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The Economics of Including Carbon Sinks in Climate Change Policy — Evaluating the carbon supply curve through afforestation in Latin America

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Contents

Abstract

After the inclusion of carbon sinks in the Kyoto Protocol, greenhouse gas mitigation policies account for abatement measurements in both the energy and forestry sectors. This report deals with the development of a methodology for estimating cost-curves of carbon sequestration from afforestation activities and its combination with existing cost-curves of carbon abatement in the energy sector, with an application to the Latin American region. For deriving the carbon supply curves, a bottom-up approach is used where the costs of carbon sequestration are first estimated on individual grids (geo-referenced area of 50 × 50 km), which are aggregated in a single cost curve. In evaluating the carbon sequestration benefits of forests, we intend to capture the life-cycle of the sequestered carbon by accounting the carbon uptake during forest growth, the carbon emissions during the harvest periods, and the residual carbon storage in short-and long-lived products.

From a number of model runs we show that (i) the cumulative carbon sequestration by 2010 could amount to about one fourth of the yearly emissions in the region's energy sector, given a carbon price of US$20/tC, (ii) the Latin American region on its own could fulfill the Kyoto Protocol demand on Clean Development Mechanism (CDM) sinks for 2008–2012 at a carbon price of US$26–32/tC, and (iii) when the supply curves of afforestation and energy are combined, the total emission reductions in 2010 are at least 15% larger than in the case of the energy sector alone. Sensitivity analysis shows that long-run projections are very sensitive to forest growth assumptions.

Acknowledgments

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We would like to stress that the data used are preliminary and the results obtained should be regarded as a numerical illustration of the methodology rather than being an exact prediction of the expected costs of carbon sequestration. For the latter a more thorough study would be needed of the land-use data. This report is registered at ECN under project number 7.7513.05.01.

About the Authors

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The Economics of Including Carbon Sinks in Climate Change Policy — Evaluating the carbon supply curve through afforestation in Latin America

Pablo Benítez and Michael Obersteiner

1 Introduction

During the Seventh Conference of the Parties (COP 7) of the United Nations Framework Convention on Climate Change (UNFCCC), held in Marrakesh in 2001, an agreement was reached in order to allow industrialized countries to enhance terrestrial carbon sinks for compliance with their emission caps set under the Kyoto Protocol (UNFCCC, 2001). The enhancement of carbon sinks is based on land use, land-use change and forestry activities (LULUCF) that result in additional carbon storage in the biosphere. The rationale of including carbon sinks in the Kyoto Protocol is that greenhouse gas (GHG) emissions could be offset cheaply and therefore the world could "buy time" until technical changes generate low-cost opportunities for emission abatements in the energy sector. In addition, the establishment of new forests offers opportunities for the replacement of fossil use, either by using biomass as a renewable source of energy or by replacing energy intensive materials in the construction sector (Marland and Schlamadinger, 1999). The Marrakesh agreement states that for compliance in the Kyoto Protocol, Annex I countries[1] could use a wide range of LULUCF activities in their own countries (e.g., afforestation, reforestation, deforestation, re-vegetation, cropland management), and a limited number of LULUCF activities in developing countries (reforestation and afforestation). In addition, the Marrakesh agreement set a cap on Clean Development Mechanism (CDM) sinks for the first commitment period of the Kyoto Protocol that is equivalent to five times 1% of the GHG emissions of Annex I countries in 1990.

The inclusion of carbon sinks in the Kyoto Protocol has important implications for the implementation of carbon abatement policies. The optimal strategy for reducing GHG emissions and complying with the Kyoto Protocol needs to consider the carbon abatement costs in the energy and forestry sectors. When forestry projects are cheap, they will be an alternative to GHG abatement measurements in the energy sector. For designing cost-efficient carbon mitigation policies it is important to develop carbon sequestration supply curves so that they could be compared with existing cost-curves of

[1] Industrialized countries and economies in transition of the Former Soviet Union and Eastern Europe.

carbon mitigation in the energy sector. The regions that have the larger potential for carbon mitigation in forests are located in the Former Soviet Union and in the developing world (Sedjo *et al*., 2001). From these regions, Latin America is of particular interest due to its active participation in implementing carbon sequestration projects (IPCC, 2000) and its land-availability and ecological conditions that favor medium- and large-scale afforestation projects.

The objectives of this study are to:

(1) perform a literature review on the costs and potential of carbon sequestration in developing countries,

(2) develop a methodology for estimating the supply curve of carbon sequestration through afforestation activities and apply this methodology for the Latin American region, and

(3) compare the supply curve of carbon sequestration in Latin America with existing cost-curves of carbon abatement in the energy sector and evaluate the economic gains of including afforestation in carbon mitigation policies.

This report is structured as follows. Section 2 provides a description of the existing methods for estimating the costs of carbon sequestration in forests. Section 3 provides a summary of the literature of the potential and costs of afforestation projects in developing countries. Section 4 presents a standard method for deriving a supply curve of carbon sequestration and shows its application for the Latin American region. Based on this supply curve, the potential and costs of carbon sequestration under the CDM are evaluated. In this section, we estimate the aggregate cost-curve of carbon mitigation in the energy and forestry sectors. Section 5 provides a summary of the major market limitations for implementing afforestation activities and the conclusions are presented in Section 6. A crucial aspect of the research is the sensitivity analysis for the estimated carbon supply curve which is shown in the Appendix.

2 Costs of Carbon Sequestration: A Methodological Overview

2.1 Land-use Economic Models

There are different economic models that are applicable for deriving cost curves of carbon mitigation in the forestry sector. Some of them are based on cost-benefit analysis while others involve more complex routines like timber supply models, equilibrium models and econometric models.

Cost-benefit analysis. The costs of carbon sequestration with afforestation projects could be estimated on the basis of the costs of converting agricultural land into forests (Parks and Hardie, 1995; de Jong *et al*., 2000). In the absence of risk and uncertainty about profits, the owner of a piece of agricultural land will convert the land into forests when the net present value of forestry with payments for carbon sequestration is larger than the net present value of agriculture. Cost-benefit analysis has been widely used for the comparison of existing land-use with alternative options.

Timber supply models. Timber supply models are optimization models of timber markets that predict how forests and plantations are managed and how much timber is produced (Sohngen *et al*., 1999; Sohngen and Sedjo, 2000). These models estimate how the supply of timber and the management of forests will respond today to the predicted prices of timber in the future. Carbon payments could be included in timber supply models by simulating the effect of subsidies for plantation projects, or by assigning a monetary value to the carbon storage in trees. Timber supply models consider that prices are constant when they are applied for a single country or "small" region. When the studied region is large, these models evaluate changes on timber demand as a response of supply. In addition, timber supply models could be limited to plantation projects or could include the timber supply from natural forests.

Equilibrium models. General equilibrium models consider that the prices of inputs (labor) and outputs (timber, agricultural products) are a function of the changes of land use. Equilibrium models could be used for evaluating the impact of taxes and subsidies in the allocation of land in a country or region. Callaway and McCarl (1996) have used general equilibrium models for evaluating the interaction of carbon payments with crop subsidies in the US agricultural sector. Partial equilibrium models are a simplified form of general equilibrium models. They consider that prices are constant in some markets while they are variable in other markets.

Econometric models. An alternative method for estimating the costs of carbon sequestration has been proposed by Stavins (1999) with the so-called revealed-preference approach. This method estimates the marginal costs of carbon sequestration by means of regional econometric analyses on the factors affecting land use. The results of Stavins (1999), based on US data, show that the heterogeneity of land brings sharply increasing marginal costs of carbon sequestration. This means that studies that provide single point estimates of the costs of carbon sequestration or even linear estimates of marginal costs may be very misleading.

2.2 Accounting Carbon Benefits

The methods used for accounting carbon benefits in sequestration projects differ across existing studies (Kolshus, 2001). By 2003, the rules for CDM forestry projects will be set, as well as standard procedures for accounting carbon offsets (UNFCCC, 2001). The Intergovernmental Panel on Climate Change (IPCC) report on LULUCF (IPCC, 2000) provides an extensive discussion on how to quantify carbon offsets in project-based activities. In this section, the following aspects of carbon accounting are briefly discussed: (i) definition of afforestation and reforestation, (ii) baseline and additionality, (iii) carbon offsets in different pools, (iv) discounting carbon benefits, and (v) carbon accounting methods.

During the Eighth Conference of the Parties (COP 8) held in Delhi in 2002, special attention was given to the issue of carbon accounting in sinks under the CDM (IISD, 2002). While different proposals for carbon accounting under the CDM where proposed, the Subsidiary Body for Scientific and Technological Advice (SBSTA) adopted procedural conclusions, calling for a workshop in early 2003 and a further consideration at its next session.

2.2.1 Definition of Afforestation and Reforestation

Afforestation and reforestation both refer to the establishment of trees on non-forested land. Reforestation refers to the establishment of forest on land that had recent tree cover, whereas afforestation refers to land that has not been a forest for a long period of time.[2] For LULUCF activities under Articles 3.3 and 3.4 of the Kyoto Protocol, a forest is considered as a minimum area of land of 0.05–1 hectares with tree crown cover of more than 10–30% (UNFCCC, 2001). Afforestation and reforestation require that forests be established through planting, seeding and/or the human-induced promotion of natural seed sources.

Based on the current definition of afforestation and reforestation, human-induced activities that lead to the regeneration of forests are applicable under the CDM as long as they convert non-forest land into forests. This means that it is not always required to plant trees, but it is enough to promote the regeneration of trees. What might be misleading, however, is how much of tree crown cover is needed for a parcel of land to be treated as a forest. If 10% crown cover is the limit between forest and non-forest, there will be more areas available for afforestation and reforestation than with a limit of 30%. In general, the definition of forest differs among countries. It might be the case that a reforestation project that takes place in a particular country is not applicable for the CDM due to differences in forest and non-forest definitions.

In this research, afforestation and reforestation have the same meaning and we therefore refer to them just as afforestation.

2.2.2 Baseline and Additionality

The baseline corresponds to the expected level of carbon emissions and sequestration in a "business-as-usual scenario" (the scenario without payments for carbon sequestration). Establishing the baseline scenario requires knowledge of historical series of conventional practices in the affected area, the local socioeconomic situation, local and regional economic trends that affect the outputs of a project, and relevant policy factors (IPCC, 2000).

Baseline studies could be done on a project scale by defining the constrained limits of the project area, or at a program scale by evaluating the patterns of land use in an entire region. When baselines are limited to the project area, there is the risk that some changes on carbon stocks, which are caused by the project activity, remain unaccounted (leakage effect).

The carbon offsets that could be traded under the CDM are the "additional" carbon benefits. They correspond to the difference in carbon sequestration between the project and the baseline scenario. If there are changes on carbon stocks in the baseline scenario, they should be subtracted from the carbon benefits of the project scenario.

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[2] More precisely, afforestation is the direct human-induced conversion of land that has not been forested for a period of at least 50 years.

2.2.3 Carbon Pools

A detailed accounting of the impact of forestry projects in the climate system does not consider only the carbon that is stored in vegetation and soils, but also the life cycle of forest products. Marland and Schlamadinger (1999) have developed the GORCAM model that estimates the carbon benefits of forestry activities. This model includes:

- changes of carbon stored in vegetation, plants, litter, and soils,
- carbon storage in wood products,
- reduction of carbon emissions because wood products replace energy-intensive materials like steel or concrete,
- recycling or burning of waste wood, and
- auxiliary fossil fuels used for the production of biofuels and wood products.

Most economic studies of carbon sequestration consider that the carbon uptake in aboveground vegetation represents the larger carbon pool. In addition, the carbon level in aboveground vegetation is estimated via the timber volume. The amount of carbon sequestered in soils, roots, and litter depends on site-specific properties. According to Nilsson and Schopfhauser (1995), the amount of carbon that could be sequestered in the soils and litter of tropical regions account for 10–35% of the carbon sequestered in aboveground vegetation. The amount of carbon that is sequestered in timber products depends on whether the timber is used for paper, sawnwood, board, or firewood. An example of a pine-oak forest in Central Mexico, where 80% of the timber is used for sawnwood, shows that the average carbon storage in timber products is about 30% of the storage in aboveground vegetation (document library of CO_2-fix model in Nabuurs *et al*., 2002; Masera *et al*., 2001a).

