Title: Estimation and economic evaluation of aboveground carbon storage of *Tectona grandis* plantations in western Panama

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Abstract

Tropical tree plantations may play an important role in mitigating CO_2 emissions through their potential to capture and sequester carbon from the atmosphere. The Clean Development Mechanism (CDM) as well as voluntary initiatives may provide economic incentives for afforestation and reforestation efforts through the generation and sale of carbon credits. The objectives of our study were to measure the carbon (C) storage potential of 1, 2 and 10-years old *Tectona grandis* plantations in the province of Chiriquí, western Panama and to calculate the monetary value of aboveground C storage if sold as Certified Emission Reduction (CER) carbon credits. The average aboveground C storage ranged from 2.9 Mg C ha^{-1} in the 1-year old plantations to 40.7 Mg C ha^{-1} in the 10-year-old plantations. Using regression analysis we estimated the potential aboveground C storage of the teak plantation over a 20 year rotation period. The CO_2-storage over this period amounted to 191.1 Mg CO_2 ha^{-1}. The discounted revenues that could be obtained by issuance of carbon credits during a 20 year rotation period were about US$460 for temporary CER and US$560 for long-term CER, and thus, contribute to a minor extent (1%) to overall revenues, only.

Keywords: aboveground carbon storage, certified emission reductions, clean development mechanism, teak plantations, Panama

Introduction

Land use change and its impact on global climate are important factors that make it necessary to improve our knowledge of carbon (C) cycling in forest ecosystems. Forests can play an important role in capturing and storing C from the atmosphere, thereby mitigating CO_2 emissions (e.g. Watson 2000; Houghton 2005). Tropical plantations are of particular interest due to their relatively fast growth.

Policy makers are aware of the benefits of afforestation and reforestation projects in the tropics. However, the upfront costs of afforestation and reforestation can be high, which hinders the realization of investments. Meanwhile, the benefits from ecosystem services such as carbon sequestration and biodiversity conservation remain undervalued (Cavatassi 2004). The recent Clean Development Mechanism (CDM) as well as voluntary initiatives provide opportunities for the forest sector in developing countries to generate and sell carbon credits, and thus, to participate in climate change mitigation (UNFCCC 1998). CDM seems to be a promising instrument to generate significant economic incentives for carbon sink projects at the local level, which might be used by developing nations to finance the high upfront costs of afforestation and reforestation projects. However, the expected income from selling carbon credits in the form of Certified Emission Reduction (CER) depends crucially on the demand of industrialized nations (Annex I countries) participating in the Kyoto Protocol. Despite several uncertainties such as non-permanence and additionality, the CER trade can be seen as a cost efficient short-term solution to meet the emission reduction commitments of industrialized countries (Schlamadinger and Marland 2000, Olschewski et al. 2005). There are currently more than 840 registered CDM projects in 49 countries, and about another 1800 projects in the project registration pipeline. The CDM is expected to generate more than 2.5 billion CERs by the time the first commitment period of the Kyoto Protocol ends in 2012 (UNFCCC 2007).

Carbon can be stored in the production of high quality timber such as teak (*Tectona grandis* Linn. f.). Teak is one of the most important tropical hardwood species in the international high-quality timber market. Strong market demand has led to the establishment of plantations within and beyond its native countries (Bhat 2000). Teak was introduced in Central America less than a century ago (de Camino et al. 1998). By the year 2000, approximately 223 000 ha of *Tectona grandis* plantations were established in Central America (Pandey and Brown 2000). In Panama, extensive areas of degraded pastures were converted to tree plantations. In 2003, Panama had 55 200 ha of plantations, of which 35 200 ha (64%) were planted with *Tectona grandis* (ANAM 2004).

Despite the importance of teak in Central America, the availability of growth and yield data for teak is limited mainly to Costa Rica. Bermejo et al. (2004) developed growth and yield models for a teak plantation in the north western region of Costa Rica. Pérez and Kanninen (2003) examined the distribution of total aboveground biomass of *Tectona grandis* plantations in different regions in Costa Rica and its relationship with diameter, age and stand density. Management scenarios for the intensive management of *Tectona grandis* plantations in Costa Rica, using competition indices as guidelines for defining the timing and intensity of thinning, were generated by Pérez and Kanninen (2005). In the only study on teak plantations in Panama to date, Kraenzel et al. (2003) measured the above- and below-ground biomass and the tissue C contents of 20-year-old teak plantation in Central Panama.

In recent years private investors established several teak plantations in the Province of Chiriquí (Western Panama) for C sequestration and timber production. Because the C sequestration rates and the total amounts of C stored in tropical ecosystems are highly variable, estimates from the study in Central Panama cannot necessarily be applied to the plantations in Western Panama. Despite this lack of data, the expected C storage rates and expected yield are critical pieces of information that stakeholders need to utilize the CDM. The objectives of this paper are (i) to estimate the aboveground C storage capacity of *Tectona grandis* over a rotation period of 20 years and (ii) to estimate the potential revenues from CER trade. To address these topics we measured forest structure on 45 plots. Tree tissue biomass and C concentration were estimated and functions were developed to assess the C storage at tree and plantation level. Finally, we estimated the revenues generated by CER issuance and conducted a sensitivity analysis to determine the impact of price changes on our results.

