. (1997) characterized the soil C content as stable with regard to land-use changes. Yang et al. (2005) showed that conversion from forest to arable land mainly reduced the C content of topsoils and much less in the deep layers. Lugo and Brown's meta-study (1993) gives a more

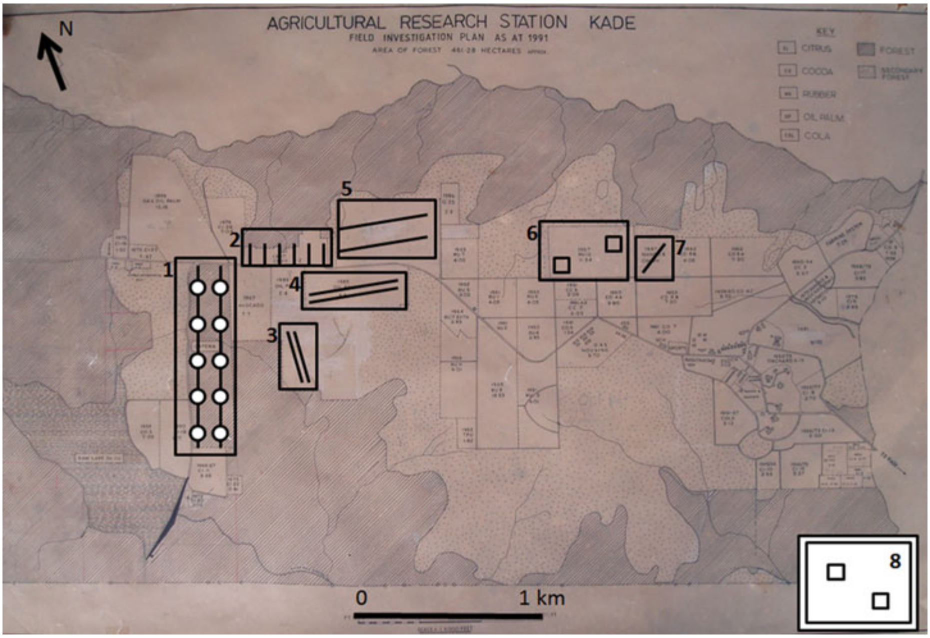

Fig. 3 Map of the Agricultural Research Centre in Kade (scale 1:5000). 1: Natural forest (> 100 years) (see Kongsager et al. (in press) for the measurement of the natural forest at ARC-Kade). 2: Orange plantation (15 years). 3: Oil palm plantation (16 years). 4: Oil palm plantation (23 years). 5: Oil palm plantation (7 years) 6: Rubber plantation (44 years). 7: Cacao plantation (21 years). 8: Rubber plantation (12 years) is located 25 km south of Kade

diversified picture and shows that the soil C content in managed systems can be lower, the same as or greater than mature tropical forests.

The C content in the belowground biomass roots was not measured since IPCC guidelines for national GHG inventories assumes that land-use change does not cause a change in C stock in belowground biomass. However, large amounts of C may actually be stored in belowground biomass. A comparison of C in the belowground biomass of natural rainforest with that of grassland and oil palm plantations reveals that C in belowground biomass is 41 tC/ha for natural rainforest, 5 tC/ha for grassland and 19 tC/ha for oil palm plantation (Wicke et al. 2008). This indicates that the assumption that land-use change does not cause a change in C stock in belowground biomass is questionable and will presumably be site-specific.

2.4 Measurement plots

The guidelines from Pearson et al. (2005) and IPCC (2003) were applied in taking the measurements. The methods applied in measuring aboveground biomass differed between plantation types since different variables are used in the chosen allometric equations. Some of the equations use diameter at breast height (DBH at 1.3 m), others height (H) or basal area (BA). Single plots were used because the plantation systems had low variation and there was therefore no need for a nested approach (Pearson et al. 2005). The selection of plot size and form was based on guidelines from Pearson et al. (2005) together with knowledge from the visual inspection used for selecting specific methods in each plantation. The area measured in each plantation was based on the assumption that approximately 5 % of a very uniform area is a sufficient sample area, as these plantations have very low variation. The number of plots was low as only small variations were present in each plantation. In total seven plantations were measured, specifically: cocoa (1), orange (1), rubber (2), and oil palm (3).

