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Site identification for carbon sequestration in Latin America: A grid-based economic approach

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Abstract

Latin America harbors a large potential for carbon sequestration and biomass production. This paper deals with the estimation of carbon supply curves for afforestation and reforestation and its implicit carbon sequestration in wood products. The methodology presented aims at determining sequestration costs for individual geographical entities, based on unit-specific land use and ecosystem information, and economic data. This approach allows us to supplement local statistics that are typically scarce and unreliable in developing countries, with independent remotely sensed data in order to have a consistent method that can be applied over a large region. The results are mapped, which allows in-depth appraisal of results in an interactive mode and quick identification of least-cost carbon sequestration sites. The model is dynamic to support decision making at various stages in the Kyoto process. After model calibration and sensitivity analysis, we conducted scenario analysis. For a carbon price scenario of $20/tC, we find that the cumulative carbon sequestration by 2012 and 2020 is about 125 MtC and 337 MtC, respectively. The net benefit by 2020 could amount up to US$ 2.3 billion using less than 4% of the area suitable for afforestation and reforestation in the next 20 years. Our long-term estimates of the cumulative sequestration potential for 100 years imply that tree planting could compensate for more than 7 years of current CO_2 emissions of the region's energy sector at low costs.
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1. Introduction

Global warming as a consequence of human-induced emissions of greenhouse gases (GHG) is perceived as a major environmental concern threatening future welfare. Scientists predict that by 2100, the globally averaged surface air temperature will increase by 1.4–5.8 °C leading to major disturbances

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for human settlements and natural ecosystems (IPCC, 2001). The Kyoto Protocol of Climate Change aims at capping GHG emissions from industrialized countries and allows emission trading between industrialized countries and developing countries through the Clean Development Mechanism, CDM (UNFCCC, 1998).

The CDM is applicable for energy-related projects as well as for afforestation and reforestation projects, where the latter are referred to as CDM-sinks or AR-projects. While for the first commitment period of Kyoto, 2008–2012, the market for CDM-sinks is limited (den Elzen and de Moor, 2002), the importance of CDM-sinks is in the large potential for afforestation and reforestation in developing countries that could be used beyond 2012. According to Nilsson and Schopfhauser (1995), the area available for plantations in the developing world is twenty-six times larger than in Europe, eleven times larger than in the US and three times larger than in the Former Soviet Union. Therefore, there is a need to develop methods for deriving cost curves of carbon sequestration in these regions and identify areas where carbon sequestration is cost-efficient. We take Latin America as a case study because of its land availability and ecological conditions favoring forestry projects, as well as its active participation for implementing carbon sequestration projects in the early stage of the Kyoto process (Brown et al., 2000). We estimate carbon supply curves for AR-projects and its potential benefits for carbon trading under the Kyoto agreement, and provide a geographic representation of the distribution of carbon costs.

Economic studies on carbon sequestration in Latin America have so far provided single point estimates of sequestration costs associated with particular sequestration levels [e.g., Fearnside (1995) for Brazil, Pereira et al. (1997) for Venezuela, Masera et al. (1997) for Mexico and, Olschewski and Benítez (in press) for Ecuador]. These studies provide information on average costs of carbon sequestration for particular regions, but do not assess how these costs increase when large-scale afforestation and reforestation programs are implemented. In contrast to these studies, we evaluate how the heterogeneity of prices (e.g., land and timber prices), and the heterogeneity in land attributes (e.g., net primary productivity and suitability for agriculture) influence sequestration costs and determine carbon supply patterns. In addition, we provide a framework for identifying least-cost sites for carbon sequestration by means of a grid-based analysis that scrutinizes all the available area for plantations in the region.

2. Methods

A myriad of economic land use change models have been developed to derive supply curves of carbon sequestration measures. Some are based on cost–benefit analysis (Sathaye et al., 2001), while others involve more comprehensive analyses like partial and general equilibrium approaches (Callaway and McCarl, 1996), econometric models (Plantinga et al., 1999; Stavins, 1999), timber supply models (Sohngen et al., 1999; Sohngen and Sedjo, 2000), and land use optimization models (Parks and Hardie, 1995). For our purpose, econometric models and general equilibrium models have limited applicability due to data constraints for our study region. For example, Stavins (1999) used a 50-year panel on land use and agricultural output for estimating the parameters for an econometric model of land use in the US. Such detailed information does not exist in most Latin American countries. In order to overcome these problems, we propose an approach where we evaluate afforestation and reforestation decisions by comparing net benefits of current agricultural practices with forestry. In estimating such benefits, we make use of the latest spatial data in order to overcome the limitations of local statistical data.

The analysis starts by creating a homogenous geographical grid (with a grid-cell size of 0.5 degrees) for the whole study area and selecting grid-cells that are suitable for AR-projects, i.e., non-forest areas where tree planting is viable and will not compromise food security of the region. We then estimate sequestration costs for each grid-cell based on estimates for net primary productivity (NPP), plantation costs, expected timber and land prices, and carbon storage in products. Finally, we obtain the cumulative sequestration cost curve by aggregating cell results, taking into account that AR-projects would take place only in cells where the carbon price exceeds sequestration costs. Besides obtaining the cost curve, the method allows identifying the geographic distribution of carbon costs and forest growth potentials throughout the region.

The sequestration decisions are made for each cell by considering the profitability of AR-projects vis-à-vis the current agricultural practice, i.e., the net present value of forestry (F_i) including payments for carbon sequestration is required to be larger or equal to the net present value of agriculture (A_i),

$$F_i \geq A_i \tag{1}$$

where the index "i" denotes cells. F_i and A_i are computed for an infinite time period and expressed in per hectare units. For one rotation interval, net present value of forestry is obtained by,

$$f_i = -\mathrm{cp}_i + \mathrm{pw}_i \cdot V_i \cdot (1+r)^{-R_i} + B_i \tag{2}$$

where f_i is the net present value of forestry computed for one rotation, cp_i is the planting costs, pw_i is the stumpage timber price, r is the discount rate, R_i is the rotation interval, V_i is the timber volume and B_i is the present value of the carbon benefits over one rotation.

2.1. Carbon benefits: full-cycle accounting

Diverse ways to estimate carbon benefits have been debated within the Kyoto Convention (Brown et al., 2000). In this study, we consider carbon uptake as a positive externality and its benefits are a function of the rate of change of biomass or timber volume over time (van Kooten et al., 1995; Creedy and Wurzbacher, 2001). If we approximate tree growth by a linear function, where ω_i is the yearly carbon uptake, the present value of the benefits of carbon uptake over one rotation is $\sum_{t=1}^{R_i} \mathrm{pc}\ \omega_i (1+r)^{-t}$, where pc is the carbon price or implicit social value of carbon.