Material and Methods

Study area and selection of study sites

This study was carried out in the district of San Lorenzo, approximately 40 km east of David, the capital of the of Chiriquí Province, Western Panama. The study area is delimited in the south by the Gulf of Chiriquí, Pacific Ocean and in the north by the Pan-American Highway (Figure 1). The sites Boca Chica (8°14’14’’N, 82°11’30’’W), San Lorenzo (08°15’16’’N, 82°05’14’W) and Boca del Monte (8°21’56’’N, 82°10’54’’W) were in distance of approx. 15 km to each other. Elevation ranged between 5 m (Boca Chica, San Lorenzo) and 35 m (Boca del Monte). The annual mean temperature is 26.7 C° (1971-1980, WorldClimate 2006). Precipitation during the dry season (December - April) varies between 20 and 100 mm per month and during the wet season between 250 and 450 mm per month. The yearly average rainfall is 2540 mm (1971-1980, WorldClimate 2006). The dominant soils are mainly Ultisols and Lixisols (Kaiser, 2006). The prevailing soil texture is loamy clay (Boca del Monte) and clay (Boca Chica, San Lorenzo). The pH (in water) varies between 4.6 and 5.2 (0-10 cm depth). Soil C stocks (0-100 cm) range from 80 to 100 Mg C ha^{-1} (Kaiser 2006).

Four different land cover types were investigated: 1-year-old teak plantations (Teak 1; San Lorenzo and Boca Chica), 2-year-old teak plantations (Teak 2; San Lorenzo), 10-year-old teak plantations (Teak 10; Boca del Monte), and a pasture site (San Lorenzo) (Table 1). We used the chronosequence approach, where measurements are taken from similar but separate locations that represent a temporal sequence in land use management (Penman et al. 2003). For each land cover type (Teak 1, Teak 2, Teak 10, pasture) five replicate sites were selected according to a stratified random sampling design. At each site, three temporal sampling plots were established (Table 1). Teak 1 and Teak 2 sampling plots were 21 by 21 m (441 m^2), and Teak 10 plots were 30 by 36 m (1080 m^2). Data was collected from a total of 60 sampling plots.

All plantation sites were previously used for cattle ranching. Site preparation for Teak 1 and Teak 2 included the removal of stumps and coarse roots and ploughing to a depth of approximately 30 cm. Initial tree spacing within the plantations was 3 by 3 m. Ground vegetation and understorey was removed by regular cutting and the application of herbicides. Organic fertilizer was applied. The rotation length was 20 years and thinning was carried out in years 4, 7, 10 and 14 (Clementino Herrera, personal communication).

Tree and biomass measurements

Within each sampling plot, tree density, diameter at breast height (DBH) and total height was measured between May and July 2005. The DBH was determined by using a circumference tape; height was measured with a VERTEX III (Haglöf Sweden AG, Langsele, Sweden).

Tree harvesting was stratified on the basis of DBH. Trees were grouped into 2 cm classes, ranging from 2 cm to 26 cm DBH. We used the Chapman-Richards, a classical growth function, to describe height-diameter relation as an actual state of the measured stands and to ensure that representative trees in a given DBH class were selected for biomass harvest. In the DBH classes 2 to 10, three individuals were selected from each class, giving a total of 15 trees. Trees were cut at ground level and divided into stem, branches and foliage. Total wet weight for each tissue type was determined in the field using a spring scale. Subsamples from each tissue type were taken and oven-dried at 70°C (48 h) to obtain the wet-to-dry mass ratio (the dry coefficient). Another subsample was ground to fine powder and then analyzed for C (NA 1500, Carlo Erba Strumentazione, Milan, Italy). Following the procedure of Kraenzel et al. (2003) the tree-specific wet-to-dry mass conversion factors for the different tissue types were used to convert total wet mass per tissue type to total dry mass per tissue type for each tree. These dry masses were then converted to tissue specific carbon storage by multiplying them by tree- and tissue-specific carbon concentrations. Total C storage per tree was estimated by adding up the amount of C stored in the stem, branches and leaves.

In the DBH classes 18-26 only one tree per class was harvested, giving a total of 5 trees. After cutting trees were cleared of branches and divided into 20 equal sections for biomass measurement. The diameter of each section was measured, beginning with the diameter of the stem at height 0. Branch and leaf sampling and processing as well as the determination of the tissue specific C concentration and total C storage followed the method described in the previous paragraph.

In all sampling plots the grass/herbaceous biomass and litter were measured (1) to assess the entire above ground biomass and (2) to use the amount of C stored in the grass/herbaceous biomass of the pasture sites as the baseline scenario. Litter was collected from 1m² quadrates and grass/herbaceous biomass was cut at ground level, weighed, oven-dried at 70°C and reweighed. Subsamples were taken to determine the C concentration and the dry coefficient. The amount of C stored in the grass/herbaceous vegetation or the litter (Mg C ha^{-1}) is the respective product of the estimated dry biomass and the C concentration.