The trees and therefore the C content were small in the cocoa and orange plantations, even though they were 21 and 25 years old. Younger cocoa and orange plantations (e.g. 10 years old) could have been measured, but the C content was deemed to be insignificant. In addition, older plantations could have been studied, but the cocoa and orange plantations measured seemed to have reached their maximum, and for these reasons it was decided only to measure one of each. Two rubber and three oil palm plantations were measured in order to examine the development in C content. Specifications regarding the measurements are shown in Table 1, and notes regarding the actual field measurements are described below.

Cocoa DBH of trees/stems with a DBH≥5 cm were measured. Species-specific equations using BA do exist (Beer et al. 1990), but we did not harvest these data due to the intricate nature of the cocoa tree bases. The plantation had mango shade trees with approximately 20 m between each tree, and these were used as the centre of plots, as was also done by Isaac et al. (2007). DBH of the shade tree was also recorded. Every second mango shade tree was used as a centre in a systematic approach to cover a wider part of the plantation.

Oil palm Only the height was recorded since biomass in palms is more closely related to height than to diameter (Pearson et al. 2005). Height was measured with a stick divided into intervals: 10 cm intervals for the 7-year-old plantation, 25 cm intervals for the 16-year-old plantation and 50 cm intervals for the 23-year-old plantation. Only the height of the stem was measured from the base up to the spot where the stem was no longer visible. No zero values occur in the dataset, as dead palms are replanted with new palms.

Orange Diameter at the base was measured, converted to BA and then used in the biomass equations for orange trees. Missing/dead trees were set to zero. To cover a wide part of the plantation a systematic approach was applied: in every third row every second tree in the row was measured.

3 Analysis

The following sections describe how the input parameters were processed and then how the C content was calculated and scaled up.

3.1 Cocoa

Isaac et al. (2007) noted that no species-specific biomass regression based on DBH could be found in the literature, so they used a general biomass equation from Brown (1997) for the tropical biome, and the same approach was applied in this study (Eq. 1). This equation was used by Pearson et al. (2005) and updated from Brown (1997). It applies to the tropical region, with only DBH as an input parameter.

$$AGB = \exp\left(-2.289 + 2.649\ln(DBH) - 0.021(DBH)^2\right) \tag{1}$$

where AGB is aboveground biomass [kg] and DBH is diameter at breast height [cm].

Table 1 Specifications of the plantation measurements

	Cocoa	Oil palm	Rubber	Orange
Variable measured	Diameter at breast height	Height	Diameter at breast height	Basal area
Total number of trees/stems measured	246	360 (120 from each year)	442 (178 from 1967 and 264 from 1999)	108 (94 alive and 14 dead/missing)
Number of plantations measured	1	3	2	1
Age	21 years old (planted in 1990). Shade trees 40 years old.	7 years old (planted in 2004), 16 years old (planted in 1995) and 23 years old (planted in 1988)	12 years old (planted in 1999) and 44 years old (planted in 1967).	25 years old (planted in 1986)
Total size of area	13.9 ha	50.04 ha (2004), 13.9 ha (1995), and 30.58 ha (1988)	55.6 ha (1999) and 38.92 ha (1967)	20.71 ha
Planting density	1,097.39 stands/ha	144 stands/ha	Unknown	266.93 stands/ha
Species	Theobroma cacao	Elaeis guineensis (Tenera)	Hevea brasiliensis	Citrus sinesis (Late valencia)
Type of plot	Since distinct rows of cocoa trees were absent, circular plots with a radius of 20 m were chosen.	Since no palms were missing in the rows, the oil palm plantations were measured in rows equivalent to two acres (0.4047 ha) as transects through each plantation.	Because of incomplete rows, we measured in 60×60 m squared plots instead of only equivalent rows. Trees were missing since no replanting took place if a tree died, as the older trees would shade the younger trees too much.	The plantation was measured in equivalent rows.
Plots	5 plots of 314.15 m^2=0.16 ha=4 % of the total population.	1 transect of 120 trees in each plantation=0.81 ha=6 % (2004), 20 % (1995) and 9 % (1988) of the total population.	2 plots of 3,600 m^2 (in both plantations)= 0.72 ha=4,5 % (1999) and 16 % (1967) of the total population.	6 rows of 18 trees=108 trees=0.405 ha=6.7 % of the total population.
Location of plots (see Fig. 3)	Maps and Global Positioning System were used to locate	Rows were randomly picked in the field, which could be done since it was concluded by visual	ArcGIS was used to divide both plantations into 60×60 m squares, and	A map was used to locate the SW corner of the plantation, and the