In a similar fashion, carbon release during harvest is a negative externality and its costs are a function of the amount of biomass or timber volume removed from the forest. The carbon stored in the forest at the end of one rotation interval equals $\omega \cdot R$. In case of instantaneous carbon release, i.e., when the forest is burnt on site, $\omega \cdot R$ tons of carbon are released to the atmosphere. In such a situation, the net carbon benefits including those of carbon uptake and carbon release are,

$$B_i = \mathrm{pc} \sum_{t=1}^{R_i} \omega_i (1+r)^{-t} - \mathrm{pc} \cdot \omega_i \cdot R_i (1+r)^{-R_i}. \tag{3}$$

2.2. Forest products and their carbon benefits

In practice, not all the carbon removed from the forest is immediately released to the atmosphere, but there is a fraction, θ, that is stored for longer time periods outside the atmosphere (van Kooten et al., 1995). This storage after harvest can take place in a wide range of products that are classified in two groups, (1) long-lived products like furniture, structures, construction materials and thick branches, and (2) short-lived products and timber waste including paper, leaves, thin branches, and wastes produced during harvesting, sawmill, processing and product fabrication. We consider aerobic decomposition of timber waste where only CO_2 is produced and exclude carbon offsets associated to the use of biofuels. This broad definition for "forest products" is used throughout this study. Including forest products, the equation for carbon benefits is now,[1]

$$B = \mathrm{pc} \sum_{t=1}^{R} \omega (1+r)^{-t} - \mathrm{pc} \cdot \omega \cdot R (1+r)^{-R} + \mathrm{pc} \cdot \theta \cdot \omega \cdot R (1+r)^{-R}. \tag{4}$$

The term θ deserves some attention. When θ=0, all the forest biomass is burnt and released immediately to the atmosphere. On the contrary, when θ=1, all the biomass is stored in forest products forever. Previous studies have made an arbitrary choice for this parameter (van Kooten et al., 1995), but here we estimate θ as a function of the decay rates of forest products.

Carbon decomposition in forest products is estimated by means of an exponential decay function (Sohngen and Sedjo, 2000). Cumulative carbon (or carbon stock) in products, $W(t)$, is,

$$W(t) = \phi \cdot \omega \cdot R \cdot e^{-k1(t-R)} + (1-\phi)\omega \cdot R \cdot e^{-k2(t-R)} \tag{5}$$

where $(t-R)$ is the time after harvest, ϕ is the fraction of the forest biomass stored in long-lived products. $k1$ is the rate of decay of long-lived products and $k2$ is the rate of decay of short-lived products and timber waste. Carbon release from forest products, $W'(t)$, is

[1] In this sub-section, we omit the subindex "i" for grids in order to simplify the reading.

estimated by taking the first derivative of $W(t)$ with respect to t,

$$W'(t) = -\phi \cdot \omega \cdot R \cdot k1 \cdot e^{-k1(t-R)} - (1-\phi)\omega \cdot k2 \cdot R \cdot e^{-k2(t-R)}. \quad (6)$$

Now we proceed to estimate the net benefits of the externalities associated with carbon uptake and release in forest products. At harvest time, the biomass that was standing in the forest is either stored in long-lived products, or decays rapidly in short-lived products and timber wastes. Therefore, the initial carbon storage in products is $\omega \cdot R$. Then carbon is released according to the exponential decay function of Eq. (6). The present value of carbon uptake/release in products (P) estimated over an infinite time period and using continuous discounting is,

$$P = \mathrm{pc} \cdot \omega \cdot R \cdot e^{-r \cdot R} - \mathrm{pc} \int_{t=R}^{\infty} W'(t) e^{-\mathrm{rt}} \mathrm{d}t. \quad (7)$$

The first term of Eq. (7) is the discounted value of the carbon uptake in forest products at the moment of harvest. The second term is the discounted value of carbon release from forest products over time. Solving Eq. (7) leads to (refer to Appendix A for details),

$$P = \left(1 - \frac{k_1 \phi}{k_1 + r} - \frac{k_2(1-\phi)}{k_2 + r}\right)\left(\frac{\mathrm{pc} \cdot \omega \cdot R}{(1+r)^R}\right). \quad (8)$$

Note that the first term of Eq. (8) is the same as parameter θ of Eq. (4). Therefore we have,

$$P = \mathrm{pc} \cdot \theta \cdot \omega \cdot R(1+r)^{-R} \quad (9)$$

and,

$$\theta = 1 - \frac{k_1 \phi}{k_1 + r} - \frac{k_2(1-\phi)}{k_2 + r} \quad (10)$$

with lower decay rates and higher discount rates, the parameter θ is larger and so the present value of carbon benefits in products.

2.3. Baseline considerations

The net carbon benefits in AR-projects are the ones that provide additional carbon storage in the biosphere as compared to the original land use. This requires subtracting the carbon level in the so-called baseline of the project (Brown et al., 2000). In our analysis, we consider that the carbon stored in the baseline represents a fraction, b_i, of the carbon stored in the forest. We call b_i the baseline factor.

By summing up carbon benefits in biomass and products (Eq. (4)) and subtracting the carbon in the baseline, we get the final expression for total carbon benefits,

$$B_i = \mathrm{pc}_i \cdot \omega_i (1 - b_i)\left\{ r^{-1}[1 - (1+r)^{-R_i}] - R_i(1-\theta_i)(1+r)^{-R_i} \right\}. \quad (11)$$

By means of Eqs. (2) and (11), we estimate net present value of forestry for one rotation interval (f_i) and from this, we obtain net present value for an infinite number of rotations (F_i). Given constant prices and fixed rotation intervals we have,

$$F_i = f_i \left[1 - (1+r)^{-R_i}\right]^{-1}. \quad (12)$$

2.4. Net present value for agriculture

The output per hectare in agriculture is obtained indirectly with a two-factor Cobb–Douglas production function. The first factor is suitability for agriculture, S_i, which is an index that reveals the aptness of the land for agricultural production given its soil, ecosystem and climate characteristics. The second is population density, D_i, which is considered a proxy for labor intensity and infrastructure. Therefore, agricultural output or yield y_i, is,

$$y_i = \eta_i \cdot S_i^{\alpha_i} \cdot D_i^{\gamma_i} \quad (13)$$

where η_i, α_i and γ_i are the parameters for the production function. Revenues for agricultural production equal crop price times yield. If we assume that costs are dependent on yield and that yield and costs remain constant over time, then the equation for net present value for agriculture, A_i, would have the same functional form as Eq. (13):

$$A_i = v_i \cdot S_i^{\alpha_i} \cdot D_i^{\gamma_i} \quad (14)$$

where v_i would also take into account the general price level existing in each country.[2] Eq. (14) provides only an approximation for net present value of

[2] Note that if yield and prices change over time, the functional form of Eq. (14) would remain the same.

agriculture, but by using it, we avoid relying on detailed land use statistics and it also prevents underestimation of agricultural revenues in case the land is not well-managed. For practical reasons, we denote A_i as the land price, knowing that in the absence of risks and uncertainties, and having competitive markets, A_i will reflect the value that a farmer will be willing to accept in exchange of his land.