2.2.4 Discounting Benefits for Carbon Sequestration

Discounting the benefits of emissions reductions is the subject of controversy. The benefits of abating GHG emissions now are avoided damages caused by global warming in the future. With high discount rates, the present value of future damages is small, so there is little need for reducing emissions now. High discount rates imply that current generations will invest little on reducing damages on future generations. This is an ethical question that is often raised in the discussions of global warming.

When policy makers have already set emission reduction caps and allow for emission trading, the benefit for an individual party to reduce carbon emissions is only the money he receives for his emission reductions. The party that sells the emission reductions treats them the same as the other goods provided by the forest (e.g., timber and fruits). Therefore, carbon benefits need to be discounted with the same discount rate as other goods. The concept of discounting carbon benefits is founded in the economic literature (Stavins, 1999; van Kooten *et al*., 1995; Creedy and Wurzbacher, 2001), although it has been omitted in particular cases (de Jong *et al*., 2000).

2.2.5 Accounting Methods

In this section we describe different methods that have been proposed for accounting carbon offsets in forests. Parties of the UNFCCC will take a decision in this respect by 2003 in COP 9.

Real carbon accounting: consider carbon uptake as benefits and carbon release as costs. This method accounts carbon uptake and carbon release at the time they occur. During the growing phase of the forest there are emission reductions — accounted as benefits. During the harvest phase of a forest there are carbon emissions — accounted as costs. This basic system for accounting carbon has not been used often in the economic analysis of carbon sequestration projects. Among the claims for not using this accounting system is that it might be difficult to *charge* for the carbon costs during harvest. Since harvest periods occur mostly after 2012, the responsibility for the emissions could be with the project developer, forest owner, host country or investor country.

The stock change and average storage method. In the IPCC Special Report on LULUCF (IPCC, 2000), two methods are highlighted for accounting carbon benefits. The first is called the *stock change method* and is applicable when forests are planted only for the purpose of sequestering carbon. In this case, the total carbon benefits of a project equal the difference between the carbon level in the baseline and the project scenario, evaluated at the end of the project.[3] When forests are planted, harvested, and re-planted again, the *average storage method* is used. This method entails averaging the amount of carbon stored in a site over the project time. The use of the *stock chang*e method and the *average carbon storage method* are shown in Figures 1 and 2 for a plantation project where the baseline is zero and only carbon in biomass is accounted. In Figure 1, the forest is never harvested completely and the carbon level is kept at a steady state after 25 years. The total number of credits assigned to the project are estimated by means of the *stock change* method and equals 100 ton/ha. When the plantation is periodically harvested (Figure 2), the *average carbon storage* method is used and the total carbon credits assigned are 45 tC/ha. For both systems, the credits that are granted every year are equivalent to the yearly changes of carbon stocks up to the level of environmental additionality. In the case of *the stock change method*, the credits for carbon sequestration are assigned until the time when the forest reaches a steady state (year 25 in Figure 1). In the case of the *average storage method*, where the forest is periodically harvested, the credits are assigned until the total carbon stock equals the average storage (year 13 in Figure 2). It should be noted that for the second and subsequent rotations, there are no more payments for carbon sequestration. Since most plantation projects are used for timber production, and these are periodically harvested, the *average storage method* is preferred. The major problem of these accounting methods is that releasing carbon does not represent any costs to the owner of the forest. Since credits are granted during the first years of the project, the forest owner will not be responsible for any carbon release after the crediting phase. Therefore, when these accounting systems are used, additional contracts need to be arranged in order to be sure that somebody is responsible for the carbon emissions.

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[3] Assuming that the baseline is constant over time.

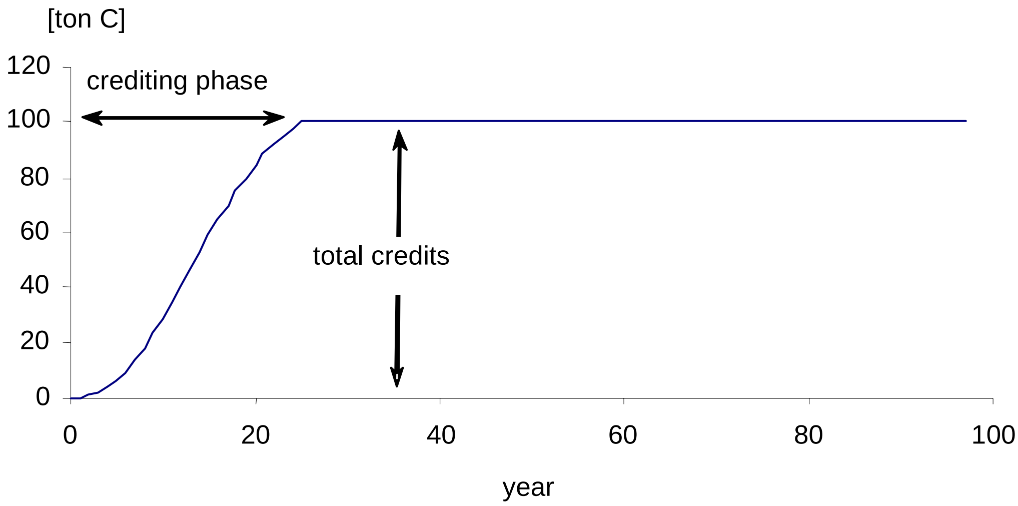

Figure 1: Crediting an afforestation project with the stock change method.

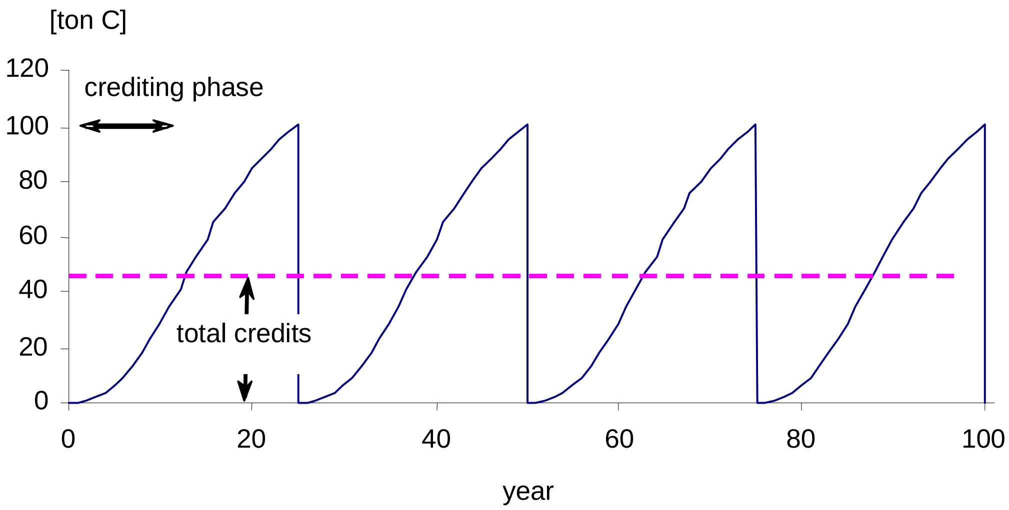

Figure 2: Crediting an afforestation project with the average storage method.

Temporary contracts and renting carbon offsets. This method has been proposed for accounting carbon offsets in short-term projects and is based on temporary contracts where carbon is *leased* or *rented*. This system has been proposed by the Colombian Government and discussed in the scientific environment (Marland *et al*., 2001). Under this system, emission reductions can not be purchased but they are rented for a certain period. Firms that rent forestry certificates of emission reductions (CER) know that after the rental period they should renew the contract or purchase emission reductions from another source. This accounting system is currently under consideration for the treatment of CDM sinks (IISD, 2002). The system of renting carbon offsets is, to some extent, comparable with a system of real carbon accounting. In both systems, harvesting involves carbon costs to the landowner. If we consider the system of renting carbon offsets, the forest owner faces the opportunity costs of not renting the carbon in the future when he harvests the trees. In the system of real carbon accounting, the forest owner must pay for the carbon release when he harvests the trees.

In Table 1, we compare the present value of the carbon benefits of the afforestation project shown in Figure 2 with different accounting systems. In estimating the present value of the carbon benefits, the carbon price is US$20/tC and the project life time is 100 years. As seen in Table 1, there is not much difference among the different accounting systems for this particular case. It can be seen that the carbon benefits decrease with higher discount rates. This implies that when the carbon benefits are not discounted, the benefits of afforestation projects are overestimated.

Table 1: Present value in US$ of carbon benefits in an afforestation project considering different accounting systems.

Method	**Discount rate**		
	3%	**5%**	**8%**
Real carbon accounting (consider carbon uptake as benefits and carbon release as costs)	621	597	511
Average carbon storage	669	568	448
Renting carbon offsets[a]	686	666	579

[a] The rental price per year equals the carbon price times the discount rate.

2.3 Remarks

There are different economic models that are applicable for estimating the costs of carbon sequestration. If the aim is to evaluate the effect of projects and policies that lead to significant changes in the land-use of countries and regions, general equilibrium models are recommended. If the aim is to study the dynamics of tree planting in the medium-and long-term and to evaluate the allocation of land in response of evolving prices of timber and carbon sequestration, timber supply models are suitable. But in the case of the CDM, where there is a limited demand for carbon sink credits for the first commitment period of the Kyoto Protocol so that changes on land-use will be relatively small, cost benefit analysis might provide good approximations.

With respect to the issue of accounting carbon offsets, there are different proposals that provide different values for the carbon benefits of plantation projects. While this needs to be resolved by 2003 in COP 9, the method for accounting and crediting CDM sink projects must account for both carbon uptake and carbon release in forestry projects.

3 Literature Study of Afforestation in Developing Countries

This section consists of a literature review of the costs of carbon sequestration in different world regions. We first focus on the Latin American region in greater detail and then provide a short review of the African and Asian regions.

3.1 Potential and Costs of Carbon Sequestration in Latin America

3.1.1 Land Available for Afforestation

The sequestration potential is defined by the availability of land for afforestation activities and the respective productivity of sequestration of the afforestation activity. The land available for afforestation consists mainly of non-forest land where agricultural production is low or unprofitable, since afforestation projects 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. The estimation of the total area suitable for afforestation is subject to discrepancy since it not only depends on the physical properties of soils, but also on the development of markets and institutions, and the acceptability to convert from traditional forms of land use to forests that maximize carbon sequestration. Another issue that triggers inconsistencies in the estimation of land availability is the fact that the definition of a forest per se depends on the extent of tree cover. Analysis of a number of land-cover maps and publically available land-use databases show that differences in global forest cover may deviate by some 30% from the average estimation.

Nilsson and Schopfhauser (1995) have estimated that the land suitable for plantations in tropical Latin America is about 535 million hectares. They point out that the area available for plantations could be much smaller than what is available, due to market and institutional constraints. Therefore, they suggest more conservative estimates of 40.8 million hectares for tropical Latin America and 4.6 million hectares for temperate Latin America. Trexler and Haugen (1995) estimate that the total area for plantations in tropical Latin America is 25 million hectares and the total area for the regeneration of forests is 130 million hectares. It should be noted that regeneration of forests could be either natural growth of forests on non-forested land or the continuation of growth of existing young forests. The latter is not an applicable activity of land-use change under the definition of afforestation and reforestation and therefore not part of the CDM.[4] Niles *et al*. (2001) consider that between 2003 and 2012, up to 17 million hectares could be reforested in tropical Latin America and Sathaye *et al*. (2001) estimate an area of 27 and 12 million hectares for Brazil and Mexico, respectively, during a period of 30 years. The summary of the land available for plantations in Latin America is shown in Table 2.

From Table 2 it can be concluded that the country with the largest area for afforestation projects is Brazil, followed by Argentina and Mexico. Other regions, such as the Andean countries,[5] might also provide an important contribution to forestation projects. According to Trexler and Haugen (1995), the potential area for plantations and regeneration in the Andean countries represents 55% of the potential in Brazil. The Central American region, which has been very active in the implementation of forestry sequestration projects, has less potential area for these activities: 13% of the Brazilian potential.

[4] The authors do not distinguish regeneration in non-forest land from regeneration in forest land.
[5] Venezuela, Colombia, Ecuador, Peru and Bolivia.

Table 2: Land available for afforestation in Latin America (literature review).