Table 1 (continued)

	Cocoa	Oil palm	Rubber	Orange
	starting point in the SW corner of the plantation, and a row was randomly picked in the field.	inspection that all the rows were highly identical.	each square was given an identification number. Two of these numbers were randomly picked by a computer program. Maps and Global Positioning System were used to locate the centres of the plots.	second row in the northern direction was used as the first row.

* *DBH* Diameter at breast height, *H* Height, BA Basal area

First, the AGB of each tree was calculated using Eq. 1, and these figures were summarized to obtain a total AGB for each plot. Subsequently, the C content of the five plots was calculated by multiplying with the biomass to C conversion factor of 0.5 as recommended by IPCC (2003). Finally, the average C content of the five plots was scaled up to a per hectare basis using an expansion factor of 31.8 (= 10.000 m^2 / 314.15 m^2) for each plot. Using the same factor for the shade trees would have resulted in an overestimate of the total C content since the shade trees were only present for every 20 m. There were thus 25 shade trees per hectare, i.e. the shade trees were scaled up by a factor of 25. As the shade trees were 40 years old, we used a rough down-scaling to the age of the cocoa trees by dividing by 2.

3.2 Oil palm

The biomass equation from Khalid et al. (1999) (Eq. 2) was used for estimating the C content of the oil palms.

$$W = 725 + 197H \tag{2}$$

where W is the total fresh weight [kg] and H is the height [m]. First, W of each palm was calculated using Eq. 2, and these figures were summarized for each plantation. Subsequently, the dry weight was calculated by applying a dry to fresh weight ratio of 0.27, which was calculated from the data provided in Khalid et al. (1999). Finally, the results were multiplied using a biomass C conversion factor of 0.5, as recommended by IPCC (2003), and scaled up to a per hectare basis.

3.3 Rubber

First, AGB of each tree was calculated using Eq. 1, and subsequently converted to C with a factor of 0.487, since this is the value observed and featured in the allometric equation of Wauters et al. (2008). Finally, the results were converted to a per hectare basis.

3.4 Orange

The aboveground C content in the orange plantation was estimated by Eq. 3 from Schroth et al. (2002).

$$Biomass = -6.64 + 0.279BA + 0.000514BA^2 \tag{3}$$

where BA is basal area [cm^2].

First, biomass was calculated using Eq. 7. The results were converted to C with the 0.5 conversion factor, and finally scaled up to a per hectare basis.

4 Results and discussion

The C contents of the seven measured plantations are presented in Table 2. The amount of C accumulated per year is also shown for each plantation, since this value often is more meaningful. However, it is difficult to calculate, as C accumulation does not increase linearly, and there is significant disagreement in the literature about the functional form of C accumulation over time (Yang et al. 2005). As in most other studies, we assumed that the amount of C sequestrated in biomass increased linearly with time in order to simplify calculations.