Subtracting the C storage of the pasture from the amount of C stored in the trees results in net C sequestration, which is the basis for calculating the amount of C credits assigned to the afforestation project. The C content of the vegetation in the understorey of the teak plantations was not considered when accounting took place. However, it was supposed to serve as an additive component, which – by following a conservative approach, and thus, not taking it into account- corrects for a possible overestimation of C-storage.

Statistical analyses

One-way analysis of variance (ANOVA), followed by a Tukey post-hoc test, was used to test for differences in C content and dry coefficient among tissue types and sites. One-way analysis of variance was also used to test whether tree height and DBH differed among the plantations. A regression function was established over all harvested trees using DBH as the independent variable and total tree C storage as the dependent variable. Prior to regression analysis, DBH and total tree C storage values were log transformed. All statistical analyses were performed with SAS 9.1 (SAS Institute Inc., Cary, NC, USA).

Modelling the cumulative aboveground carbon storage over a 20 year rotation period

The C storage of *Tectona grandis* on a stand level was estimated as follows: In Teak 1 and Teak 2 approx. 19% of the trees had not reached DBH-height yet. However, knowing their biomass is necessary to model aboveground C storage of teak in the course of stand development. Tree C storage for trees below 1.3 m height was calculated using the regression: ln (Tree C storage, <1.3 m height) = 1.56797 x ln (Height) + 2.23946; $r=0.95$, $p<0.05$. Tree C storage for trees above 1.3 m was estimated using the regression: ln (Tree C storage, >1.3 m height) = 2.55174 x ln (DBH) + 1.54636; $r=0.96$, $p<0.05$.

As no field data could be obtained for a 20-year-old teak plantation we applied a time series approach to estimate the potential C storage over a rotation period of 20 years. Using the DBH/age function of Pérez and Kanninen (2005) for site class II, which represents 80% of the potential growth and comes closest to the empirical values observed at our teak sites, a DBH was assigned to the respective age. Knowing the DBH/age and the DBH/C storage relationships, C storage can be estimated for every age by means of linking these two functions. The C storage of a tree at a particular age was converted into per-hectare values by multiplying the quantity of stored C by the per hectare tree density. By calculating density indices, Pérez and Kanninen (2005) found optimal thinning intensities of: 50% (556 trees ha^{-1} remaining) for the first thinning at age 4; 40% (333 respectively 200 trees ha^{-1} remaining) in the second at age 7 and in the third at age 10; and, 25% (150 trees ha^{-1}remaining) in the fourth thinning at age 14. The tree densities reported by Pérez and Kanninen (2005) were similar to those of the plantations where this study took place.

Economic evaluation

In contrast to permanent credits, where CO_2 emissions are avoided at the source, carbon credits generated by afforestation and reforestation projects are referred to as non-permanent credits. These credits expire after the trees are harvested at the end of a rotation, or after a certain period based on the specific accounting regimes of the CDM. There are two types of tradable non-permanent credits: lCER and tCER, which differ in their respective periods of validity. Temporary CER (tCER) expire at the end of the commitment period subsequent to the period in which they were issued, for example; tCER issued during the first commitment period (2008-2012) expire at the end of the following period (2017). In contrast, lCER are valid until the project comes to an end after 20 or 30 years (UNFCCC 2007).

We calculated the revenues from tCER assuming that credits are issued near the end of a commitment period, which results in an expiry time of five years. The methodology for calculating revenues from lCER is similar but differs in validity length and, accordingly, results in different credit prices. In order to estimate the revenues from carbon credit trade the price of tCER has to be determined. We assumed that potential buyers (in Annex I countries) would be indifferent between purchasing a permanent credit today, and purchasing a tCER today and replacing it by a permanent credit after the tCER expired (Olschewski and Benítez 2005). In this case, the tCER price (P_{tCER}) was calculated based on equation (1), where P_∞ is the price of a permanent credit and d* is the discount rate (3%) determined by the interest rate for long-term bonds in Annex I countries. T indicates the expiring time and '0' refers to credit prices today.

$$P_{tCER_0} = P_{\infty_0} - \frac{P_{\infty_T}}{(1+d^*)^T} \tag{1}$$

As CER are traded as CO_2 units, C storage was converted into CO_2 quantities (Mg CO_2 ha^{-1}) multiplying C storage (Mg C ha^{-1}) by the molar conversion factor 3.667.