Region/Country	Land available (million hectares)	Reference
Tropical Latin America	535 (suitable area) 40.8 (available area)	Nilsson and Schopfhauser (1995)
Temperate Latin America	4.6	
Tropical Latin America	17	Niles *et al*. (2001)
Tropical Latin America	25 (plantations) 130 (regeneration)	Trexler and Haugen (1995)
Brazil Mexico	26.6 12.1	Sathaye *et al*. (2001)
Mexico Venezuela	10.8 4.9	Kauppi and Sedjo (2001)
Argentina	17.3	Sedjo and Ley (1995)
Chile	5.1	Mosnaim (2001)
Venezuela	0-93–4.9	Pereira *et al*. (1997)

The amount of carbon that could be sequestered in a parcel of land depends on ecological factors such as soil quality, precipitation, and temperature, as well as the way in which the forest is managed such as tree species selection, rotation interval, plantation density, and end-use of timber products (Sohngen and Sedjo, 2000). General estimates of carbon uptake in plantation projects are between 50 and 200 tC/ha (Nilsson and Schopfhauser, 1995; Trexler and Haugen, 1995; Winjum *et al*., 1993). These levels of carbon uptake per hectare could be achieved both in tropical and temperate areas, with the difference that the growth rate in temperate areas is slower than in the tropics (Nilsson and Schopfhauser, 1995).

3.1.2 Carbon Sequestration Costs

Current studies of carbon sequestration in Latin America acknowledge the low cost of forestry-based carbon emission reductions. There are several differences, however, on the methods used for estimating these costs. Some of these are (for a comparison see Table 3):

- *Carbon pools.* The biomass or vegetation pool is included in all studies as it is the most relevant. The carbon storage in soils and products has been included in a quarter of the studies. The inclusion of these pools represents lower costs of carbon sequestration as there is more carbon uptake per unit of land. The carbon uptake in soils and products represents about 20–70% of the carbon uptake in biomass. In terms of economic value, however, this ratio is less since carbon accumulation in these pools occurs later in time than in biomass (see the example of a pine-oak forest in the document library of CO_2-fix model, Nabuurs *et al*., 2002; Masera *et al*., 2001a).

- *Accounting method for carbon benefits.* As shown in Table 3, the most used method for accounting carbon benefits is the average storage method. With respect to discounting carbon benefits, most studies do not discount. This means that the estimated costs of carbon are lower than when carbon benefits are discounted.

Table 3: Point estimates of the costs of carbon mitigation with afforestation projects in Latin America.

Country or Region	Cost (US$/tC)	Carbon pools	Including opportunity costs of land	Include timber benefits	Discount carbon benefits	Reference
Argentina	20	B	Y	Y	Y	Sedjo (1999)
Argentina	6–22	B, P	N	N	N	Sedjo and Ley (1995)
Argentina Brazil	16 4–41	B	N	N	N	Dixon *et al*. (1994)
Argentina Brazil Mexico	18–31 10 4	B B B	N	N	N	Winjum *et al*. (1993)
Argentina Central America Brazil Mexico	31 4 10 4–11	B B B, S B, S	N	N	N	Brown *et al*. (1996)
Brazil	0	B, S, P	N	Y	Y	Fearnside (1995)
Brazil Mexico	0 0	B, S, P	Y	Y	N	Sathaye *et al*. (2001)
Brazil Mexico Venezuela	0–1.4 5–7 17	n/a	n/a	n/a	n/a	Kauppi and Sedjo (2001)
Chile[a]	5–223	n/a	n/a	n/a	N/a	Mosnaim (2001)
Costa Rica	10	n/a	n/a	n/a	N/a	Moura-Costa and Stuart (1998)
Costa Rica	5	B	N	N	N	UNFCCC (1999a)
Ecuador	8	B	Y	Y	Y	Benítez *et al*. (2001)[b]
Mexico	10–35	B, S, P	Y	N	N	Masera *et al*. (2001b)
Mexico	10	B, S, P	n/a	n/a	N	IPCC (2000)
Mexico	10–40	B, S	Y	Y	N	de Jong *et al*. (2000)
Mexico	9	B, S, P	Y	Y	N	UNFCCC (1999b)
Mexico	7	B, P	N	y	N	Masera *et al*. (1997)
Mexico	7	B, P	N	Y	N	Masera *et al*. (1995)
Mexico Venezuela	24 25	n/a	n/a	n/a	N	USCSP (1999)
Mexico	5–11	n/a	n/a	n/a	N	Kolshus (2001)
Venezuela	17	n/a	n/a	n/a	n/a	Pereira *et al*. (1997)

[a] Provides marginal cost curve for the entire region.
[b] Estimated with a discount rate of 7%.
Abbreviations: B = Biomass; S = Soils; P= Products; Y = Yes; N = No; n/a = not available.

- *Including relevant cost and benefits of projects.* It is often found in the literature that the costs of carbon sequestration correspond to the initial costs of planting trees, excluding the opportunity costs of land and the timber benefits of projects (Winjum *et al*., 1993; Dixon *et al*., 1994; Brown *et al*., 1996). This causes a large bias in the estimated price of carbon and limits the comparison between studies.

The difference in the costs of carbon sequestration across countries is not large. Based on existing literature, it seems that in Brazil, there are some zero-cost options (or no-regret), which means that converting agricultural land into forestry is profitable without carbon payments. In Mexico, the costs of sequestering carbon ranges from zero to US$40/tC. The studies in Mexico suggest that both industrial plantations and restoration plantations are cost-efficient options for sequestering carbon. The costs of carbon sequestration in Argentina seem to be slightly higher than in Brazil and Mexico. However, there have been public policies in Argentina aimed at supporting plantation projects with subsidies (Sedjo and Ley, 1995). This means that there is governmental support and there are institutions capable of managing CDM funds. The costs of carbon sequestration in Central America and in the Andean countries are comparable with the average in Latin America. In these regions, there are already some carbon sequestration projects going on, such as the forest protection and reforestation program in Costa Rica (Moura-Costa and Stuart, 1998) and the Profafor-FACE project in Ecuador (Verweij and Emmer, 1998).

The existence of no-regret options, where the establishment of forests is profitable without carbon payments, raises the problem of additionality. It is clear that there are market and institutional barriers that prevent the initiation of afforestation projects. But it is also clear that there are some afforestation projects going on, in the absence of carbon payments. For example, in Brazil there have been 135,000 hectares of trees planted each year (FAO, 2001). Therefore, for the real implementation of *industrial* plantation projects under the CDM, it might be necessary to examine the baseline and additionality with particular attention, which could significantly change the economics of the projects.

3.2 Potential and Costs of Carbon Sequestration in Asia and Africa

In this section, we provide a brief summary of the potential and costs of carbon sequestration in Asia and Africa on the basis of studies found in the literature. We first review the land availability for plantations and later the costs of carbon sequestration in these regions.

3.2.1 Land Available for Afforestation

According to Nilsson and Schopfhauser (1995) the area suitable for plantations in Asia and Africa is about 1,000 million hectares. As in the case of Latin America, the area that is available for plantations is just a fraction of that, namely 166 million hectares. Whereby 80% of this amount is located in Asia and the rest in Africa. In the Asian continent, most of the available land is in the temperate regions and China, while in Africa most of the available land is in the tropics (Figure 3). If we compare these values with Latin America, we find that the land available for plantations in Asia and Africa together is 3.7 times larger than in Latin America.

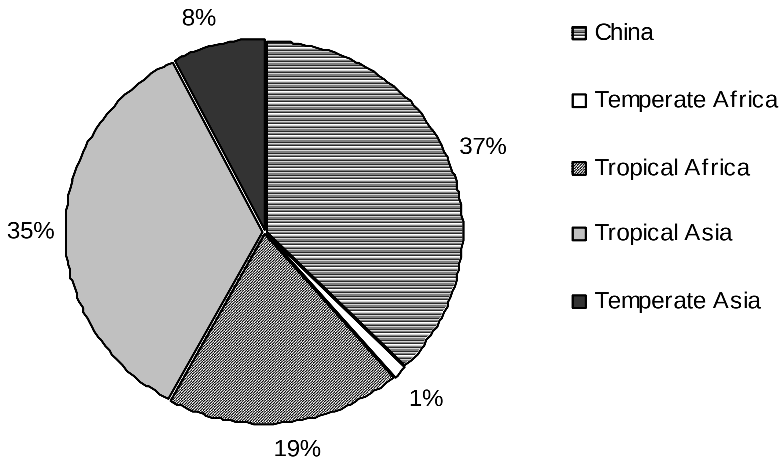

Figure 3: Land available for plantations in Asia and Africa. Source: Nilsson and Schopfhauser (1995).

We should be aware that the potential for carbon sequestration not only depends on the land available for plantations but also on how fast the trees grow. It is generally acknowledged that trees grow faster in the tropics than in the temperate and boreal zones. Following Brown *et al*. (1996), the mean annual increment (MAI) of plantations in tropical Asia and Africa is about five times larger than in China.[6] This means that for reaching a certain sequestration target in 2010, we will need five times more land in China than in tropical Asia or Africa.

3.2.2 Carbon Sequestration Costs

Most of the economic studies that refer to the costs of carbon sequestration in Asia and Africa are based on single point estimates. Generally, the costs of carbon sequestration in these regions are between 0 and US$15/tC, similar to the Latin American case. Table 4 shows a summary of the carbon sequestration costs in selected countries of Asia and Africa.

Table 4: Costs of carbon sequestration in Asia and Africa.

Country	Practice	Cost (US$/tC)	Reference
China	Reforestation	10	Winjum *et al*. (1993)
China	Plantations	0–2	Xu (1995)
India	Reforestation	15	Winjum *et al*. (1993)
India	Plantations	0–1.1	Kolshus (2001)
Malaysia	Reforestation	5	Winjum *et al*. (1993)
Indonesia	Plantations	0–1	Sathaye *et al*. (2001)
Tanzania	Plantations	0-3	Sathaye *et al*. (2001)
South Africa	Reforestation	9	Winjum *et al*. (1993)

[6] The MAI measures the timber productivity (m^3/ha/yr). The yearly rate of carbon uptake is proportional to the MAI.

3.3 Remarks

The literature study shows that there are significant methodological differences on estimating the cost of carbon sequestration across the different studies. Therefore, we should be careful about comparing costs from one region to another. These methodological differences suggest the use of a uniform method for aggregating information from different countries and regions so that a supply curve of carbon sequestration could be obtained.

Let us briefly compare the costs of carbon mitigation in developing countries, with the expected price of carbon permits under the Kyoto Protocol taking up a specific study. According to den Elzen and de Moor (2001), the equilibrium carbon price for the first commitment period will be between US$15/tC and US$30/tC. This price is higher than most of the carbon sequestration options in Latin America, Asia and Africa. Also at lower prices, the potential supply is still significant according to our review and own calculations. Thus, one could expect considerable economic gains by including carbon sinks in the CDM mechanism without a cap in the Kyoto Protocol.

4 Estimating the Carbon Supply Curve in Latin America

In this section we develop a methodology for deriving supply curves of carbon sequestration with afforestation activities and use this method for estimating the supply curve in Latin America. Section 4.1 describes the method and Section 4.2 describes the data for Latin America. In Section 4.3 we present the results that include the evaluation of the potential carbon sequestration for the first commitment period of the Kyoto Protocol and the comparison of cost curves in the forestry and energy sectors.

4.1 Methodology

4.1.1 Outline

As stated in Section 2, there are different land-use economic models that are applicable for deriving cost curves of carbon sequestration in forests. Some of these models are based on cost-benefit analysis (Parks and Hardie, 1995) while others involve more complex routines like timber supply models (Sohngen *et al*., 1999; Sohngen and Sedjo, 2000), equilibrium models (Callaway and McCarl, 1996) and econometric models (Stavins, 1999). The scale that is used in a model is relevant. Some models take countries and regions as a single unit, while others divide countries and regions in grid-cells of a geographically explicit location (see spatially explicit models in, de Koning *et al*., 1999).

For the purpose of this study, general and partial equilibrium models are not used because we consider that the conversion of the less-productive agricultural areas into forests will have a small impact in the prices of agricultural products. Using econometric models for estimating the land-use choice of private landowners, as in Stavins (1999), requires credible and uniform time series of land-use, which are hard to find in the studied region. What is of major interest in this research is to study how the heterogeneity on land attributes, such as suitability for agriculture, net primary productivity and population density, influence the costs of carbon sequestration across the Latin American region. Consequently, we develop a methodology for estimating the costs of carbon sequestration at a disaggregated level of geographically explicit grid-cells.