Table 2 Carbon content in plantations

Type	Age [years]	Aboveground [tC/ha]	Accumulation [tC/ha/year]
Cocoa	21	65.0	3.1
Oil Palm	7	21.7	3.1
Oil palm	16	28.0	1.8
Oil Palm	23	45.3	2.0
Rubber	12	61.5	5.1
Rubber	44	213.6	4.9
Orange	25	76.3	3.1

4.1 Cocoa

Isaac et al. (2007) found 20 tC/ha for 8-year-old cocoa under shade trees in a cocoa plantation in Western Ghana (172 km due west of ARC-Kade), and Beer et al. (1990) found 18 tC/ha and 14 tC/ha for 10-year-old cocoa trees under two different types of shade trees in Costa Rica. These studies correspond well with our results of 41 tC/ha for cocoa trees that are around or more than twice as old. Conversely Gockowski and Sonwa (2011) calculated a C stock equilibrium value of 88.7 tC/ha in a 40-year-old shaded cocoa plantation in Cameroon. The large difference can probably be explained by the higher precipitation in Cameroon and the high density of shade trees: 120 per ha versus 25 in our study site.

The substantial contribution of biomass from the shade trees is a result of the large average of DBHs from trees that were originally part of a mango tree plantation and are therefore quite old and large. Thus, while the total C content of the cocoa tree plantation at ARC-Kade is quite considerable, the actual contribution from the cocoa trees is more modest and at an expected level. Consequently, this must be taken into account when considering using cocoa plantations for C sequestration, as varieties of cocoa trees that do not need shade will reduce the C content in a cocoa plantation considerably.

4.2 Oil palm

Published values on oil palm aboveground C in biomass range from 25 tC/ha to over 50 tC/ha towards the end of the plantation’s economical life span after 25 years (Germer and Sauerborn 2008). Our result of 45.3 tC/ha (accumulation: 1.98 tC/ha/year.) for a 23-year-old plantation corresponds well with this. The measurements in the study by Khalid et al. (1999), from which the applied equation originates, were made on palms with heights ranging from 6 to 9 m which raises the question of whether our results will be valid when using heights below this range. We have nonetheless chosen to utilize the equation due to lack of other alternatives and the fact that the most important figures we derived were based on data within the empirical range.

Khalid et al. (1999) found 85.3 t biomass per ha based on scaling up the average dry weight in plantations to 136 palms per ha. In Kade there were 144 palms per ha, and when adjusting our results for the 23-year-old oil palm plantation to a level of 136 stands per ha we get an average dry-weight biomass of 85.6 t/ha. For the 23-year-old plantation we found the average weight of biomass per palm to be 543 kg, while Khalid et al. (1999) observed

627 kg and Corley et al. (1971) estimated an average of 556 kg for 27½-year-old oil palms. Given the differences in age and mean height, the similarities lead us to believe that our figures were in a reasonable range, and thus we consider our estimates to be acceptable for the 23-year-old oil palms. In addition, Corley et al. (1971) found the mean palm biomass weight to be 252 kg and 493 kg for oil palms at the ages of 7½ and 16 years respectively. Our results showed 261 and 343 kg for the 7-year-old and 16-year-old oil palms respectively. While this is consistent with the 7-year-old oil palms, the 16-year-old palms seem a bit skewed until one looks at the linear regression calculated from the data of Corley et al. (1971) (Fig. 4), which makes 343 kg/palm at the age of 16 more likely.

For comparison, in Fig. 5 data from the three plantations in our study are plotted against aboveground biomass data from 51 oil palm plantations taken from several studies (Germer and Sauerborn 2008). There are large variations between the estimates, which can be explained by variations in growing conditions and management practices in the different study areas. The curve shows quick initial growth and thereafter a minor increase in C accumulation, and our results from the 7- and 23-year-old plantations follow the curve. The 16-year-old plantation falls below the curve, but this estimate is still comparable with results from other studies of plantations of that age.

4.3 Rubber

The 213.6 tC/ha from the 44-year-old rubber plantation seems high, but the result was assessed as reasonable, given that the average DBH in the 1967 plantation was twice the average in a primary forest, where 130.2 tC/ha with Eq. 1 was found (see Kongsager et al. in press). Furthermore, the 1967 plantation has a *breast height area* of 37.9 m^2/ha compared to 22.3 m^2/ha in the primary forest at ARC-Kade (see Kongsager et al. in press), which makes the high rubber C content possible.