Revenues from trade of carbon credits are generated *ex post* every five years until year 15. In year 20 no credits are to be issued because the timber is harvested and the project ends. Estimating CO_2 storage of each commitment period and discounting it according to equation (2) results in the present value, B^T (Olschewski et al. 2005).

$$B^T = \frac{P_5 C_5}{(1+d)^5} + \frac{P_5 C_{10}}{(1+d)^{10}} + \frac{P_5 C_{15}}{(1+d)^{15}} \tag{2}$$

C_t is the cumulative C storage in the forest at the time t, which is measured in Mg of CO_2 and refers to the net-C accumulation (excluding the C stock of the project baseline). P_tC_t represents the revenues from issued carbon credits, where the number of temporary credits is multiplied by the respective price of a five-year tCER. These revenues are discounted by applying a rate of 4.8% determined by the interest rate of long-term bonds in the Non-Annex I (developing) country where the project is implemented. The first credits of the afforestation project are generated in year 5 and equal the net cumulative CO_2 (C5) at this time. These credits expire in year 10 but can be reissued together with the additional certificates obtained between years 5 and 10. Therefore, a total of C10 are assigned in year 10. The same holds for the next period. As the validity period of the certificates is always 5 years, following equation (1), the certificate price remains constant, assuming a constant price of permanent credits. The last tCER are issued in year 15, and correspond to the carbon accumulation between years 10 and 15. These credits expire in year 20 and cannot be reissued because final harvest takes place in the same year.

Results

Stand characteristics and tree carbon storage

As shown in Table 2, tree density declined from 1079 trees ha^{-1} (Teak 1) to 383 trees ha^{-1} (Teak 10). Mean tree height increased from 2.1 m (Teak 1) to 20.5 m (Teak 10). Mean DBH of Teak 1 (3.7 cm) and Teak 2 (3.6 cm) did not differ. The 10-year old teak plantation had a mean DBH of 22.5 cm.

Figure 2 shows how the proportion of stem, branches and foliage of total tree biomass changed over DBH classes. In the smaller diameter classes, foliage contributed up to 50% of the total biomass, whereas in the upper DBH classes the proportion of foliage was about 10%. Mean C concentration ranged between 44% and 47%, and did not vary significantly among DBH classes and tissue types.

Based on the biomass harvest, carbon storage per tree ranged from 0.6 kg tree^{-1} (Teak 1) to 99.2 kg tree^{-1} (Teak 10). On a stand level between 0.9 Mg C ha^{-1} (Teak 1) and 38.0 Mg C ha^{-1} (Teak 10) were stored in the tree biomass (Table 2). Carbon storage of teak over a rotation period of 20 years was 57 Mg C ha^{-1}.

Carbon storage of grass/herbaceous vegetation and litter

The average C concentration in the grass/herbaceous vegetation and litter varied little (42-44%) and did not differ significantly ($P = 0.479$) among land cover types. In contrast, the amount of dry biomass varied significantly across land cover types. Under Teak 1 and Teak 10 considerably less carbon was stored in the grass/herbaceous and litter layer as compared to Pasture and Teak 2 (Table 2). Total aboveground C (tree + grass/herbs/litter) ranged from 2.9 Mg C ha^{-1} (Teak 1) to 40.7 Mg C ha^{-1} (Teak 10) (Table 2).

The amount of C stored in the Pasture (5.1 Mg C ha^{-1}) represents the baseline scenario of CER accounting of plantations. The average observed quantity of C stored in the grass/herbaceous vegetation and litter layer of Teak 1, Teak 2 and Teak 10 was 3.6 Mg C ha^{-1}. Thus, C storage in the herbaceous/litter layer was on average reduced by 1.5 Mg C ha^{-1} (5.5 Mg CO_2 ha^{-1}) if the land use type changes from pasture to teak. This corresponds to 5.5 CER units, which must be subtracted from the gross carbon accumulation when calculating carbon credit revenues.

Timber and carbon revenues

By analyzing the joint production of timber and carbon credits, we assessed to what extend each products contributes to the overall revenues of a teak afforestation project. We calculated teak timber volume after 20 years based on the biomass fresh weight of the trees per ha. The proportion of the stem to the total biomass (based on fresh weight) of the trees per ha was on average 62%. We multiplied the total biomass fresh weight by 0.62 (stem proportion) and 0.6 g cm^{-3} (wood density of teak) to derive the timber volume. Revenues were estimated by multiplying the resulting timber volume of 95 m^3 ha^{-1} by the average price of US$525 m^{-3}. Finally and for a later comparison of timber and carbon revenues, we calculated the present value of timber revenues applying a discount rate of 4.8% for the Non-Annex I country, resulting in US$60 236 ha^{-1} for one rotation period. Given that the focus of our study was on comparing timber and carbon revenues, we neither considered harvesting and management costs nor carbon credit certification costs.

Figure 3 shows the cumulative gross CO_2 storage for a rotation period of 20 years. After five years, the merchantable amount of tCER was 37.3 Mg CO_2 ha^{-1}. It increased to 65.5 Mg CO_2 ha^{-1} in year 10. After 15 and 20 years 105.0 Mg CO_2 ha^{-1} and 161.0 Mg CO_2

ha^{-1} were stored, respectively. Note that for calculating the amount of temporary certificates the baseline of 5.5 Mg CO_2 ha^{-1} was subtracted, resulting in 31.8, 60.0 and 99.5 units accountable as tCER in the respective years. In sum, a total of 191.3 tCER is generated (Table 3, Figure 3).