In order to derive a supply curve of carbon sequestration, three major aspects are needed (see Figure 4). First, we need to know how much area is available for afforestation and reforestation in each country. For this purpose we use Geographical Information System (GIS) databases on land-use. This information is obtained at the grid level (0.5 degree grids which size is about 50 × 50 km depending on latitude). Second, we estimate how much carbon could be sequestered in each grid. This depends principally on the net primary productivity (NPP) that is obtained at a grid-level from GIS databases. Third, we estimate what the costs of carbon sequestration are for each cell. We consider that the costs of carbon sequestration are equal to the *break-even price of carbon* under which keeping the land for agricultural purposes (non-forest) provides the same rent as using the land for growing trees. Some of the variables that are needed for the economic analysis are obtained from secondary sources while other variables, like the price of land, are computed for each grid as a function of known parameters (e.g., population density and suitability for agriculture). By sorting the costs in ascendant order and aggregating the results of all cells, the carbon-sequestration supply curve is obtained. For estimating the costs of carbon sequestration for each grid and aggregating the information, a simulation model is developed.

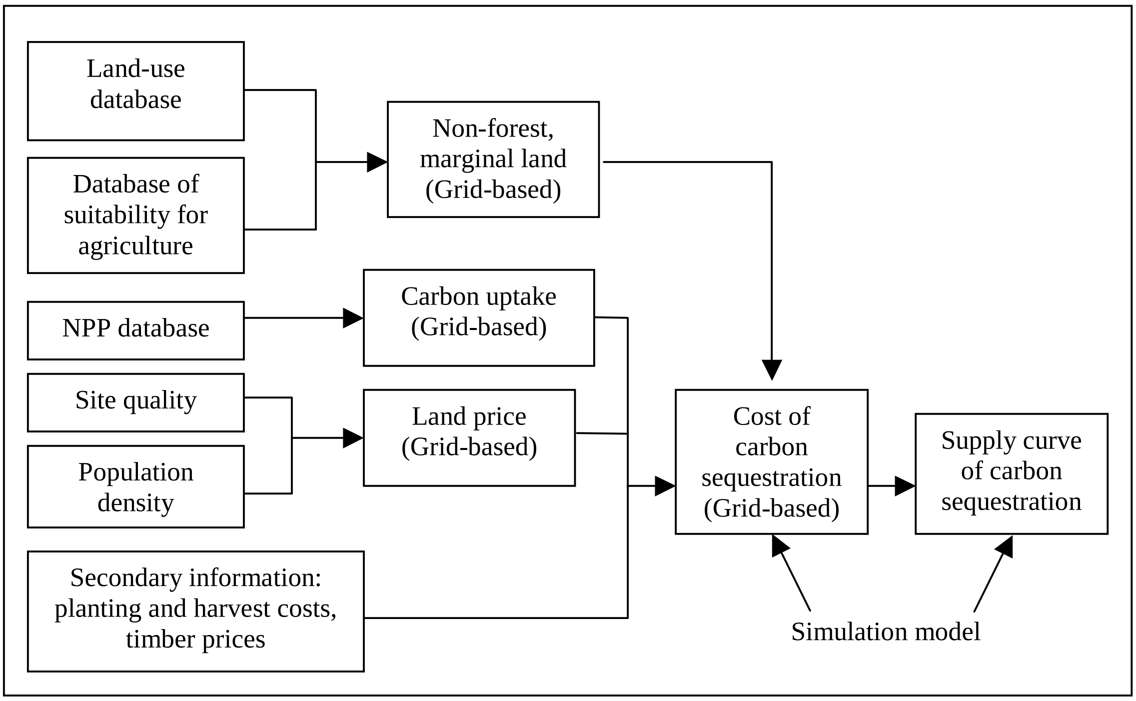

Figure 4: Methodological overview.

4.1.2 Grid-based Simulation Model

If the grid cells are sufficiently small, we could assume that the land quality, land price, accessibility and carbon sequestration potential are constant for each grid. Thus, the costs of carbon sequestration will be constant for each grid. Based on this and in order to derive the supply curve of carbon sequestration, we use an iterative process that computes the costs of carbon sequestration and the quantity of carbon sequestered for each individual grid. Then, we sort the costs in ascendant order and aggregate costs and quantity of carbon sequestration in a single supply curve.

The model is written in Visual Basic/Excel and the input data is entered through a worksheet. Some of the calculations are done in the worksheet itself and other calculations, which need an iterative process, are done by using Visual Basic. In the following section we describe first how the costs of carbon sequestration are estimated for each grid and then how to estimate the quantity of carbon sequestered at different times.

Economic analysis

The aim of the economic analysis is to determine the costs of carbon sequestration for each grid. For simplicity, we assume that the prices of inputs and outputs are constant in time. From the definition of *break-even price of carbon*, the cost of carbon sequestration are the ones that allow forestry to be as profitable as agriculture. This means that the net present value of forestry, Π^F, is the same as the net present value of agriculture, Π^A:

$$\Pi^F = \Pi^A . \tag{1}$$

These present values are estimated for a long period of multiple rotation intervals. Before we solve the problem for multiple rotations, we first look at the problem of one rotation interval.

We denote the present value of forestry for one rotation interval with small caps, π^f. In accounting the net present value of forestry, we include plantation and harvest costs, timber benefits, and carbon sequestration benefits.[7] For one rotation interval, the net present value of forestry is:

$$\pi^f = -Cp + \frac{(Pw\text{-}Ch) \cdot V}{(1+r)^R} + CB \tag{2}$$

where *Cp* are the planting costs, *Pw* is the timber price, *Ch* are the harvest cost per unit of timber, *r* is the discount rate, *CB* is the present value of the carbon benefits, and *V* is the volume of timber at the end of the rotation interval, *R*. The rotation interval is considered exogenous in the model so that independently of the price of timber, price of carbon and discount rate, the time between planting and harvesting is the same.[8]

[7] In reality, forests provide other benefits such as water and soil protection, recreational benefits, and biodiversity conservation. These ancillary benefits could easily be included in the analysis when data is available.
[8] See van Kooten *et al*. (1995) for carbon supply curves where the rotation interval is endogenous.

Forestry projects sequester carbon in different pools such as biomass, soils and products (IPCC, 2000). Accounting for the carbon in biomass and products requires knowledge of the NPP or the timber productivity in each grid, and the end-use of timber products. The carbon uptake in soils is dependent on a range of factors that include biomass growth rate, environmental conditions, forest intervention (harvest, thinning) and a history of the land (IPCC, 2000; de Koning *et al*., 2002). Dealing with the complexity of soil carbon sequestration is beyond the purpose of this study, and we only consider biomass and products. In accounting the net carbon sequestration benefits we consider that carbon benefits occur during the growing phase of the forest and carbon costs occur during the harvest period where carbon is released to the atmosphere. The carbon benefits in an afforestation project are the ones that provide additional carbon storage in the biosphere as compared with the original land-use. This requires subtracting the carbon level in the so-called baseline of the project (IPCC, 2000). We consider the carbon level in the baseline as a carbon cost and it is denoted by ϕ. By denoting CB^b and CB^w, the present value of the carbon benefits in the biomass and products respectively, the total carbon benefits are:

$$CB = CB^b + CB^w - \phi . \tag{3}$$

Carbon uptake in the biomass

The biomass pool refers to the carbon stored in live-vegetation. It includes the different tree compartments such as stem, branches, leaves and roots. We consider linear tree growth where the average carbon uptake per year, σ, is constant. At the end of the rotation interval, the amount of carbon that has been sequestered during the growing phase is released from the biomass pool. If the price of carbon, Pc, is constant in time and the carbon revenues are paid at the end of each period, we have:

$$CB^b = \text{carbon revenues during growing phase} - \text{carbon cost during harvest}, \tag{4}$$

$$CB^b = Pc \cdot \left(\sum_{t=1}^{R} \frac{\sigma}{(1+r)^t} \right) - Pc \cdot \frac{\sigma \cdot R}{(1+r)^R} , \tag{5}$$

$$CB^b = Pc \cdot \sigma \cdot \left(\frac{1-(1+r)^{-R}}{r} - \frac{R}{(1+r)^R} \right) . \tag{6}$$

Equation (6) shows that the carbon benefits in the biomass are proportional to the carbon price and the yearly carbon uptake. In addition, they increase with long rotation intervals but decrease with the discount rate. If the discount rate is zero, the carbon benefits for one rotation interval are zero simply because the quantity that is sequestered in the forest is the same as the quantity that is released during harvest. However, since we have positive discount rates, the forest owner could earn money by storing carbon for a limited period of time, even if there are not net carbon emission reductions. This concept of temporary carbon sequestration in forests has lead to a discussion in the UNFCCC about issuing emission reduction certificates with temporary validity under the CDM (IISD, 2002).

Carbon uptake in products

After each harvest period, the carbon is released from the biomass pool and stored in the products pool. We consider two types of products, namely (i) long-lived products that consist of timber materials such as furniture and paper, and (ii) short-lived products that consist of the remaining biomass such as roots, leaves, branches, and timber wastes that decompose inside or outside the forest after the harvest take place. The carbon stored in products is released to the atmosphere following an exponential decay function (Sohngen and Sedjo, 2000). We use this function for both the short- and long-lived products.

The exponential decay function requires two parameters. The first is the initial carbon storage in products, just after the harvest period. For long-lived products this value depends on how much timber is harvested and how efficient the conversion is of raw timber into elaborated products. If we denote *fp* as the fraction of the biomass that is later stored in long-lived products, the initial carbon storage equals $fp \cdot \sigma \cdot R$. For short-lived products, the initial carbon storage is, $(1-fp) \cdot \sigma \cdot R$. The second parameter of the exponential decay function is the decay rate. We denote $k1$ and $k2$ as the decay rate in long- and short-lived products, respectively. Following the exponential decay model, the cumulative carbon in products, $C^{w}_{(t')}$, at a time t' after the forest has been harvested is:

$$C^{w}_{(t')} = fp \cdot \sigma \cdot R \cdot e^{-k1 \cdot t'} + (1 - fp) \cdot \sigma \cdot R \cdot e^{-k2 \cdot t'} \ . \tag{7}$$

The first term of equation 7 represents the carbon storage in long-lived products of decay rate $k1$, and the second term represents the carbon storage in short-lived products of decay rate $k2$. The decay rate is estimated on the basis of the half-life time of timber products ($t_{1/2}$) by means of the following relationship:

$$k = \ln(2)/t_{1/2} \ . \tag{8}$$

The carbon uptake/release of each year is estimated by subtracting the storage value of consecutive years or by taking the derivative of equation (7). The net carbon benefits in the products are equivalent to the carbon uptake in products during harvest minus the carbon released afterwards. If we first compute the present value of the carbon storage in products at the time of harvest, $CB^{w}_{(R)}$, and we discount in continuous time, we have:

$$CB^{w}_{(R)} = Pc \cdot \sigma \cdot R - \int_{t=0}^{\infty} Pc \cdot fp \cdot \sigma \cdot R \cdot k1 \cdot e^{-k1 \cdot t} \cdot e^{-r \cdot t} dt - \int_{t=0}^{\infty} Pc \cdot (1 - fp) \cdot \sigma \cdot R \cdot k2 \cdot e^{-k2 \cdot t} \cdot e^{-r \cdot t} dt \ . \tag{9}$$

The first term of equation (9) represents the initial carbon benefits in products just after harvest. The second term represents the carbon costs caused by the slow decomposition of the carbon stored in long-lived products and the last term represents the carbon costs caused by the fast decomposition of short-lived products. By solving equation (9) we obtain:

$$CB^{w}_{(R)} = Pc \cdot \sigma \cdot R \cdot \left(1 - \frac{k1 \cdot fp}{k1 + r} - \frac{k2 \cdot (1 - fp)}{k2 + r}\right) , \tag{10}$$

or

$$CB^{w}{}_{(R)} = Pc \cdot \sigma \cdot R \cdot \beta \qquad (11)$$

$$\beta = 1 - \frac{k1 \cdot fp}{k1 + r} - \frac{k2 \cdot (1 - fp)}{k2 + r} \ . \qquad (12)$$

Finally, we should estimate the present value of carbon benefits in products at time zero instead of time *R*,

$$CB^{w} = \frac{Pc \cdot \sigma \cdot R \cdot \beta}{(1+r)^{R}} \ . \qquad (13)$$

In accounting the carbon costs in the baseline, we consider that they represent a fraction of the total carbon benefits in the forest. The baseline determination requires knowledge about the expected land-use and carbon level of each grid in the business-as-usual scenario. We expect that in the business-as-usual scenario, there will be some patches of forests that, in the absence of carbon payments, will be planted and harvested anyway. In addition, there will be other types of vegetation, like shrubs and grass, which will continuously grow, be harvested (or burned) and grow again. The carbon costs in the baseline are estimated as a fraction *fb* times the carbon benefits in the forests. By integrating the carbon benefits in biomass and products, and carbon costs in the baseline we obtain:

$$CB \ = Pc \cdot \sigma \cdot (1 - fb) \cdot \left(\frac{1 - (1+r)^{-R}}{r} - \frac{(1-\beta) \cdot R}{(1+r)^{R}} \right) \ . \qquad (14)$$

Based on equations (2) and (14) we find the net present value of forestry for one rotation interval to be π^{f}. With π^{f}, we estimate the net present value of forestry for an infinite number of rotations (Π^{F}). When prices remain constant over time, we have:

$$\Pi^{F} = \frac{\pi^{f}}{1 - (1+r)^{-R}} \ . \qquad (15)$$

The value of agricultural land

The value of land (Π^{A}) could theoretically be considered as the discounted net benefits obtained from agricultural activities during an infinite time period. There are different methods in which the value of agricultural land could be estimated, namely (i) direct estimation based on the costs and benefits of agricultural production, (ii) use the market prices of land, and (iii) obtain a conjecture of the value of land using GIS parameters.