In comparison, Yang et al. (2005), Cheng et al. (2007) and Song and Zhang (2010) also found a high potential for C fixation in rubber plantations in China. Yang et al. (2005) applied two allometric equations and estimated an average sequestration rate of 4.9 [4.7-5.1] tC/ha/yr in vegetation along a 38-year chronosequence, compared to 5.0 [4.9-5.1] tC/ha/yr in our study. Cheng et al. (2007) estimated that rubber plantations could sequestrate 272.08 tC/ha within a 30-year-life span. Song and Zhang (2010) estimated the biomass C stock to be 123.49 tC/ha, but this was for a plantation with a higher elevation (550-600 m) than at ARC-Kade (114 m), and therefore a less suitable planting region.

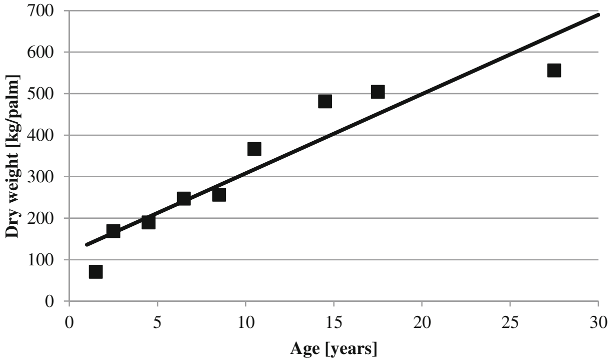

Fig. 4 Mean dry weight [kg/palm] and linear regression of oil palms (data from Corley et al. 1971)

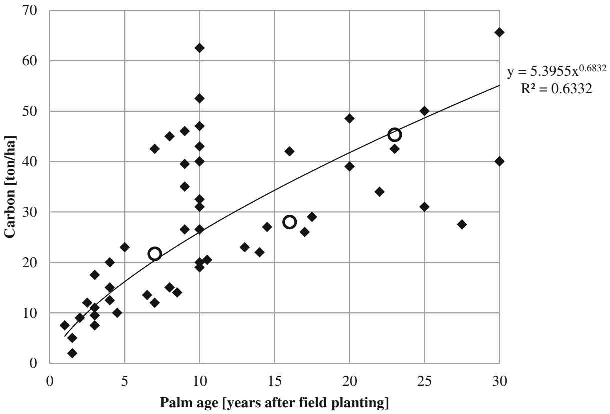

Fig. 5 Aboveground carbon in oil palm plantations. The squares are oil palm biomass results from 51 fields that have been converted to carbon (carbon=biomass * 0.5). These data are from Germer and Sauerborn (2008). The circles are the results from our study: 7 years (43.4 tC/ha), 16 years (56.0 tC/ha), 23 years (90.6 tC/ha)

4.4 Orange

The C content was estimated to be 76.3 tC/ha for a 25-year-old orange plantation, or an accumulation rate of 3.1 tC/ha/yr. In comparison, Liguori et al. (2009) estimated the C fixation of a single tree to be 10.7 kgC/yr in a traditional system similar to the one at ARC-Kade. Converted with the tree density at ARC-Kade (266.93 stands/ha), Liguori et al. (2009) reported an accumulation rate of 2.9 tC/ha/yr.

The applied equation from Schroth et al. (2002) was developed from destructive harvesting and measuring. It has an empirical range in BA of 40-240 cm^2, which is below the range of the trees at ARC-Kade, where the range was 78-1,385 cm^2. Hence, the validity of the estimates beyond the empirical range is questionable. The trees measured by Schroth et al. (2002) were only 7 years old, whereas the trees at ARC-Kade were 25 years old. Figure 6 presents the relationship between BA and C content. Equation 1 has DBH as an input parameter, but the diameter from the base of the tree has been used as input, which results in an overestimate, since the DBH are smaller than the diameter at the base. In spite of this it still provides an idea of how C content grows with increases in BA. The two equations follow similar development paths, which supports the validity of Eq. 3 and the result. It is not possible to subtract per hectare C content from the work of Schroth et al. (2002) for comparisons, since the derivation of the allometric equations was part of a calculation of total biomass content in multi-strata agroforestry plantations.