According to equation (1), the tCER price depends on the current price of credits for permanent emission reduction. During the course of the year 2007 the market price of such credits traded within the European Emission Trading Scheme (ETS) floated between US$20 and US$30 and was about US$40 per ton of CO_2 in April 2008 (PointCarbon 2008). We assumed an average price of US$30 per permanent credit and applied a discount rate for Annex I countries of 3%, resulting in US$4.10 per tCER.

Multiplying the amount of temporary credits by this price gives the undiscounted revenues of US$131 ha^{-1} in year five, US$246 ha^{-1} in year ten and US$408 ha^{-1} in year 15 (Table 3). By discounting these values by applying the discount rate of the Non-Annex I countries (4.8%), the present value sums up to US$461 ha^{-1} (Table 3), which can be achieved additionally to revenues from timber. A comparison of these figures clearly demonstrates that timber revenues are the main source of income in plantation forestry and that CER revenues, accounting for less than 1% of the timber revenues, represent only a small additional incentive to establish new teak plantations.

Discussion

Aboveground carbon storage of teak plantations

We applied the growth function developed by Pérez und Kanninen (2005) to assess and predict the aboveground C storage potential of the studied young teak plantations over a rotation period of 20 years. Pérez and Kanninen (2005) measured the aboveground biomass of over 10 000 teak trees collected in different regions in Costa Rica. Although various growth functions are available for *Tectona grandis* (Phillips 1995; Bermejo et al. 2004), we considered the model developed by Pérez and Kanninen (2005) to be the most representative as their model not only included teak plantations grown under different climate conditions but also under different site qualities and management options. Their model is based on a fitted Chapman-Richards-Function and was adapted to the growth conditions of the sites in Chiriquí. The allometric model fitted to the DBH/C-storage data predicting about 96% of the variation in C storage with the variable DBH, which allows using it not only for the estimation of the C storage of the studied plantations, but also for the prediction of C storage of other sites. The fitted model can also be applied to predict aboveground C storage of teak at different ages. Predicting C storage for an entire rotation period is possible, when the growth function of Pérez und Kanninen (2005), is adapted to the mean DBH that is observed on a site of a certain age and is linked to the DBH/C function. When thinning is considered in the resulting age/C function, estimates can be made of the amount of tradable CER generated by a stand. However, Losi et al. (2003) pointed out that regressions should not be applied to trees whose sizes are outside the range of trees that were used to develop the regressions. Additional data in the higher DBH classes would therefore be necessary to improve the regression.

This study found that tree carbon storage in the 10-year old teak plantation in Chiriquí was 99.2 kg C. In the 20-year-old teak plantations in Central Panama, 138-248 kg C are stored per tree (Kraenzel et al. 2003). Although the stands that Kraenzel et al. (2003) studied in Central Panama are 10 years older, the teak stand in our study in Boca del Monte has already reached a similar profile of DBH and tree heights. Differences between the stands might be explained by site factors and management. Measurements of tree density indicate that intensive thinning was undertaken at Chiriquí. Furthermore, in these plantations undergrowth is removed regularly and fertilizer is applied. In contrast, the plantations studied by Kraenzel et al. (2003) received very little management with only natural thinning and no underground removal.

As afforestation and reforestation projects such as teak plantations are often established on pastures or abandoned land, these land cover types form the baseline of CDM projects. The amount of C stored in the grass/herbaceous vegetation at our pasture sites was within the range found in other studies. Olschewski und Benítez (2005) estimated 4.9 Mg C ha^{-1} on pasture sites in North-West Ecuador. Schelhaas et al. (2004) examined temperate grasslands and found 7.0 Mg C ha^{-1}. In *Tectona grandis* plantations, Kraenzel et al. (2003) found on average 3.4 Mg C ha^{-1} in the herbaceous/litter layer, which corresponds to the average value we found in the three *Tectona grandis* sites in Chiriquí (3.6 Mg C ha^{-1}). The substantial differences of the grass/litter C contents between Teak 1 and Teak 2 might be explained by former land use. Teak 2 was established on so-called improved pastures (*Pasto mejorado*), whereas Teak 1 was established on abandoned pasture sites. *Pasto mejorado* contains some persistent grass varieties, which are cut regularly and generally persist until the canopy is closed.

Economic evaluation

Our finding that carbon revenues only play a minor role in the economic outcome of the joint production process contrasts with results of other carbon sink studies in the tropics. For example, Olschewski and Benítez (2008) found that carbon revenues might contribute substantially to the overall economic attractiveness and even have considerable impact on the harvesting decision for fast growing species in the tropics. However, their study refers to *Cordia alliodora* plantations, a species with a timber price much lower than the one for teak.

We conducted a sensitivity analysis to determine the impact of important variables on the results and considered timber and carbon prices as well as the discount rates in Annex I and Non-Annex I countries. We simulated price and discount rate changes of ± 25% to capture the economic uncertainty related to long-term forestry investments.