(i) If the data on costs and benefits of agricultural land is known, the net present value of agriculture could be estimated directly. Unfortunately, there are several problems with this method. First, there is little information on the current rent of agricultural activities for each grid. Second, the current rent of agricultural activities could be too low as in the case that the optimal crop has not been used or when the crop management system is not appropriate. And third, current agricultural revenues do not reflect losses of soil fertility (lower output in the future) and technological change (higher output in the future).

(ii) The information on land prices does not always represent the real value of the land. This occurs when there are market imperfections, speculation, and transaction costs. From a financial point of view, however, it is appropriate to use the price of land for estimating project returns. As in the case of estimating the costs and benefits of agriculture, there is little information available on land prices.

(iii) The third option for estimating the value of land is to take into account known parameters. We assume that the value of land depends on two factors. The first is denoted as site quality or suitability of the land for agricultural use, (*S*), and it incorporates land properties and environmental conditions. The second factor is the population density, (*D*), and represents the infrastructure that surrounds the land (more populated areas have more roads and railroads) and the accessibility to markets in order to sell agricultural products. Considering a Cobb-Douglas production function we could estimate the value of land, (*L*), as follows:

$$\Pi^{A} = K \cdot S^{\alpha} \cdot D^{\gamma} \ . \qquad (16)$$

The constant *K* is dependent on country-specific characteristics. In general, it will be related to the Gross Domestic Product (GDP) per capita, which is higher in the richer countries.

Costs of carbon sequestration

By replacing the correspondent terms of equations (15) and (16) in equation (1), the price of carbon, *Pc*, that causes the landowner to be indifferent between agriculture and forestry is derived,

$$Pc = \frac{\left[K \cdot S^{\alpha} \cdot D^{\gamma} - \dfrac{K \cdot S^{\alpha} \cdot D^{\gamma}}{(1+\mathrm{r})^{R}}\right] + Cp - \left[\dfrac{(Pw - Ch) \cdot V}{(1+r)^{R}}\right]}{\sigma \cdot (1 - fb) \cdot \left(\dfrac{1-(1+r)^{-R}}{r} - \dfrac{(1-\beta) \cdot R}{(1+r)^{R}}\right)} \ . \qquad (17)$$

From our definition, the price of carbon of equation (17) corresponds to the costs of carbon sequestration for each grid. In order to have the supply curve of carbon sequestration, we need to estimate the cumulative carbon sequestration for each grid.

Cumulative carbon sequestration

Policy makers and firms are interested in the time profile of carbon sequestration in sinks. This means that they would like to know what the supply curve is of carbon sequestration at different times (or equivalent, the changes over time of carbon stocks at different carbon prices). In order to estimate these changes on carbon stocks, we should consider the following:

- The rate of carbon sequestration on a single stand changes over time due to growing and harvest cycles. As shown in Figure 5, during the first 20 years there is a fixed rate of carbon uptake in biomass. At the end of the rotation interval (year 20), carbon is released from biomass and stored in products. The same year where a harvest occurs, new trees are planted again and new carbon is stored in the biomass. When products have a long life-span (e.g., furniture), they accumulate the carbon of different rotation periods.
- For each grid there is a rate of tree planting (*Prate*(*i*)) during a fixed time period (*Yp*(*i*)). If the grid is small and there is enough capital and labor, planting might occur during one year and there is only one stand in the grid. Otherwise, planting occurs over time and there are several stands of different ages in each grid. Therefore, it is necessary to calculate the sum of carbon uptake and release of the different stands in each grid.
- For a given price of carbon, there are multiple grids where tree planting is economically feasible. The aggregated supply curve of carbon is obtained from the cumulative sum of carbon flows and stocks of all these grids.

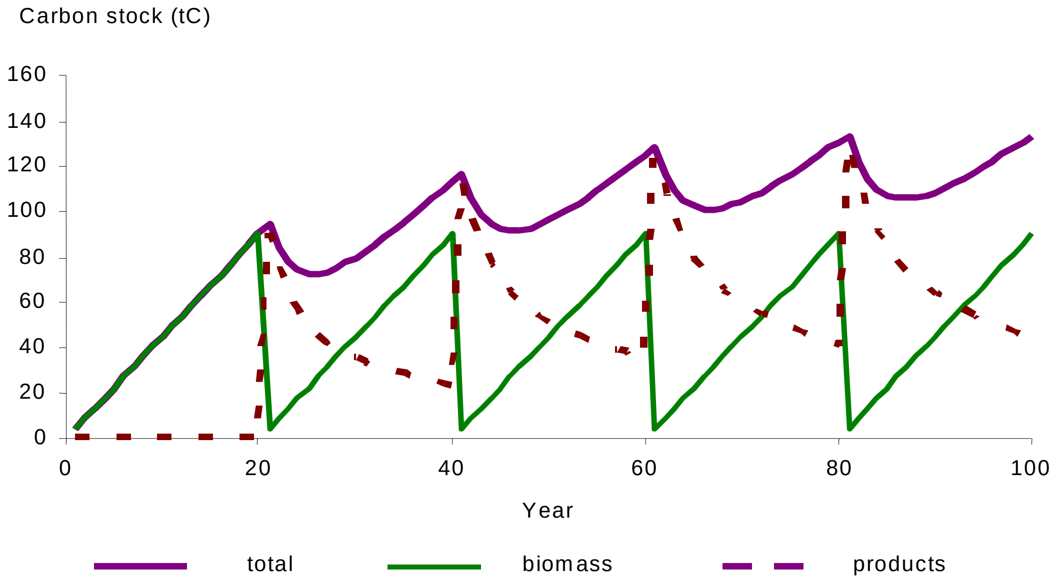

Figure 5: Time profile of carbon sequestration in a forest stand; example of a 20 year rotation.

In order to account the net carbon sequestration, the carbon level in the baseline is subtracted. As previously discussed, the carbon level in the baseline is a fraction of the carbon level in biomass and products.

Given the cumulative carbon, *C*(*t*), for a given carbon price, *Pc**, is the sum of the cumulative carbon in biomass and products of all the grids where the costs of carbon are lower than *Pc**. Since each grid *i* contains a number *k* of stands of different age, we have:

$$C_{(t)} = \sum_{i=1}^{n} \sum_{t=1}^{k} A_{(i,k)} \cdot \left(1 - fb_{(i)}\right) \cdot \left(C^{b}{}_{(i,k,t)} + C^{w}{}_{(i,k,t)}\right) \tag{18}$$

where $A_{(i,k)}$ is the area of stand k in region i, $C^{b}_{(i,k,t)}$ and $C^{w}_{(i,k,t)}$ denote the cumulative carbon in biomass and products at time t in stand k of region i. It should be noted that the total carbon is corrected with the baseline factor of each grid, fb_i. We find $C^{b}_{(i,k,t)}$ with:

$$C^{b}{}_{(i,k,t)} = \sigma_{(i)} \cdot (t - tp_{(i,k)}) - nh_{(i,k)} \cdot \sigma_{(i)} \cdot R_{(i)} \tag{19}$$

where $tp_{(i,k)}$ is the time at which the stand k of grid i is planted and the integer number, $nh_{(i,k)}$ denotes the number of harvest periods that have occurred at time t for the given stand. The first term of equation (19) represents the carbon uptake during the growing phase and the second term is the carbon release during harvest. The cumulative carbon in products, C^w is:

$$C^{w}{}_{(i,k,t)} = \sum_{s=1}^{nh} fp_{(i)} \cdot \sigma_{(i)} \cdot R_{(i)} \cdot e^{-r \cdot k1 \cdot (t - s \cdot R)} + (1 - fp_{(i)}) \cdot \sigma_{(i)} \cdot R_{(i)} \cdot e^{-r \cdot k2 \cdot (t - s \cdot R)} \;. \tag{20}$$

By running the model with different prices of carbon, we generate the time profile of carbon sequestration for different Pc^*.

4.2 Data Used in the Model

This section describes the data that is used for estimating the carbon sequestration supply curve in Latin America. It also explains the economic information such as the prices of land and timber, as well as the ecological information such as the rates of carbon uptake.

4.2.1 Countries Studied

The Latin American and Caribbean region includes a total of 45 countries. In order to exclude the less-representative countries, it is considered that the relevant countries for afforestation and reforestation projects are those that have the largest non-forest area. Eight countries are included in this study and represent 91% of the total non-forest area of Latin America and the Caribbean. The other 37 countries are not considered because they are either too small (e.g., the Caribbean Islands, Central America) or have small areas of non-forest land (e.g., Guyana, Suriname). Table 5 shows the non-forest area of the selected countries for 1999.

4.2.2 Land Suitable for Plantations

The amount of land that is suitable for afforestation and reforestation corresponds to the non-forest areas where the conditions are appropriate for tree growth and where tree planting is economically feasible. Since agriculture generally provides higher revenues than forestry, the establishment of plantations must take place in marginal agricultural areas.

Table 5: Forest and Non-Forest Area in Latin America, 1999.

Country	Land Area[a] (million ha)	Forest Area[b] (million ha)	Non-Forest Area[c] (million ha)	Non-Forest Area (% of total region)
Brazil	845	544	302	29
Argentina	273	35	239	23
Mexico	191	55	136	13
Peru	128	65	63	6
Chile	75	16	59	6
Bolivia	108	53	55	5
Colombia	104	50	54	5
Venezuela	88	50	39	4
Total (selected countries)	*1814*	*867*	*947*	*91*
Total: Latin America and Caribbean	***2018***	***964***	***1053***	***100***

[a] Source: FAO (2002).
[b] Source: FAO (2001).
[c] Difference between land and forest area.

In order to estimate the non-forest area we consider the Data and Information System of the International Geosphere-Biosphere Programme (IGBP-DIS) Global Land Cover Classification System that uses 17 land cover classes (Belward, 1996; EROS, 2002). From these classes, only three are considered suitable for afforestation and reforestation. These classes are grasslands, savannas, and open shrub lands and amount to 22% of the total area. Table 6 shows the IGBP classes and the share of each class in the studied region, based on an aggregation level of 0.5 degrees. It should be noted that there are some other land-classes where it is possible to capture carbon by planting trees, but these are not considered in this study. For example, trees could be planted within woody savannas, closed shrublands, and crops. These activities are not considered in this study since they correspond more to agroforestry and forest restoration.

It should be noted that simple comparisons with more recent land cover classification products indicate large differences with the IGBP-DIS map. However, these differences do not mean that the IGBP-DIS map provides less quality in the assessment. The differences only indicate how poor the databases are that are frequently used by analysts dealing with land cover change.