2.5. Costs for carbon sequestration

When we set A_i=F_i, we find the minimum carbon price (which we define as the carbon costs) that allows forestry to be as profitable as agriculture,

$$\mathrm{pc}_i = \frac{A_i\left[1-(1+r)^{-R_i}\right] + \mathrm{cp}_i - \mathrm{pw}_i \cdot V_i(1+r)^{-R_i}}{\omega_i(1-b_i)\left\{r^{-1}\left[1-(1+r)^{-R_i}\right] - R_i(1-\theta_i)(1+r)^{-R_i}\right\}}. \tag{15}$$

Eq. (15) allows for the estimation of the carbon costs for each cell on the basis of parameters available from GIS databases and existing economic data available from public statistics and publications. Note that there might be cells where forestry without payments for carbon sequestration provides higher revenues than agriculture. This situation will show a negative sign for pc_i.

2.6. Time-profile of carbon sequestration

In the previous equations, we determined the (minimum) carbon price a landowner requires for converting non-forest land into forests. Now our interest is to know how much carbon is sequestered at any given time among all available cells, if the carbon price has a certain market value, pc*. Under a market price pc*, sequestration would take place only in the cells that have their minimum carbon price, pc_i, below pc*. Also we have stands of different ages within a cell. We use the subindex "k" for stands. Every stand of each cell has an area $A_{i,k}$. The net cumulative carbon sequestration up to time T is the sum of the carbon sequestered in the "K" stands of the "I" cells, minus the carbon in the baseline,

$$C_T = \sum_{i=1}^{I}\sum_{k=1}^{K} A_{i,k}(1-b_i)\left(C^b_{i,k,T} + C^p_{i,k,T}\right), \forall i|\mathrm{pc}_i<\mathrm{pc}^*. \tag{16}$$

$C^b_{i,k,T}$ measures the cumulative carbon sequestration per hectare in the biomass of stand "k" of cell "i" at time T. $C^p_{i,k,T}$ measures the cumulative carbon sequestration in forest products. We estimate sequestration in biomass with,

$$C^b_{i,k,T} = \omega_i\left(T - \mathrm{tp}_{i,k}\right) - h_{i,k,T} \cdot \omega_i \cdot R_i \tag{17}$$

and,

$$h_{i,k,T} = \mathrm{floor}\left(\frac{T - \mathrm{tp}_{i,k}}{R_i}\right) \tag{18}$$

where $\mathrm{tp}_{i,k}$ is the time at which the stand k of cell i has been planted and the integer number, $h_{i,k,T}$, denotes the number of harvest periods that have occurred at time T for the given stand. The first term of Eq. (17) sums the biomass that grows each year in the forest and the second term subtracts the biomass removed during each harvest. The cumulative carbon in products is estimated as,

$$C^p_{i,k,T} = \sum_{s=1}^{h_{i,k,T}}\left\{\phi_i \cdot \omega_i \cdot R_i \cdot e^{-k1_i(T-s\cdot R_i)} + (1-\phi_i)\omega_i \cdot R_i \cdot e^{-k2_i(T-s\cdot R_i)}\right\}. \tag{19}$$

Eq. (19) deserves some explanation. Carbon in products is the sum of the carbon stored in short- and long-lived products of the different rotations for a given stand. For example, if the rotation interval is 20 years and the stand has been harvested already at years 20, 40 and 60, total carbon in products is the sum of the carbon accumulation of the products of these three harvests. Therefore, the summation in Eq. (19) goes from 1 to $h_{i,k,T}$.

2.7. Revenues for carbon trading

Estimating the potential revenues of carbon trading requires knowledge of the market carbon price, pc*, and the time period, T. For a given cell, where pc_i<pc* holds, the net revenues of carbon sequestration (π_i) over a period T are,

$$\pi_i = \sum_{t=1}^{T}\left(\mathrm{pc}^* - \mathrm{pc}_i\right)\cdot\left(C_{i,t} - C_{i,t-1}\right)\cdot(1+r)^{-t} \tag{20}$$

where $C_{i,t}$ and $C_{i,t-1}$ denote cumulative carbon levels at year t and $t-1$ in cell "i", including all K

stands. The difference between these two values is the net carbon uptake at year t. In order to solve the above-described model, a MATLAB algorithm is developed.

3. Data

The analysis considers 0.5 degree cells (about 50×50 km depending on latitude) and includes 8 countries that represent more than 90% of the Latin American region (FAO, 2001, 2002). The ecological and economic data used for the analysis are discussed below.

3.1. Land available for plantations

The land available for AR-projects consists mainly of non-forest land where agricultural production is low or unprofitable, since tree plantations can hardly compete on productive agricultural lands with traditional forms of land use. In addition, the UNFCCC and the Kyoto Protocol prescribe that land use change for carbon benefits should not endanger food security. For estimating non-forest areas available for plantations, we used the International Geosphere Biosphere Programme (IGBP) land use classification systems (Belward, 1996; EROS, 2002). This classification uses 17 land classes. From these classes, only three are considered suitable for AR-projects: grasslands, savannas, and open shrub lands that sum up 22% of the total Latin American area.

From the pre-selected land classes we also exclude (i) highly productive land where the indicator of suitability for agricultural is above 50% (Ramankutty et al., 2002; SAGE, 2002), (ii) areas where the population density is over 100 hab/km^2 (CIESIN, 2002), (iii) areas where the net primary productivity of C is below 0.1 kg/m^2/year like in deserts (SAGE, 2002) and (iv) areas where the altitude is above 3500 m, so that the unique Andean ecosystem, Páramo, is kept untouched. Applying the abovementioned constraints, the area available for plantations is reduced to 237 million ha or 13% of the total land area of Latin America. As shown in Table 1, Argentina and Brazil have the largest share of this land.[3]

Table 1
Area suitable for plantations in the major Latin American countries

Country name	Land area (million ha)	Area suitable for plantations (million ha)
Argentina	273	74
Brazil	845	70
Mexico	191	42
Venezuela	88	17
Colombia	104	13
Bolivia	108	9
Chile	75	8
Peru	128	4
Total	1812	237

3.2. Carbon sequestration parameters

Grid data on tree growth are estimated as a function of net primary productivity (NPP), (SAGE, 2002). For converting NPP values to carbon uptake, a factor of 50% is used.[4] This leads to rates of carbon uptake between 0.6 and 6.2 tC/ha/year across the region. These values are comparable with data from Trexler and Haugen (1995) who propose rates of carbon uptake from 0.3 to 1.5 tC/ha/year for the dry tropics and 6 to 12 tC/ha/year for the humid tropics.