Concerning timber price changes we found that even a 25% price decrease would not substantially improve the relative contribution of carbon payments, which will remain at about 1% of overall revenues.

Table 4 shows the further results of the sensitivity analysis for the tCER trade scenario. The greatest influence on CER revenues is caused by price changes of permanent credits. The future price of permanent CER is still subject to uncertainty. Calculations in this study were based on average prices during 2008 (PointCarbon 2008). However, earlier studies show that the carbon market is characterized by a high volatility (Lecocq 2005). Equation (1) indicates on the one hand that a high price of permanent credits *today* makes tCER more attractive. On the other hand, rising prices in the *future* mean higher replacement costs when tCER expire and thus, result in a reduced attractiveness of temporary CER today. As a result, a reduction of today's permanent credit price by

25% would lead to a decrease in tCER revenues by 25%. A 25% higher permanent price would increase tCER revenues by 25%.

The discount rates in Annex I and Non-Annex I countries differ as people in developing and developed countries face different economic conditions (Olschewski et al 2005). The discount rate in Annex I countries has the second largest impact on the results in the sensitivity analysis. Regarding the discount rate in Annex I countries, revenues of tCER increased by 22% if a discount rate of 3.75% was assumed and decreased by 23% if a discount rate of 2.25% was applied. Assuming a 25%-change of discount rates in Non-Annex I countries, leads to an increase of tCER-revenues by 14% at a discount rate of 3.6% and a decrease by 12% at a discount rate of 6%.

Olschewski et al. (2005) found similar results for afforestation projects in North-western Patagonia: the attractiveness of carbon projects decreases with lower discount rates in Annex I countries. In contrast, changes of the discount rate in Non-Annex I countries was the least influential factor in the sensitivity analysis.

Accounting regimes

Our study focussed on the accounting of temporary CER. Alternatively, long-term CER could be issued for an afforestation project. In this case, credits for the net C accumulation during the first five years (31.8 Mg ha^{-1}) can be issued with an expiring time until the end of the project (15 years). For the C accumulation between year 5 and 10, an additional 28.2 lCER with an expiring time of 10 years could be issued, and finally in year 15, 39.5 lCER with a duration of five years were generated. The price of lCER depends on the validity period and can be calculated according to equation (1). The resulting present value of carbon revenues amount to about US$560 ha^{-1}, indicating that in our study the difference between the accounting regimes is rather small (about

US$100 ha^{-1} for a 20 years project). Similar results were found by Olschewski and Benítez (2005) for plantations and secondary forests in north-western Ecuador.

There are several arguments favouring either tCER or lCER. Trading of tCER is favourable because the handling of tCER has operational advantages and offers more flexibility (Bird et al. 2004). Thinning that is carried out on well-managed plantations like those that were examined may complicate the accounting of lCER. In that case, the lCER carbon credits that were sold become partly invalid by the loss of biomass that occurs when thinning is carried out (Dutschke 2002). However, for landowners it might be attractive to sell lCER because they generate higher revenues at an early stage of the project. In contrast, the lCER revenues will be reduced towards the end of the project due to lower growth increments of the mature stand.

Significantly, afforestation and reforestation projects are subject to uncertainty, as there are technical risks including fire and pests, in addition to the institutional and market risks. Therefore, especially the issuance of lCER bears the danger that commitments cannot be fulfilled in the longer term, and investors must take liability issues into account. This will probably cause potential demanders to buy tCER instead of lCER in order to reduce their risk exposure. Finally, in both cases, the costs that arise for monitoring, evaluation and certification must be taken into account. According to Leuba (2005) these costs might amount to more than 10% of the expected revenues from CER trade.

Conclusions

This study reveals that in afforestation projects with fast growing, high quality timber species such as teak plantations in Panama, revenues from carbon sequestration play a minor role, only. The additional monetary incentive just sums up to about 1% of the timber revenues. However, high growth rates of teak during the first years can generate additional income from carbon trade, which can be used to at least partly compensate the establishing costs of the plantation.

A comparison of temporary and long-term credits results in the finding that issuing tCER accounting is the superior to lCER, given that the present values of revenues are similar, while taking into account that tCER entail a more flexible accounting regime. This is especially important when considering risk and uncertainty aspects both on the demand and supply side.

Reliable estimates of aboveground carbon storage are essential to investors and policy makers, particularly in the context of the CDM. We were able to extrapolate biomass data obtained from young teak plantations to a 20 year rotation period by applying an existing growth model. The strong agreement between this study's predicted aboveground C storage capacity and the field data from teak plantations throughout Central America indicates that this approach may also be applicable to other sites.

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Table 1. General characteristics of the study sites in Chiriquí, Panama.