It is clear that it will not be feasible to plant trees in 22% of the Latin American region. For example, there are sites of good quality or where population density is high, so these could be used for agriculture in the future. Also, there are regions where tree growth is not possible (or very limited). Therefore, the following grids are *excluded*:

- Grids where the indicator of suitability for agricultural use is over 50% of the maximum value. This indicator of suitability for agriculture is described in Ramankutty *et al*. (2002) and represents the fraction of each grid cell that is suitable to be used for agriculture. The database is obtained from the Center for Sustainability and Global Environment (SAGE, 2002).
- Grids where the 3.5 degree averaged population density is over 100 hab/km^2. The data source for grid-based population density is from the Center for International Earth Science Information Network (CIESIN, 2000).

- Grids where the net primary productivity is below 0.1 kg-C/m^2/yr (1 tC/ha/yr). In these regions, the options for tree planting are very limited.[9]. The data source for grid-based NPP is SAGE (2002).
- Grids where the altitude is over the 3500 m. In these grids, not only the trees grow too slow, but also contain the ecological zone *Paramo* that constitutes a major water reserve of the Andes.

After this selection we end up with 13% of the Latin American area that is suitable for plantations (237 million ha). The land suitable per country is shown in Table 7.

Table 6: IGBP-DIS land classes: definition and distribution in Latin America.

Land class	**Major land-cover characteristics**	**Share in Latin America**[a]
Suitable for afforestation and reforestation		***22.3%***
Grasslands	Lands with herbaceous type of cover. Tree and shrub cover: 0–10%	7.4%
Open Shrublands	Lands with woody vegetation less than 2 meters tall. Shrub cover: 10–60%	8.5%
Savannas	Lands with herbaceous and other understory systems. Forest cover: 10–30%	6.4%
Non-suitable for afforestation and reforestation		***77.7%***
Woody Savannas	Lands with herbaceous and other understory systems. Forest cover: 30–60%	10.6%
Barren or Sparsely Vegetated	Lands with exposed soil, sand, rocks, or snow. Less than 10% vegetation cover	2.7%
Closed Shrublands	Lands with woody vegetation less than 2 meters tall. Shrub cover: more than 60%	2.7%
Cropland Natural Vegetation Mosaic	Mosaics of crops, forest, shrubs and grasslands in which no one component comprises more than 60%	14.3%
Croplands	Land covered with temporary crops	6.6%
Deciduous Broadleaf Forest	Deciduous forest cover: more than 60%	0.6%
Evergreen Broadleaf Forest	Deciduous forest cover: more than 60%	34.0%
Evergreen Needleleaf Forest	Evergreen forest cover: more than 60%	0.8%
Mixed Forest	Mixed forest cover: more than 60%	1.9%
Permanent Wetlands	Mixture of water and vegetation	0.4%
Snow and Ice	Snow and ice throughout the year	0.2%
Urban and Built-Up	Buildings and other manmade structures	0.1%
Water Bodies	Fresh or salt water bodies	2.6%

[a] Sources: Belward (1996), EROS (2002).

[9] As a comparison, the NPP in the humid tropics is approximately 10 times larger.

Table 7: Area suitable for plantations in major Latin American countries.

Country	**Area suitable for plantations (million ha)**	**Share of the area suitable for plantations in Latin America**
Argentina	74	31.2%
Bolivia	9	4.0%
Brazil	70	29.6%
Chile	8	3.4%
Colombia	13	5.4%
Mexico	42	17.6%
Peru	4	1.8%
Venezuela	17	7.1%
Total	***237***	***100.0%***

4.2.3 Price Difference Across Countries

The GDP per capita of the selected countries ranges from US$2355 in Bolivia to US$12277 in Argentina[10] (World Bank, 2000). These differences in income and other economic variables (unemployment level, monetary policy, taxes) cause the prices of commodities and costs of products to differ across countries. In this research, we evaluate the cost of carbon sequestration in a single currency, namely constant US$$_{2000}$. For this purpose, we adjust the plantation costs, land costs, and timber prices for the eight studied countries on the basis of the purchasing power parity (PPP) and the official exchange rate. If we know the US$ price of one commodity in one country ($P1$), which has been estimated on the basis of the official exchange rate, we could estimate the US$ costs in another country ($P2$) by means of the following relationship:

$$P1 \cdot \frac{Xrate_1}{PPPc_1} = P2 \cdot \frac{Xrate_2}{PPPc_2} \qquad (21)$$

or $P1=P2 \cdot f1/f2$ and $fi=PPPc_i/Xrate_i$, where Pi is the US$ price of product in country i, $Xrate_i$ is the official exchange rate in local currency units per US$, $PPPc_i$ is the PPP conversion factor in local currency units per international US$ and f_i is the relative price factor for country i.

Following equation (21), if we know the US$ price of one product in one country, we could estimate the US$ price of the same product in another country. By setting a reference price of one for the United States, we can estimate the relative price index for the different Latin American Countries (Table 8). This shows that Venezuela was the most expensive country in 1999 and Colombia was the cheapest.

[10] Measured as PPP-GDP per capita.

Table 8: Relative price index in Latin America. Source: Estimated, World Bank (2000).

Country	**GDP per capita, PPP**	**Relative price index in 1999 (United States = 1)**
Argentina	12277	0.63
Bolivia	2355	0.44
Brazil	7037	0.45
Chile	8652	0.52
Colombia	5749	0.36
Mexico	8297	0.60
Peru	4622	0.45
Venezuela, RB	5495	0.78

It should be noted that the factor used for relative prices might change significantly due to variations in the exchange rate. In addition, we expect that in the future, the difference in prices among countries will be smaller due to increasing trade in the region. Therefore, we take this factor into account for the investments that occur in the near future, namely plantation costs and land price. For the harvest costs and timber revenues that occur after 20–30 years, we consider that prices will be the same across the countries.

4.2.4 Land Price

As discussed in Section 4.1, our model considers the price of land as a function of the suitability of agriculture and population density, following a Cobb-Douglas relationship. The parameters are conjectured and applied at a grid level from land-use databases. The level of aggregation for the suitability of 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[11] 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.

Due to the limited information on land prices, it is not possible to run a regression analysis. Therefore, we just set upper and lower limits for the price of land. This means that we set a value for the lower price of land that corresponds to the worse quality and less populated area, and a higher price of land for the best quality and crowded area. Some information on land prices is available from Mexico, Ecuador, Argentina, and Brazil. According to de Jong *et al*. (2000), the opportunity costs of land for converting pasture area into forestry, range from US$390/ha to US$1520/ha in Southern Mexico.[12] In West Ecuador, Benítez *et al*. (2001), estimated that the rent of cattle ranching is between US$110 and US$2200/ha, based on a 5% discount rate. The baseline study for a carbon sequestration project in Brazil, suggests that the price of land is below US$500/ha (EcoSecurities, 2002). In the Patagonian region of Argentina, Sedjo (1999) proposes a value of land of US$100/ha for marginal areas.

[11] One degree is about 100 km depending on the latitude.
[12] Considering a 10% discount rate.

Taking into account the current information on land prices, we set the upper and lower limits of the land price for the country with the larger potential for carbon sequestration (Brazil). The lower limit is the case where both population density and the index of agricultural suitability is zero. In this situation the value of land should be zero or very small. We set a value of US$200/ha that represents basically some transaction costs and the option of using this land some time in the future. For the upper bound we use a value of US$2000 for a grid of population density of 100 hab/km^2 and a suitability index of 50% for agriculture. Considering these upper and lower limits on land price, we estimate the parameters of the Cobb-Douglas production function (K, α) by assigning equal weights for population density and suitability for agriculture.[13] Therefore we have:

$$\ln(L) = \ln(K) + \alpha \cdot \left(\ln(S^*) + \ln(D^*)\right) \tag{22}$$

where S^* is the normalized indicator of suitability for agriculture (between 1 and 10) and D^* is the normalized indicator of population density, between 1 and 10. It should be noted that the price of land is valid for Brazil. For estimating the prices in other countries, we use the same function but correct the price of land with the PPP and currency factor previously described. Due to the uncertainties in the price of land, a sensitivity analysis is required.

4.2.5 Plantation Costs

In this study, we refer to plantation costs as being the present value of the planting and maintenance costs for one rotation interval. There are multiple studies that refer to these costs in Latin America. For pine plantations, the costs are about US$1000/ha in Argentina (Sedjo, 1999) and US$890/ha in Chile (Noe, 1999). The establishment costs of eucalyptus plantations in Brazil are between US$625/ha (Fearnside, 1995) and US$1060/ha (EcoSecurities, 2002). For *cordia alliodora*, the total establishment costs in Ecuador are US$810/ha (Benítez *et al.*, 2001).

In this research we use a generic value of plantation costs, which is independent of the tree species. This is a good approximation as long as the plantation density and management intensity remains the same for the different tree species. We set a reference value for plantation costs in Brazil of US$800/ha. In order to take into account country differences, we include the relative price index shown in Table 8.

4.2.6 Tree Growth and Carbon Sequestration Parameters

The rate of carbon uptake in biomass is considered to be a linear function of the NPP of the existing vegetation. The data on NPP is available from SAGE (2002). In order to convert from NPP to carbon uptake in live biomass, we should estimate how much is in the aboveground biomass and how much is in the roots. Data from Mexican forests, show that the wood increment, the root increment, and the fine root production corresponds to 61% of the NPP (Martinez-Yrizar and Maass, 2001). In this research we

[13] This is a strong assumption, but a sensitivity analysis shows that the weights assigned for population density and suitability for agriculture have a small impact in the supply curve of carbon sequestration.

use a conversion factor of 50%, so that the rate of carbon sequestration for the studied area will be between 0.6 and 6.2 tC/ha/yr. This is comparable with the data shown in Trexler and Haugen (1995), where the carbon accumulation rate in the dry tropics is between 0.3 and 1.5 tC/ha/yr and in the wet tropics between 6 and 12 tC/ha/yr.

For the rotation interval we consider 30 years for plantations in temperate regions and 20 years for plantations in tropical regions (Nilsson and Schopfhauser, 1995). In order to estimate the timber productivity from the rate of carbon uptake, we first subtract the roots from the live biomass, considering that roots represent 20% of the biomass pool (Nilsson and Schopfhauser, 1995) and then convert above biomass units into timber units. Average values of carbon content per cubic meter of stem wood are 0.3 tC/m^3 in temperate regions and 0.4 tC/m^3 in tropical regions (Nilsson and Schopfhauser, 1995). With respect to forest products it is assumed that 50% of forest biomass is stored in long-lived products with a half-life time of 20 years. For the short-lived products, a half-life time of one year is considered. The carbon level in the baseline with respect to the forest is assumed to be 5% for grassland and 20% for savannahs and open shrublands. This assumption follows the IGBP definition of grasslands (up to 10% of the forest) and savannahs (10–30% of the forest).

As discussed in Section 3, the number of years required for planting trees in each grid is an exogenous variable of the model. We consider that tree planting in each grid requires 50 years for completion and occurs at a constant rate. As a reference, Trexler and Haugen (1995) used planting scenarios of 50 years for estimating the potential carbon storage with tree plantations in the tropics.

4.2.7 Price of Timber and Harvest Costs

The price of timber is dependent on the accessibility of the forests, the transportation costs and the demand of timber. This means that the stumpage price of timber differs across cells, depending on the level of infrastructure and the distance to markets. Due to the limited information on the road infrastructure in Latin America and the domestic prices of timber, we consider that the stumpage price of timber only depends on population density. As in the case of the land price, we set lower and upper limits for the stumpage timber price and adjust the values in-between according to the population density. We consider a linear dependency between the price of timber and population density. For the lower limit of the timber price we consider that the stumpage price of timber (price minus harvest costs) equals a small value,[14] US$5/$m^3$. For the upper limit of the timber price we use the current export price minus the harvest costs.

The FAO forestry statistics (FAO, 2002) show the price and volume of timber exports for the different countries. As an average for the region, the freight on board (FOB) price for round wood in 1999 was about US$50/$m^3$. Regarding the harvest costs, we include the costs of felling and storing the timber at the forest site as well as the transport costs from the forest to the market. For a highly populated grid, the transport distance is considered to be the size of the grid (50 km). Based on Benítez *et al*. (2001),

[14] In practice, when the stumpage price of timber is low compared with the carbon value, it will be more profitable not to harvest the trees.

the total harvest costs of round wood for this distance are US$13/m^3. Therefore, the stumpage price of timber in a highly populated site is around US$35/m^3.