Timber volume is proportional to biomass accumulation in the aboveground forest. We consider that 20% of the carbon uptake is in the roots, and the carbon content in the aboveground forest is in the range of 0.3 tC/m^3 for temperate regions and 0.4 tC/m^3 for tropical regions (Nilsson and Schopfhauser, 1995). This leads to a timber/carbon ratio of 2 m^3/tC in the tropics and 2.6 m^3/tC in temperate regions. Rotation intervals are 20 years for the tropics and 30 years for temperate regions (Nilsson and Schopfhauser, 1995). The baseline factors, b_i, described in the previous section are 5% for grassland and 20% for savannahs and open shrublands. This assumption

[3] We assume that 100% of the area within a selected cell would be used for afforestation. But, in practice there would be areas within a selected cell where no tree planting takes place and areas within non-selected cells were tree planting takes place. This type of error could be reduced by using a smaller cell-size when more detailed GIS datasets would be available.

[4] Data from Mexican forests shows that carbon uptake – wood increment, root increment, and fine root production – corresponds to 61% of the NPP (Martinez-Yrizar and Maass, 2001). For our study a more conservative value of 50% is used.

follows the IGBP definition of grasslands and savannahs.

Regarding the parameters for the decay function of forest products, we consider that 50% of the forest biomass is stored in long-lived products with a half-life time of 20 years and the remaining biomass, consisting of short-lived products and timber waste, has a half-life time of 1 year only. Finally, we assume that tree planting in each cell requires 50 years for completion and that planting occurs at a constant rate as in Trexler and Haugen (1995). The assumption of a 50-year period to complete planting in each cell reflects the enormous effort that is required to start large-scale AR-projects in areas where trees have never existed before.

3.3. Prices

As discussed in Section 2, our model considers the price of land as a function of the suitability for agriculture and population density, following a Cobb–Douglas relationship. The level of aggregation for the suitability for agriculture is 0.5 degrees. For the population density, the level of aggregation is 3.5 degrees. This value is selected in order to capture the average population density in a radius of approximately 175 km. If the population density was selected for 0.5 degrees only, a cell that is located just 25 km from a big city could be assigned a low price for the land.

For fitting the parameters of the land price function (A_i), we set minimum and maximum bounds, so that the upper bound corresponds to cells where suitability for agriculture and population density are the highest, and the lower bound corresponds to cells where these indicators are the lowest. In our benchmark scenario, we assign equal weights for both indicators, so that $\alpha_i=\gamma_i$ in Eq. (14), but we test the impact of this assumption with a sensitivity analysis. For Brazil, the higher bound for land prices is set at \$2000/ha which is in agreement with data for sites of good quality in Latin America (de Jong et al., 2000; Olschewski and Benítez, in press). The lower bound is set to \$200/ha. Plantation costs in Brazil are \$800/ha which is within the range provided by Ecosecurities (2002) and Fearnside (1995). Note that Brazil has been chosen as a reference country for prices, given its large potential for carbon sequestration. For estimating land prices and plantation costs in other countries, we correct prices with the price index which is the ratio between the purchasing power parity (PPP) conversion factor and official exchange rate (World Bank, 2001).

Stumpage timber prices across cells are estimated with a similar procedure as for the land price. In the absence of a detailed infrastructure map that allows a precise estimation of transportation costs, we assume that stumpage timber prices are dependent on population density. Taking into account that transportation costs are major determinants of stumpage timber prices, we expect that in areas of high population density, transportation costs will be low since distances to markets are small and infrastructure availability is high. The higher bound for timber price is \$35/m^3, based on an export price of \$50/m^3 (FAO, 2002) and harvesting and transportation costs of \$15/m^3. This price is set for the cells with highest population density. The lower bound for timber price is \$5/m^3 and the values in between are adjusted linearly with population density. Finally, we use a real interest rate of 5%, which is consistent with similar studies in the energy sector (Gritsevskyi and Schrattenholzer, 2003). Given the rough approximation for land and timber prices, an in-depth sensitivity analysis is crucial.

4. Results

4.1. Cost curve for 2012 and 2020

Based on the model and data described in the previous sections, we estimated the Latin American carbon supply for the years 2012 and 2020 considering 2000 as starting year. We consider 2012, since it is the end of the first commitment period of Kyoto and 2020 for providing insights into the post-Kyoto era. As shown in Fig. 1, we find zero-cost options for carbon sequestration at the left-side of the curve (the carbon price appears to be negative), where timber benefits would provide sufficient incentive to convert non-forest land into timber production.

Payments between 0 and 15 \$/tC have a small impact on carbon sequestration. But, starting from \$15/tC, the quantity of carbon sequestered increases rapidly and slows down with carbon prices over

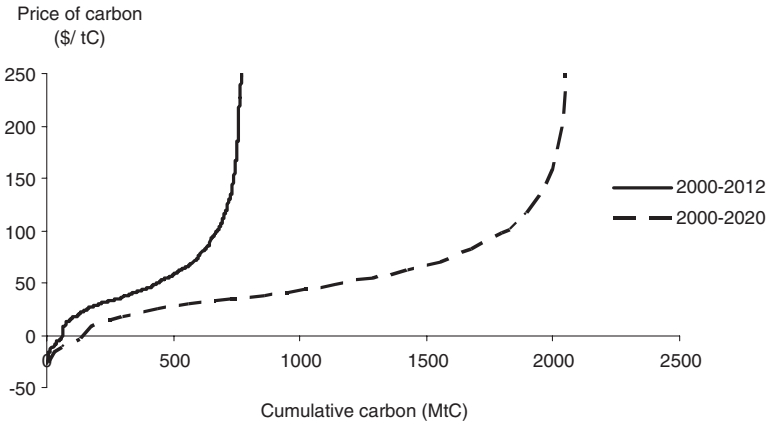

Fig. 1. Supply curve of carbon sequestration through AR-projects in Latin America.

$100/tC, where most of the cells available for AR-projects are already in use. The 2000–2020 curve provides 3 times more carbon sequestration than the 2000–2012 curve, illustrating that more forests have been planted and that trees have taken more time for growing.

4.2. Long-term sequestration potential

Long-term predictions require strong assumptions on future rates of tree growth and prices. If we assume constant prices and exclude effects affecting future net primary productivity, e.g., CO_2 fertilization and soil depletion, we get an impression of the long-term carbon sequestration for the region. Fig. 2 indicates that a carbon price of $20/tC would lead to cumulative sequestration in year 2050 of some 1340 MtC and in year 2100 of some 2100 MtC. By comparison, carbon emissions in the energy sector for Latin America amounted to about 320 MtC in 1997 (Marland and Boden, 2000), which leads to the conclusion that 100 years of carbon sequestration triggered by a carbon price of $20/tC compensate for 6.7 years of current fossil fuel emissions. A higher carbon price of $50/tC will lead to sequestration levels that compensate 23 times the current emissions.