Land cover	**Location**	**Area**	**Establishment**	**Elevation**	**Number of sites/ sampling plots**
		ha	year	m	n
Pasture	San Lorenzo		1950-1960	5-10	5/15
Teak 1	Boca Chica, San Lorenzo	107	2004	5-10	5/15
Teak 2	San Lorenzo	364	2003	5-10	5/15
Teak 10	Boca del Monte	99	1995	35	5/15

Table 2. Descriptive characteristics of teak trees and stands in Chirqui, Panama. The values are mean ± standard deviation (in parentheses) of n = 5 sites. Different letters indicate differences among stands (ANOVA with post-hoc Tukey, $P < 0.05$)

Land cover	**Tree density**	**Height**	**DBH**	**Aboveground C storage**		
				Trees	**Grass/litter**	**Total**
	trees ha^{-1}	m	cm		Mg C ha^{-1}	
Pasture					5.1 (0.3)	5.1 a
Teak 1	1079	2.1 (1.6)	3.7 (1.5)	0.6 (1.4)	2.3 (0.1)	2.9 b
Teak 2	990	2.8 (2.0)	3.6 (2.0)	0.8 (2.1)	5.8 (0.3)	6.6 a
Teak 10	383	20.5 (3.0)	22.5 (3.6)	38.0 (3.4)	2.7 (0.1)	40.7 c

Table 3. Payment flow for temporary Certified Emission Reduction (tCER)

Payment	**CO_2-storage CER**	**tCER units**	**Price**	**Payment**	**Payment discounted**
Year	Mg CO_2 ha^{-1}		US$ $tCER^{-1}$	US$ ha^{-1}	
5	37.3	31.8	4.1	131	104
10	65.5	60.0	4.1	246	154
15	105.0	99.5	4.1	408	203
Sum	207.8	191.3		785	461

Table 4. Sensitivity analysis of the change in discount rate in Non-Annex I and Annex I countries and of the price of permanent Certified Emission Reduction (pCER)

Discount rate						**pCER price**	
Non-Annex I			**Annex I**				
	US$ $tCER^{-1}$	% change		US$ $tCER^{-1}$	% change	US$ $tCER^{-1}$	% change
75% (3.6)	524	14	75% (2.25)	353	23	576	25
100% (4.8)	461	0	100% (3.0)	461	0	461	0
125% (6.0)	407	12	125% (3.75)	564	22	346	25

Table 5. Tree density and carbon storage of different *Tectona grandis* stands in Panama. The values are mean ± standard deviation (in parentheses).

Study site	**Age**	**Tree density**	**Height**	**DBH**	**Carbon storage**
	years	trees ha^{-1}	m	cm	kg $tree^{-1}$
Boquerón, Central Panama[1]	20	586	20.7 (4.1)	23.7 (7.6)	180
Penas Blancas, Central Panama[1]	20	566	19.4 (4.4)	26.6 (8.6)	248
Tranquilla, Central Panama[1]	20	621	20.6 (4.3)	25.3 (6.7)	217
Aguas Claras, Central Panama[1]	20	723	20.6 (4.2)	21.9 (5.0)	138
Boca del Monte, Western Panama[2]	10	383	20.5 (3.0)	22.5 (3.6)	99.2

[1] Kraenzel et al. (2003)

[2] this study

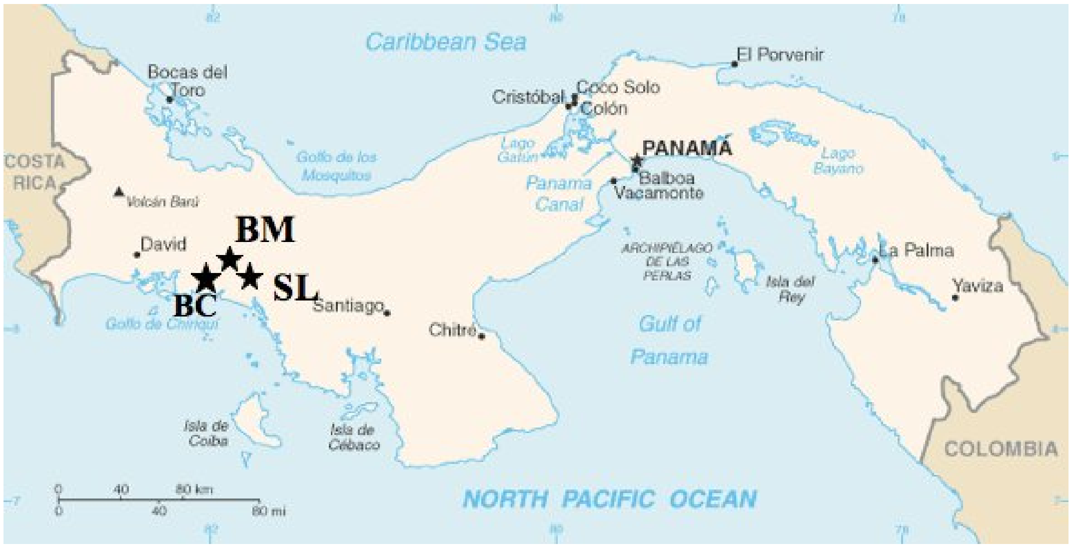
Figure captions

Figure 1. Location of the study sites Boca del Monte (BM), Boca Chica (BC) and San Lorenzo (SL), Chiriquí, Panama. Source: CIA Factbook