As in the price of land, the stumpage price of timber is uncertain due to the unknown developments on the road infrastructure and the development of the international timber market. Therefore, the impact of the stumpage timber price in the costs of carbon sequestration is evaluated by sensitivity analysis.

4.3 Results

4.3.1 Supply Curve of Carbon Sequestration

In this section we show the results of the model simulations for Latin America. As a reference value, we chose a discount rate of 5% that is often used for carbon mitigation studies in the energy sector. The model starts at 2000, which is the starting year for CDM projects. The parameters used for the model are shown in Box 1.

Box 1: Summary of the Parameters used in the Model

The model simulations were based on the following parameters: Starting year: 2000. Discount rate: 5%. Land price: Estimated as a function of population density and suitability for agriculture. Minimum and maximum value for Brazil: US$200–2000/ha. Land prices for other countries are corrected according to the exchange rate (Xrate) and purchasing power parity index (PPP_c). Plantation costs: $800/ha for Brazil and adjusted for other countries according to Xrate and PPP_c. Timber price: Estimated as a function of population density. Range: US$5–35/m^3. Rotation interval: 20 years in tropical regions, 30 years in temperate regions. Carbon uptake: linear function of NPP of existing vegetation. Biomass/NPP conversion factor: 50%. Carbon uptake in roots: 20% of total uptake in biomass. Ratio of aboveground biomass and timber volume: 0.4 in the tropics and 0.3 in temperate regions. Carbon stored in products with respect to carbon in biomass before harvest: 50%. Half-life time of long-lived products: 20 years. Half-life time of short-lived products: 1 year. Carbon in baseline: 5% with respect to forest biomass for grasslands, 20% for open shrub lands and savannahs. GIS databases: Land-use: EROS (2002); Suitability for agriculture: Belward (1996), SAGE (2002); Population density: CIESIN (2000); NPP: SAGE (2002).

The supply curve of carbon sequestration shows the price of carbon as a function of the cumulative carbon sequestered in the forest. Since the quantity of carbon stored in the forest is time dependent, the supply curve of carbon sequestration must be specified for a fixed year. In Figure 6 we show the supply curve of carbon sequestration at 2010 and 2020. As can be seen in the Figure, for a given price of carbon, the cumulative carbon sequestered after 20 years is about four times larger than after 10 years. This is caused by two reasons: (i) longer time periods allow more carbon storage per hectare of land, and (ii) longer time periods allow the use of larger areas of land as there is a constant rate of tree planting. When we look at the left side of the supply curve we find no-regret options for carbon sequestration, which means the timber benefits are enough for converting non-forest areas into forests. This result is compatible with what has been found in the literature (see Section 3). For carbon prices between US$15 and US$60/tC, the costs of sequestration increase with an approximate linear relationship with the sequestration level, but for higher prices they increase exponentially. If we take as a reference a carbon price of US$20/tC we expect up to 90 MtC to be sequestered by 2010.[15] This amount of emission reductions is significant compared with the carbon emissions in the energy sector in Latin America that accounted up to 320 MtC per year in 1997 (Marland and Bodden, 2000). Carbon prices of US$10/tC and US$40/tC will represent cumulative sequestration levels in 2010 of 52 MtC and 245 MtC, respectively.

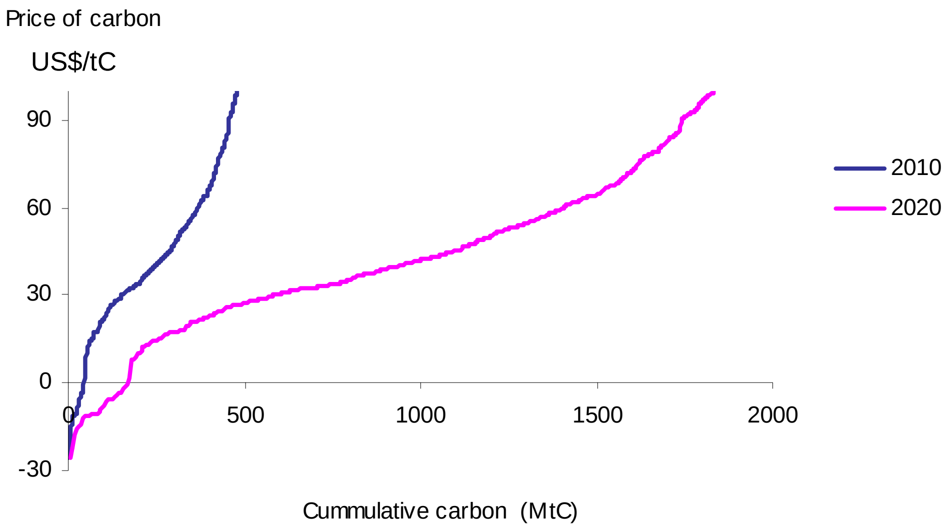

Figure 6: Supply curve of carbon sequestration through afforestation activities in Latin America for 2010 and 2020.

The results of this research could be compared with current studies found in the literature. Sathaye *et al*. (2001) propose that with a discount rate of 10%, up to 450 million tC could be sequestered in Brazil after 30 years at zero cost. Our model simulations show that with a discount rate of 5%, up to 335 million tC could be sequestered in 30 years at zero cost in the entire region, but with a discount rate of 10% no carbon is sequestered, meaning that our results are more conservative. In addition, our model proposes increasing the costs of carbon sequestration, while Sathaye *et al*. (2001) propose that the costs of carbon sequestration remain constant for a wide range of carbon sequestration.

4.3.2 Emission Reductions for the First Commitment Period

For the first commitment period of the Kyoto Protocol, it is allowed to bank emissions reductions under the CDM. This means that the total emission reductions that occur until the end of 2012 could be sold during the five years of the commitment period. As

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[15] MtC denotes 10^6 tons of carbon. Note that a price of US$20/tC is equivalent to US$5.5/t$CO_2$ and 100 MtC is equivalent to 366 Mt CO_2.

we know, there is a cap on CDM sinks that is either 50 or 33 MtC/yr depending on the US ratification of Kyoto (den Elzen and de Moor, 2001). For the five years of the commitment period, the cap on sinks equals 250 or 165 Mt C. In Figure 7 we plot the supply curve during the first commitment period with the market limitations for CDM sinks. The cap on sinks could be interpreted as the demand for carbon sequestration in the case where Latin America is the only supplier of CDM sinks. Under these conditions, the equilibrium price of carbon sequestration is between US$26/tC (US$7/tCO_2) and US$32/tC (US$9/tCO_2) when the market for CDM sinks is cleared.

These results are interesting. Even if we exclude afforestation projects in Asia and Africa, the whole cap on sinks could theoretically be fulfilled just with projects in Latin America. The estimated equilibrium price of carbon is comparable with the expected price of carbon for the first commitment period that ranges between US$15/tC and US$30/tC (den Elzen and de Moor, 2001).

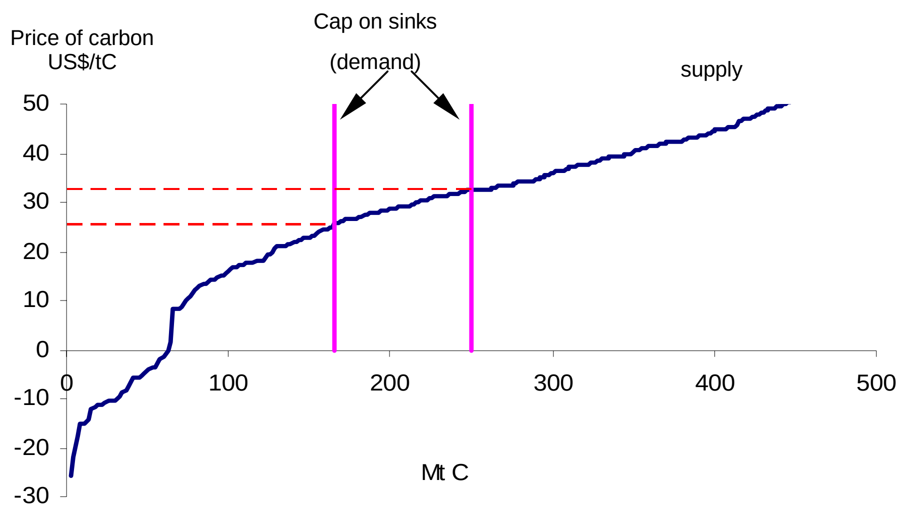

Figure 7: Supply and demand for CDM sink credits. Cumulative emission reductions 2000–2012. The analysis considers market clearance and that Latin America is the only supplier of CDM sink credits.

As Asia and Africa will also be suppliers of carbon sequestration, the equilibrium price of carbon for CDM sinks will be lower than the ones shown in Figure 7.

4.3.3 Aggregate Carbon Supply Curve of Energy and Forestry

An efficient climate change policy should look at the least-cost options for GHG mitigation in the different sectors. It is therefore not appropriate to look at emission reductions in the energy sector and in sinks separately, but we should integrate both alternatives in order to find a cost-effective GHG mitigation strategy. Previous studies have estimated the carbon supply curve in the energy sector for the different world regions. In this research we use the carbon supply curve in the energy sector of Latin America obtained by van der Linden (1999) and Sijm (2000). The supply curve referred to in these studies, shows the carbon price as a function of the yearly emission reductions in 2010, without considering the banking of emissions. In order to combine both supply curves we should, (i) find the yearly emission reductions in sinks for 2010 by dividing the total emission reductions until 2012 by the five years of the commitment period, and (ii) adjust the emission reductions in the energy sector for *banking*, by multiplying the emission reductions with a factor of 12/5.[16] Figure 8 illustrates the aggregate demand curve of energy and forestry.

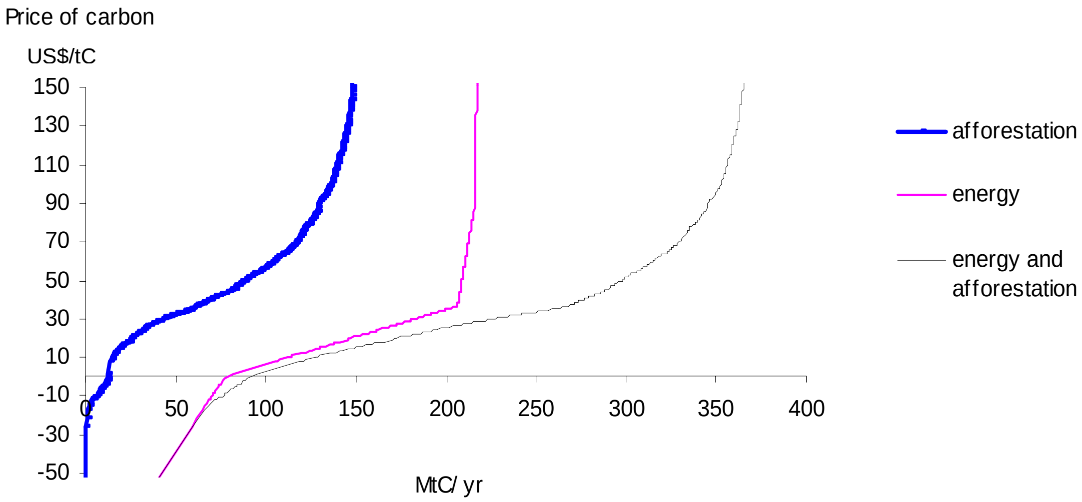

Figure 8: Carbon supply curve in the energy and forestry sector in Latin America, 2010.

From the aggregate supply curve in the energy and forestry sector, we could estimate what the gains are of using forest sinks for reducing GHG concentrations. If we take a given price of carbon we could find out how much emission reductions occur in the energy sector and how much in the forestry sector. This is shown in Table 9 for different carbon prices. When the carbon price is zero (the no-regret options), the emission reductions in the forestry sector are equivalent to about 16% of the emission reductions in the energy sector. A similar relation holds for a carbon price of US$20/tC. But, if the carbon price rises to US$50/tC, then the emission reductions in forestry rise up to 42% of the emission reductions of the energy sector.

Table 9: Potential emission reductions in the energy and forestry sector in Latin America, 2010.