In terms of policy implications, there are no doubts that Latin America could offset a substantial proportion of its emissions by tree planting at low carbon

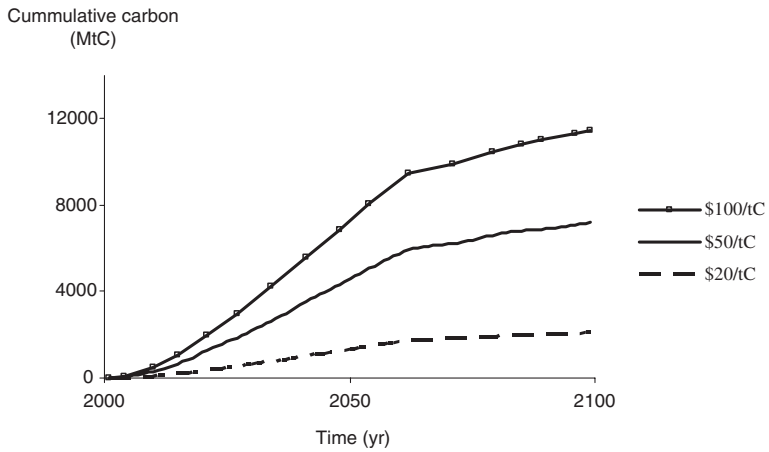

Fig. 2. Time-profile of carbon sequestration through AR-projects in Latin America.

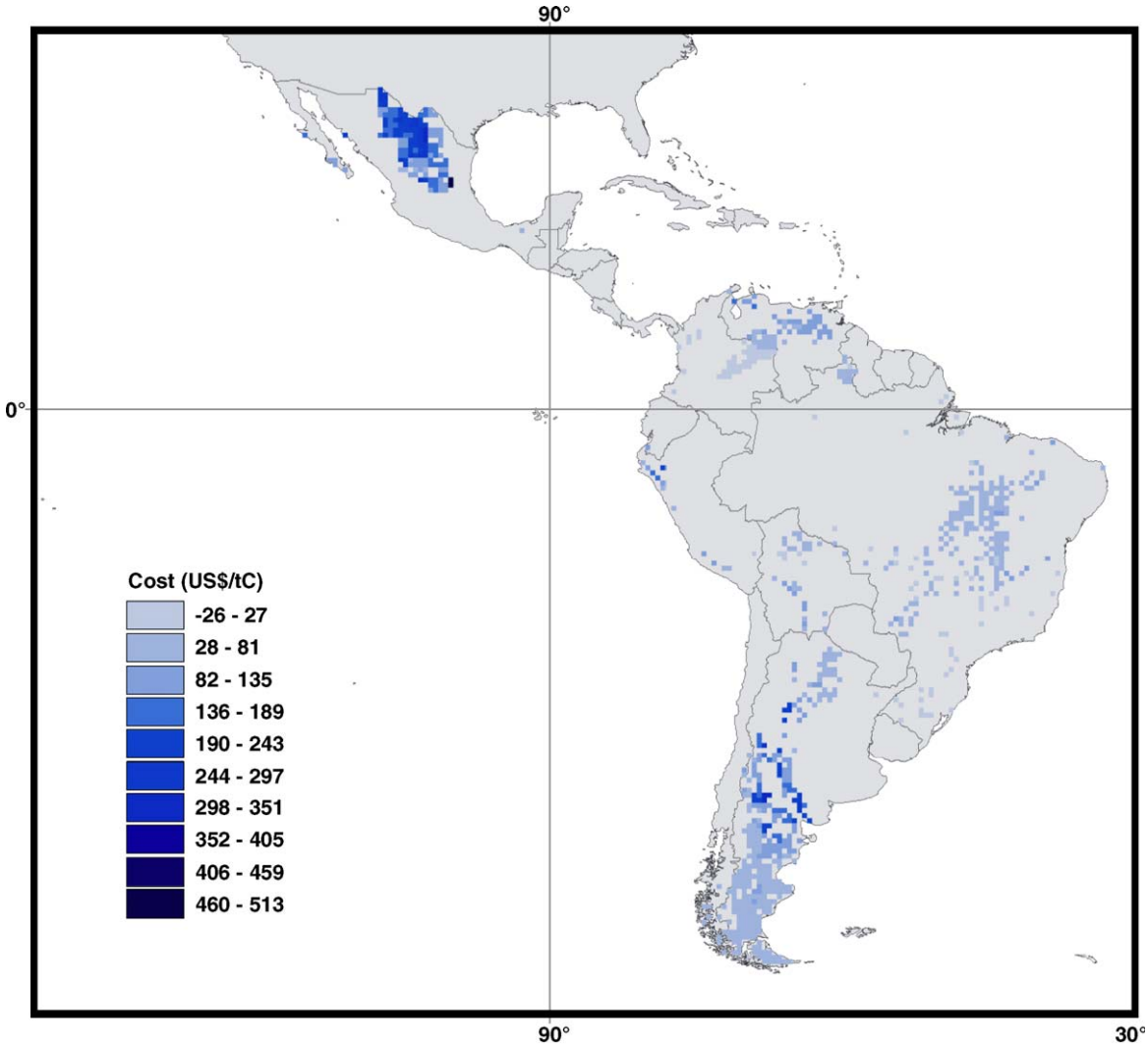

Fig. 3. Geographical distribution of carbon sequestration costs in Latin America. Note: countries with land areas below 500,000 km^2 are excluded.

prices.[5] But, regarding global emissions in a more general context outside the Kyoto agreements, Latin American contribution through AR-projects would still be limited. For example, a 100-year scenario considering a carbon price of $20/tC would only offset 20% of the global emissions of one single year (for 1997, global GHG emissions in the energy sector where 6650 MtC—Marland and Boden, 2000). Therefore, the present methodology should be applied globally, including other relevant regions for carbon sequestration such as Asia, Africa and the Former Soviet Union.

4.3. Geographical distribution of carbon costs

High rates of carbon sequestration and low carbon costs are located mostly in the tropics, particularly Brazil and Colombia (refer to Figs. 3 and 4).

[5] According to Nordhaus and Boyer (2000), 100-year average carbon prices lie between $34/tC and $312/tC depending on the policy scenario. Therefore, $20/tC could be considered low for the long term.