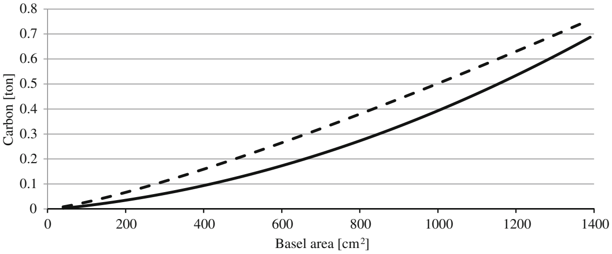

Fig. 6 Comparisons of Eq. 3 (*full line*) and Eq. 1 (*dotted line*)

5 Conclusion

The C sequestration potential in plantations can be achieved, but it requires plantations to be established on land with modest C content, such as degraded forest or agricultural land. For example, the transformation of agricultural areas to grassland ecosystems is a common problem (Cotter et al. 2009), and converting these land-use types into plantations could be beneficial from both C and economic perspectives (Li et al. 2008). The consequences of converting old-growth forest to plantations have shown to result in large C debts except for rubber plantations, where the C payback time will be around 40 years. In our study, it was also found that rubber plantations have the highest C content and can sequester C at an equal or higher level than natural forests in the area. The potential for conserving C is so high that it may be considered a good practice to be included in future mitigation agreements under a revised Clean Development Mechanism. Rubber plantations also have the dual economic potential of both latex and timber production (Rahaman and Sivakumaran 1998), and the sequestrated C can go into long-term storage if it is converted into permanent wood products, or decays over a moderate period of time if the wood is used for disposable products (Yang et al. 2005). Wood from cocoa, orange, and rubber plantations can also serve as fuelwood and thereby reduce the pressure on forest areas.

For oil palm the possible biofuel C savings were not taken into account; yet, C payback times for clearing tropical forests are unacceptably large in the context of any reasonable C mitigation efforts. Conversely, C benefits are possible from planting oil palm in already degraded lands or replacing other crops (Danielsen et al. 2009; Fargione et al. 2008; Gibbs et al. 2008) if this is done in way that does not compromise local farmer's livelihoods and food security. Furthermore, the C debt produced by converting land to plantations greatly depends on the region where these plantations are planted: for example, the oil palm yield in Africa is three times lower than in Asia and America (Gibbs et al. 2008). In general, expansion of plantations into natural tropical ecosystems will always lead to net C emissions, while expanding on to degraded or already cultivated land will provide almost immediate C savings. For instance, expansion into West Africa's degraded scrublands, where cocoa plantations once grew, could provide C accumulation (Gibbs et al. 2008).

Overall, there is considerable potential for smallholder plantations especially to serve the dual purpose of mitigating GHG emissions while increasing local incomes and thereby strengthening the adaptive capacity that is often claimed to be necessary to adapt to inevitable climate variability and change (Osbahr et al. 2008; Mertz et al. 2009; Mertz et al. 2010). Unfortunately, establishing plantations is often less environmentally desirable compared to afforestation in many situations. Plantations are man-made ecosystems that in many cases do not favour biodiversity and often decrease ecosystem services such as biodiversity, erosion control and water supply. Hence, it is also questionable whether plantations will be acceptable under a REDD+mechanism in which safeguarding biodiversity plays an important part in the negotiations.

Finally, we have shown that, compared to destructive and other C measurement methods, the methods applied in this study only have very limited material needs and are less time-consuming. The results show that the simple approach gives reliable results, and it is feasible to perform these very simple measurements and calculations to estimate C contents in countries with limited resources and capacity. This is important, as it is questionable whether such analyses would be conducted in many developing countries if only complex, resource-dependent methods are used. This could restrict the ability of such countries to participate in mitigation projects in future C payment schemes.

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