Figure 2. Proportion of foliage, branch and stem biomass over DBH classes, Chiriquí, Panama

Figure 3. Temporary CER units (numbers in rectangles) based on cumulative CO_2 storage in a teak plantation with a rotation period of 20 years, Chiriquí, Panama

Figure 1



Caribbean Sea
El Porvenir
Bocas del Toro
Cristóbal
Coco Solo
Colón
PANAMÁ
COSTA RICA
Golfo de los Mosquitos
Lago Gatún
Lago Bayano
Panama Canal
Balboa
Vacamonte
Volcán Barú
BM
David
SL
BC
Santiago
Golfo de Chiriquí
Chitré
ARCHIPIÉLAGO DE LAS PERLAS
Isla del Rey
La Palma
Yaviza
Gulf of Panama
Isla de Coiba
Isla de Cébaco
COLOMBIA
NORTH PACIFIC OCEAN
0 40 80 km
0 40 80 mi

Figure 2

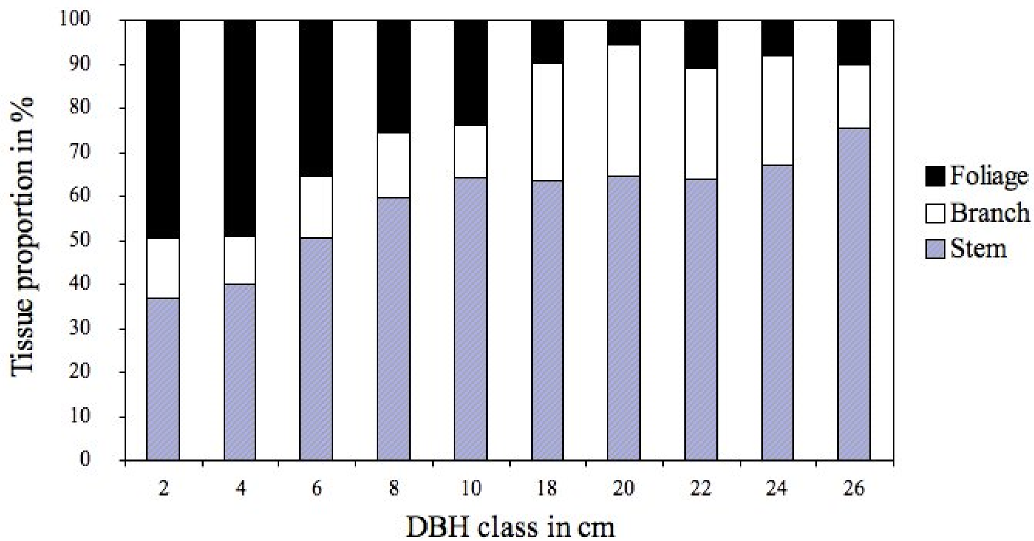
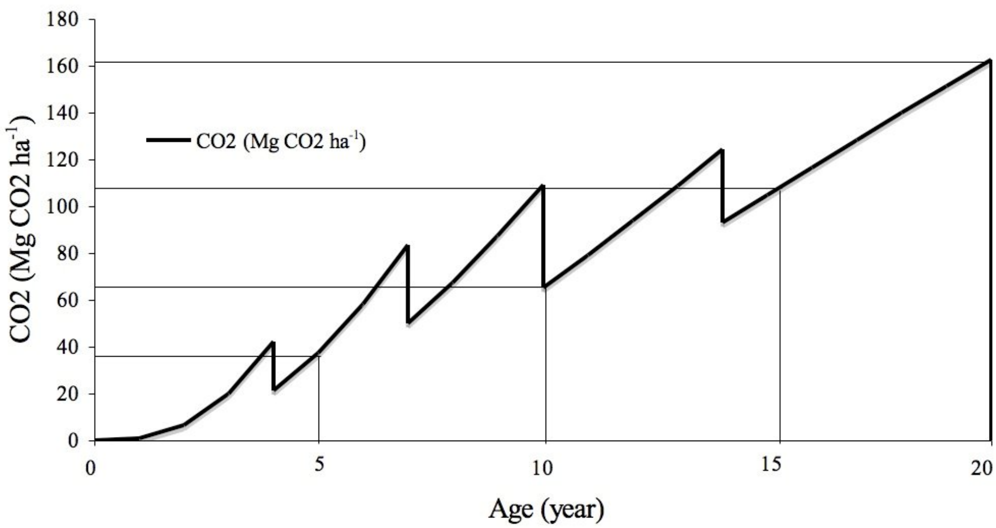

Tissue proportion in %
100
90
80
70
60
50
40
30
20
10
0
2
4
6
8
10
18
20
22
24
26
DBH class in cm
Foliage
Branch
Stem

Figure 3


CO2 (Mg CO2 ha-1)
180
160
140
120
100
80
60
40
20
0
0
5
10
15
20
Age (year)
CO2 (Mg CO2 ha-1)