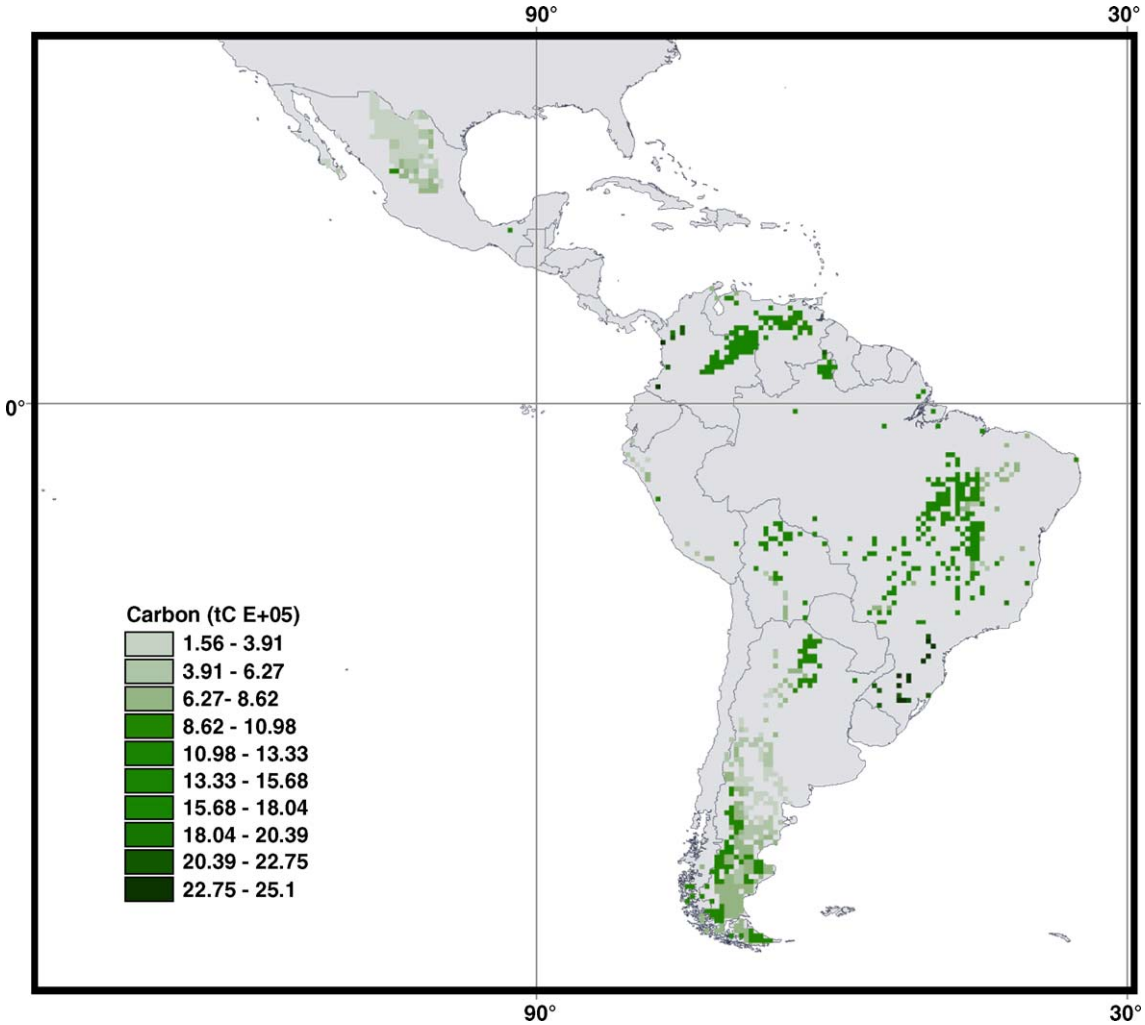

Fig. 4. Cumulative carbon sequestration through afforestation in Latin America between 2000 and 2012. Notes: (1) countries with land areas below 500,000 km^2 are excluded. (2) The map shows the cumulative sequestration for each grid if the carbon price is above its carbon costs shown in Fig. 3.

Temperate regions exhibit relatively higher carbon costs due to lower rates of tree growth. Southern (temperate) Latin America (Argentina and Chile) provides economically more favorable afforestation and reforestation conditions than northern (temperate) Latin America (Mexico) due to the higher NPP. On the basis of these considerations, our country comparison suggests that Brazil, Colombia and Argentina are the most interesting countries for AR-projects. Nevertheless, we should be aware that investors might account for social risks, which might put constraints on the implementation of AR-projects. For example, investors might avoid AR-projects in Colombia due to risks related to conflicts between government and revolutionary armed forces.

4.4. Recent rules for carbon accounting under the CDM

So far, we evaluated carbon uptake benefits in the context of the externalities provided by AR-projects and accounting the full-cycle of carbon in forests and products. Recent decisions on CDM-sinks, however, state that two alternative ways for carbon accounting

should be used instead: temporary crediting (tCER) and long-term crediting (lCER) (UNFCCC, 2003). Both tCER and lCER accounting consider that carbon credits issued from sink projects expire after a given lifetime and carbon sequestration in products should be excluded. tCER differ from lCER on their expiring time: 5 years for the first ones and less than 30 years for the latter (refer to Locatelli and Pedroni 2004 and Olschewski and Benítez (in press) for a detailed discussion on lCER and tCER). In this section, we evaluate the carbon cost curve using tCER accounting and Appendix B provides a detailed description on how to estimate such costs.

As shown in Fig. 5, tCER accounting results on higher costs for carbon sequestration (about 70% higher than in the case of full-cycle accounting) implying that latest agreements regarding CDM-sinks would result in efficiency losses in climate change mitigation. As tCER accounting is only valid for projects in non-Annex-I countries, AR-projects in industrialized countries and economies in transition would have a comparative advantage over projects in developing countries.

4.5. Net revenues of carbon sequestration

For the assessment of net revenues of carbon sequestration and trading, we use Eq. (20). Net benefits are estimated for carbon prices of $10, $20 and $30 per tC, and for the periods 2000–2012 and 2000–2020. This range of prices is consistent with estimates for the carbon price during the first commitment period of Kyoto given by den Elzen and de Moor (2002), Point Carbon (2003) and World Bank (2003). The results are shown in Table 2, indicating the area planted, the total amount of sequestered carbon and the net benefits of carbon sequestration for the two systems of carbon accounting. Under full-cycle accounting, a carbon price of $20/tC would allocate 8 million ha for AR-projects between 2000 and 2020, which corresponds to less than 4% of the suitable area for AR-projects in the region. Emission trading under this price represents net revenues of 2.2 billion dollars in a 20-year period. When the tCER accounting method is used, however, net revenues are reduced by about 20%.

It is worth noting that AR-projects need a detailed baseline assessment that might influence the carbon supply. According to UNFCCC (2003), project developers must select one of the following approaches for baseline assessment: (a) existing or historical changes in carbon stocks; (b) changes in carbon stocks from a land use that represents an economically attractive course of action, taking into account barriers to investment; (c) changes in carbon stocks from the most likely land use at the time the project starts. For Latin America, we found that in 96% of the suitable area for plantations, agriculture is economically more attractive than forestry, which

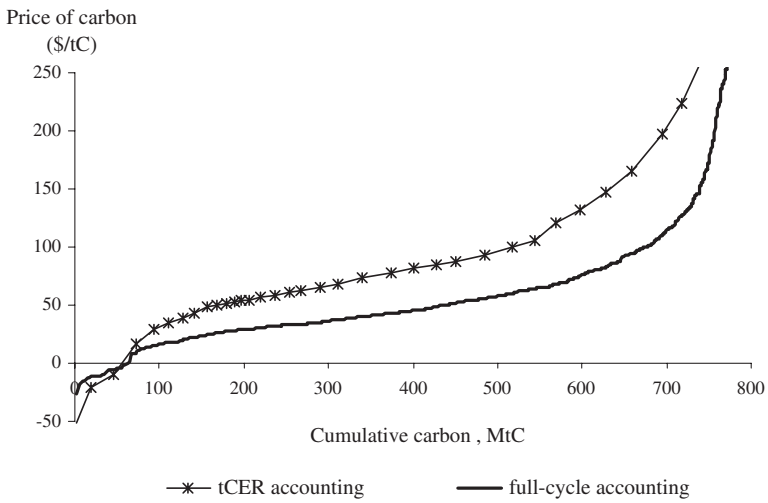

Fig. 5. Carbon supply curve in Latin America using different accounting methods.

Table 2
Net benefits of carbon sequestration in Latin America

Period	Area planted in million hectares			Cumulative carbon (MtC)			Present value net benefits (million US$)		
	$10/tC	$20/tC	$30/tC	$10/tC	$20/tC	$30/tC	$10/tC	$20/tC	$30/tC
Full-cycle accounting									
2000–2012	2.5	4.8	9.1	72	125	213	438	1075	2165
2000–2020	4.1	8.0	15.1	192	337	574	926	2274	4576
COP-9 accounting: tCER									
2000–2012	2.2	2.5	3.3	64	72	93	428	882	1445
2000–2020	3.6	4.1	5.6	173	192	251	906	1866	3055

means that AR-projects in these lands would be additional according to criterion "b". Also, in the remaining area, it is likely that landowners would face barriers to investment in forestry, e.g., there is no access to long-term loans, and non-forest land uses would be preferred. Therefore, we could claim that additionality would have a relatively small impact on the aggregated carbon supply of Latin America.

Table 3
Sensitivity analysis of supply curve of AR-projects in Latin America

	Cumulative carbon sequestration 2000–2012 (MtC)*		
	Carbon price: US$20/tC	Carbon price: US$50/tC	Carbon price: US$100/tC
1. Discount rate			
3%	200	537	714
Main scenario: 5%	125	434	675
8%	54	321	607
2. Land price			
50% Lower for each cell	165	528	722
Main scenario	125	434	675
50% Higher for each cell	95	375	625
3. Land price-production function			
$A_i = v_i \cdot S_i^{\alpha_i} \cdot D_i^{\gamma_i}$			
$\alpha_i = 2\gamma_i$	123	419	656
Main scenario ($\alpha_i = \gamma_i$)	125	434	675
$2\alpha_i = \gamma_i$	135	460	681
4. Timber price			
50% Lower for each cell	72	376	645
Main scenario	125	434	675
50% Higher for each cell	197	489	698
5. Carbon uptake			
25% Lower for each cell	57	204	436
Main scenario	125	434	675
25% Higher for each cell	254	703	907
6. Transaction costs			
Main scenario: 0 (low)	125	434	675
$5/ha/year (medium)	108	413	661
$10/ha/year (high)	95	381	648

* The full-cycle accounting method is used.

4.6. Sensitivity analysis

There is a myriad of uncertainties in the assessment of carbon sequestration with respect to parameter choice and input data. We test the sensitivity for relevant factors like discount rate, land price, timber price and rate of carbon uptake. In testing the sensitivity for land prices, we evaluate our assumption for the Cobb–Douglas function for the land price by changing the relative weight of suitability for agriculture (S) and population density (D), i.e., change the relative ratios between α and γ. In addition, we evaluate transaction costs per hectare resulting from project design and implementation, land-acquisition or land-rent contracts, and carbon monitoring and verification. Experience gained from carbon sequestration projects in India and Costa Rica suggests that the yearly costs of monitoring and verification are between $3 and $5 per hectare (Brown et al., 2000). In Table 3, we show the summary of the sensitivity analysis with respect to these main factors, showing three selected points of the curve for every test.

Three main issues arise from the sensitivity analysis: (i) carbon uptake is the most sensitive parameter because it influences both the carbon sequestration potential and the timber productivity. This implies that more reliable information and models on these parameter is highly important for policy making, (ii) land prices have a lower impact on the supply curve, but it is difficult to have accurate estimates since ultimately, land prices depend on particular preferences, attitudes of landowners and land market policies, and (iii) carbon prices have a strong influence on the sensitivity where the higher the carbon price is, the more robust the sequestration results are.

The sensitivity analysis shows how our results depend on the validity of input data and the choice of parameter values. The results should be regarded as a numerical illustration of the methodology rather than an exact prediction of the expected costs of carbon sequestration.

5. Conclusions

This paper describes a methodology for deriving supply curves of carbon sequestration through AR-projects. The method is based on determining sequestration costs for cells of a homogenous geographical grid. For each cell, spatial information obtained from GIS databases was used for estimating carbon uptake, timber production and land prices. Major advantages of the method are that (i) there is no need to entirely depend on comprehensive data that are often scarce in developing countries, instead, major parameters are estimated indirectly from more general databases and GIS datasets available worldwide, and a consistent method could be applied over a large region. (ii) Results are obtained for each cell, so that maps with the geographical distribution of carbon costs can be elaborated. This facilitates comparison across countries and identification of least-cost regions for carbon sequestration. (iii) Supply curves are estimated for multiple years to support decision making at different stages of the Kyoto process. (iv) Estimation of sequestration costs takes the entire life-cycle of the sequestered carbon into account, including carbon uptake during the growing phase, carbon emissions during harvest, and residual carbon storage in short and long-lived products. Explicit treatment of the full-cycle helps to avoid problems with carbon accounting because it includes both carbon uptake and carbon release in AR-projects.

The model illustration for Latin America suggests that under reasonable assumptions concerning the land and timber price and given a real interest rate of 5% and carbon prices of $20/tC, the potential carbon sequestration by 2012 and 2020 would amount to 125 MtC and 337 MtC, respectively. This would imply afforestation and reforestation of 8 million ha of land by 2020, representing less than 4% of the suitable area for plantations of the region. Given this price scenario and considering full-cycle accounting, net benefits of carbon sequestration for the period 2000–2020 would be approximately US$ 2.3 billion. When the tCER accounting method is used, however, net revenues would be reduced by 20%. Long-term estimates of the cumulative sequestration potential for 100 years suggest that AR-projects could compensate for between 7 and 23 years of current CO_2 emissions by the region's energy sector at costs of between $20/tC and 50/tC. Therefore, there are no doubts that Latin America could offset a substantial proportion of its emissions by tree planting at low carbon prices.

With respect to the geography of supply, as illustrated by our grid map, we find that most least-costs projects are located in tropical Latin America, particularly in areas with high net primary productivity and low land prices (Brazil and Colombia). In addition, temperate Latin America, in particular Argentina, provides large areas suitable for AR-projects. But, due to the lower rate of tree growth, these areas are less favorable than in the tropics.

The demonstrated applicability of the method for Latin American conditions suggests that the model approach can be expanded to global scales. However, there is still a need to improve data quality to reduce uncertainty. In addition, further work should consider risk more explicitly, which in case of forestry is a major determinant for decision making due to the long-term nature of these investments. Another limitation of our study is the exclusion of interactions between AR-projects and energy systems. When forest biomass is used as a source of energy, substitution of fossil fuels could represent significant amounts of emission reductions. Also, when timber products are disposed of in landfills under anaerobic conditions, methane is produced and GHG emissions might increase. These are areas for future research.

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Appendix A

We need to solve,

$$P = \mathrm{pc}\cdot\omega\cdot R\cdot e^{-r\cdot R} - \mathrm{pc}\int_{t=R}^{\infty} W'(t)e^{-\mathrm{rt}}dt$$

We know that,

$$W'(t) = -\phi\cdot\omega\cdot R\cdot k1\cdot e^{-k1(t-R)} - (1-\phi)\omega\cdot k2\cdot R\cdot e^{-k2(t-R)}.$$

Replacing $W'(t)$ in P,

$$P = \mathrm{pc}\cdot\omega\cdot R\cdot e^{-r\cdot R} - \mathrm{pc}\int_{t=R}^{\infty}\phi\cdot\omega\cdot R\cdot k1 e^{-k1(t-R)}e^{-\mathrm{rt}}\mathrm{d}t - \mathrm{pc}\int_{t=R}^{\infty}(1-\phi)\cdot\omega\cdot R\cdot k2 e^{k2(t-R)}e^{-\mathrm{rt}}\mathrm{d}t$$

which equals,

$$P = \mathrm{pc}\cdot\omega\cdot R\cdot e^{-r\cdot R} - \mathrm{pc}\cdot\phi\cdot\omega\cdot R\cdot k1\int_{t=R}^{\infty}e^{-k1(t-R)}e^{-\mathrm{rt}}\mathrm{d}t - \mathrm{pc}\cdot(1-\phi)\cdot\omega\cdot R\cdot k2\int_{t=R}^{\infty}e^{-k2(t-R)}e^{-\mathrm{rt}}\mathrm{d}t.$$

We proceed to solve the following integral,

$$\int_{t=R}^{\infty}e^{-k1(t-R)}e^{-\mathrm{rt}}\mathrm{d}t = \int_{t=R}^{\infty}e^{-k1(t-R)-\mathrm{rt}}\mathrm{d}t = \int_{t=R}^{\infty}e^{(-r-k1)t+k1\cdot R}\mathrm{d}t = 0 - \frac{e^{(-r-k1)R+k1\cdot R}}{-r-k1} = \frac{e^{-r\cdot R}}{r+k1}.$$

Replacing in P leads to

$$P = \mathrm{pc}\cdot\omega\cdot R\cdot e^{-r\cdot R} - \frac{\mathrm{pc}\cdot\phi\cdot\omega\cdot R\cdot k1\cdot e^{-r\cdot R}}{r+k1} - \frac{\mathrm{pc}\cdot(1-\phi)\cdot\omega\cdot R\cdot k2\cdot e^{-r\cdot R}}{r+k2}$$

and finally,

$$P = \mathrm{pc}\cdot\omega\cdot R\cdot e^{-r\cdot R}\left(1 - \frac{\phi k1}{r+k1} - \frac{(1-\phi)k2}{r+k2}\right).$$

This is approximately equal to

$$P = \left(\frac{\mathrm{pc}\cdot\omega\cdot R}{(1+r)^R}\right)\left(1 - \frac{\phi k1}{r+k1} - \frac{(1-\phi)k2}{r+k2}\right).$$

Appendix B

For illustrating the tCER accounting method, we use as an example an AR-project having a rotation of 20 years and linear carbon accumulation of 2 tC/year where the forest owner receives credits for temporary carbon sequestration every 5 years (see Fig. 6). In this case, at year 5, the forest owner

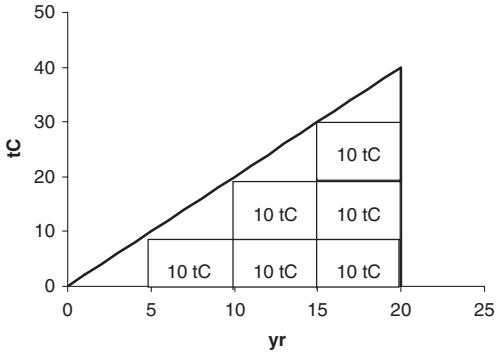

Fig. 6. Example of the tCER accounting method.

receives 10 tC which expire at year 10. These credits are re-issued again in year 10 together with 10 tC corresponding to carbon accumulation between years 5 and 10. At year 15, a total of 30 tC are issued which expire at year 20. Following this rationale, net revenues for temporary carbon sequestration (net to the baseline) are,

$$B_i = (1 - b_i) \sum_{j=1}^{R_i/5-1} \mathrm{pc}^{\mathrm{temp}} \cdot \omega_i \cdot 5j \cdot (1+r)^{-5j}$$

where $\mathrm{pc}^{\mathrm{temp}}$ is the price for a temporary unit of carbon sequestration in \$/tC. By combining this equation with the equations for estimating land prices and forest net revenues (see Section 2), we find the price for a temporary certificate of emission reduction,

$$\mathrm{pc}^{\mathrm{temp}} = \frac{A_i\left[1-(1+r)^{-R_i}\right] + \mathrm{cp}_i - \mathrm{pw}_i \cdot V_i(1+r)^{-R_i}}{5\omega_i(1-b_i)\sum_{j=1}^{R_i/5-1} j(1+r)^{-5j}}.$$

For comparing the results of tCER accounting with the approach of full-cycle accounting developed in this paper, prices for temporary credits need to be converted in equivalent prices for permanent credits. For this, we use the following (Locatelli and Pedroni, 2004),

$$\mathrm{pc}_0^{\mathrm{temp}} = \mathrm{pc}_0 - \frac{\mathrm{pc}_T}{(1+r)^T}$$

where T denotes the expiring time of temporary credits (in our case, 5 years), the index "0" refers to credits bought today and r is the discount rate. If carbon prices are constant over time we have, $\mathrm{pc}_0 = \mathrm{pc}_T = \mathrm{pc}$. Substituting and rearranging the equation for pc, leads to,

$$\mathrm{pc} = \frac{A_i\left[1-(1+r)^{-R_i}\right] + \mathrm{cp}_i - \mathrm{pw}_i \cdot V_i(1+r)^{-R_i}}{5\omega_i(1-b_i)\sum_{j=1}^{R_i/5-1} j(1+r)^{-5j}} \cdot \left(1 - \frac{1}{(1+r)^5}\right)^{-1}.$$

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