Carbon price (US$/tC)	Energy (MtC/yr)	Afforestation (MtC/yr)	Total emission reductions (MtC/yr)
0	77	12	89
20	149	25	174
50	209	88	297
100	217	134	351

[16] This factor assumes that mitigation projects in the energy sector will be fully operational starting from 2000, which is not the case in practice. However, since the aim is to compare the supply curve of energy and forestry, the same banking assumptions are needed for both supply curves, meaning that projects start in 2000.

4.3.4 Potential Carbon Sequestration in the Medium- and Long-term

Let us examine what potential carbon sequestration is in the medium- and long-term. In Figure 9, we show the time profile of carbon sequestration for different carbon prices. When the price of carbon is US$20/tC, the total carbon sequestered in the whole region studied after 50 years is 1340 MtC and after 100 years 2100 MtC. This amount of carbon sequestered increases about three times with a carbon price of US$50/tC and five times with a carbon price of US$100/tC. As shown in Figure 9, the quantity of carbon sequestered increases sharply during the first 60 years and later it slows down towards a stable level around 2100. It should be noted that the cumulative emission reductions in the long-term, considering a carbon price of US$50/tC, are about 1.1 times the world's yearly emissions from fossil fuel combustion at the 1990 level (IPCC, 2000).

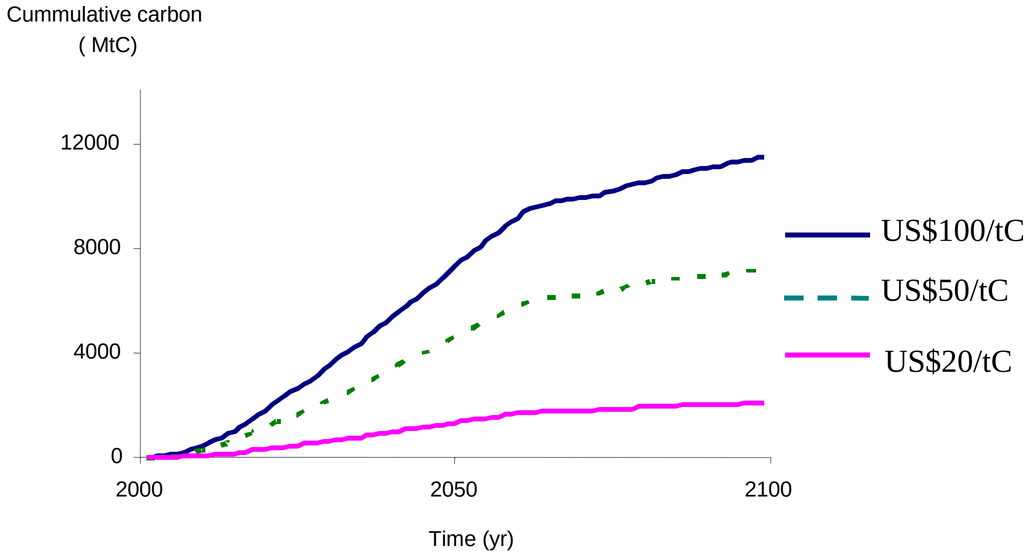

Figure 9: Time profile of carbon sequestration through afforestation activities in Latin America considering different carbon prices.

Given the uncertainty on the parameters used in the model, a sensitivity analysis is carried out and it is fully described in the Appendix.

5 Market Limitations of the Carbon Sequestration Potential in Sinks

There are multiple factors that restrict the potential carbon sequestration in afforestation activities. In this section we discuss some of these limitations, such as restrictions stated in the Kyoto Protocol, transaction costs, and ecological and economic risks.

5.1 Kyoto Protocol Limitations

The Kyoto Protocol itself limits the potential carbon sequestration in forests. Some of these limitations are:

- *Cap on CDM sinks*. As previously mentioned, there is a cap on sinks that is equivalent to five times 1% of the GHG emissions of Annex I countries during the first commitment period. This means that the yearly emission reductions on CDM sinks during 2008–2012 should be below 33MtC/yr independent of how costly they are (considering that the US will not ratify the Kyoto Protocol).
- *Exclusion of areas that have been recently deforested.* In a baseline scenario natural forests have been deforested, so there is a continuous increase in the area available for plantations. In order to avoid "perverse incentives for deforestation", reforestation projects in areas that have been recently deforested will be excluded from the CDM. If the definition of reforestation under the CDM is the same as reforestation under joint implementation (JI), reforestation projects that are implemented in areas that have been deforested after 1990, could not gain carbon credits. This restriction limits the carbon sequestration potential. Between 1990 and 2000, about 4 million hectares of land in Latin America have been deforested. Therefore, if the maximum year for deforestation is 1990 instead of 2000, the area available for plantations will be about 4 million hectares less. Although this represents less than 2% of the total available area in the region, the costs of carbon sequestration in this *excluded area* are expected to be low since the prices of land in forest areas are generally low (road infrastructure and population density are low).
- *Exclusion of wood products.* The Kyoto Protocol excludes accounting for carbon storage in timber products for the first commitment period. If this exclusion continues in the future, it will cause significant reductions in the carbon sequestration potential in forests in the medium-and long-term.
- *Biodiversity issues.* There are rising concerns on the effect of plantation projects on biological diversity. According to the Climate Action Network (CAN, 2002), the establishment of monoculture industrial plantations threatens biological diversity as well as affects local sustainable livelihoods. These concerns on industrial plantations might limit the participation of the private sector in carbon sequestration projects, thus reducing the potential carbon sequestration.

5.2 Transaction Costs

Transaction costs are involved in diverse activities such as project design and implementation, land acquisition or landrent, and carbon monitoring, certification and verification. By now, there is experience on carbon sequestration activities that provide information on transaction costs. According to IPCC (2000), the yearly costs of monitoring and verification in a carbon sequestration project in India were some US$5/ha, while in Costa Rica they amounted to about US$3.5/ha. Since the projects need to be monitored for a long time, these costs represent a current value of US$70–100/ha, discounting with 5%. The costs related to land acquisition or land rent are more uncertain. If property rights are not clear, it might be required to spend additional time and money on bureaucratic activities. In Table 10, we show the effect of transaction costs on the potential carbon sequestration in Latin America. If the transaction costs are in the order of US$10/ha/yr then the emission reductions at a carbon price of US$20/tC are about 25% less. It should be noted that this is a very rough approximation since the transaction costs are also a function of other variables like the project scale and the level of fragmentation of land property.

Table 10: Effect of transaction costs in the potential carbon sequestration in Latin America.

	Cumulative Emission Reductions 2000–2012 (MtC)		
Transaction costs	***Carbon price: US$20/tC***	***Carbon price: $50/tC***	***Carbon price: $100/tC***
0 (low)	*127*	*434*	*675*
US$5/ha/yr (medium)	108	413	661
US$10/ha/yr (high)	95	381	648

5.3 Risks and Uncertainties

The model described in Section 4 is based on a deterministic approach, i.e., the decision making of converting non-forest land into forests is only based on expected costs and benefits and not on their variability. This approach is a good approximation when individuals and firms are risk neutral. In the real world, individuals and firms are risk averse, meaning that they are willing to pay for reductions in the variability of the payoffs of projects and portfolios of projects. Carbon sequestration projects face two types of risk, namely economic and ecological risks.

- *Economic risks* are caused by the uncertainty over future markets and prices. In forestry projects we find uncertainties with regard to the prices of carbon, timber and land as well as to the exchange rate. The price of carbon is uncertain mainly because of uncertainties with regard to the implementation of climate change policies — notably the Kyoto Protocol — in the short-, medium-, and the long-term. This uncertainty causes investors to speculate over the different possible scenarios before they decide on investing in carbon sequestration projects. The prices of timber are also dependent on climate change policy since high carbon taxes will represent increased demand of timber for biomass and timber for replacing energy intensive materials. Regarding prices of land, these are dependent on the potential rent of agricultural production. Open markets and low subsidies for agriculture in the US and Europe might represent a higher rent of agriculture in developing countries. The extent to which agricultural subsidies will be maintained in the Northern Hemisphere is unknown and this causes uncertainty on predicting the prices of land in the developing world. In addition to the uncertainty in prices, the exchange rate in several developing countries is unpredictable, and this causes aversion for investing in long-term forestry projects.
- *Ecological risks* refer to uncertainty over the evolution of the relevant ecosystem. In carbon sequestration projects, ecological risks are caused by the occurrence of catastrophic events such as fire and pests and the uncertain growth of forests. These effects are influenced by climate change. With global warming, the probability of

fire and pest attacks might increase. In addition, the rise in concentrations of CO_2 might cause the effect of forest fertilization, leading to higher rates of carbon sequestration. The same holds truie for agriculture. Since climate change might represent decreased agricultural productivity in certain regions, this will cause a direct impact on the prices of land. While this last effect will be beneficial for forestry projects, the extent of these changes is quite unknown.

6 Conclusions

There are different methods for deriving supply curves of carbon sequestration through afforestation activities. In this research we developed a bottom-up approach where the potential and costs of carbon sequestration are estimated at a grid-level (geo-referenced areas of 50 × 50 km) and, subsequently, aggregated in a single carbon supply curve. The central element of the analysis is the estimation of the *break-even price of carbon* that allows forestry to be as profitable as agriculture in each grid. In accounting carbon sequestration benefits of forestry, we included the carbon uptake during forest growth, the carbon emissions during harvest and the residual carbon storage in short- and long-lived products. This approach that considers the life cycle of forest carbon provides a better understanding of the short- and long-term implications of carbon storage in forests. In addition, by discounting the financial benefits of carbon sequestration, the preference of investors towards projects with rapid rates of carbon uptake has been considered. The method developed in this research could be further used for other world regions, particularly Russia, Asia, and Africa, where information on supply curves of carbon sequestration is limited.

The model suggests that under reasonable assumptions of land and timber prices and using a discount rate of 5%, the potential carbon sequestration in Latin America by 2010 will be about 90 MtC given a carbon price of US$20/tC. Doubling this carbon price will raise the amount of sequestered carbon by a factor 2.5. These quantities of emission reductions are significant compared with the yearly emissions in the energy sector of the Latin American region, which were 320 Mt C/yr in 1997.

The Latin American region offers large opportunities for implementing CDM sink projects during the first commitment period of the Kyoto Protocol. By comparing the supply curve of carbon sequestration with the total demand of CDM sinks (1% cap), we find an equilibrium price for carbon of US$26–32/tC. This means that even if Asia and Africa will not implement afforestation projects, the carbon price for sinks will be around US$30/tC. As these regions will implement afforestation projects, the expected price of carbon for CDM sinks will be below US$32/tC.

In order to have a cost efficient carbon mitigation policy, abatement options in the energy and forestry sectors have to be considered in a comprehensive manner. When the supply curves of the afforestation and energy sectors are combined, the total emission reductions in 2010 are at least 15% larger than in the case of the energy sector alone. This highlights the importance of including sinks in a global carbon mitigation strategy. In addition, we should be aware that there are other land-use activities like deforestation, cropland management and agroforestry that could reduce the global costs of carbon mitigation.

A sensitivity analysis shows that the sequestration costs are significantly affected by changes in the carbon uptake in biomass as well as by the prices of timber and land, particularly for cases in which the carbon prices are low. In addition, we should be aware that discount rates over the 5% considered in this study, will represent less carbon sequestration potential.

Further research must consider the inclusion of risk and uncertainty in the decision-making of carbon mitigation investments. In the case of forestry this is particularly important due to the long-term nature of these projects. In the risk analysis of forestry both economic and ecological risks need to be considered. Ecological risks refer to uncertainty in the growth of forestry and extreme events like fire and pests. Economic risks are related to the unknown prices of timber, carbon sequestration and land. Further research toward the evaluation of these risk aspects, will contribute to the decision making on using carbon sinks in the medium- and long-term climate change policy.

References

Belward, A.S. (1996). The IGBP-DIS Global 1 Km Land Cover Data Set (DISCover)-Proposal and Implementation Plans. Working Paper No. 13. Data and Information System of the International Geosphere-Biosphere Programme (IGBP-DIS), Toulouse, France.

Benítez, P., R. Olschewski, F.D. Koning and M. López (2001). Cost-Benefit Analysis of Land Use and Carbon Sequestration in Forestry Systems of Northwest Ecuador. Report TWF-30s. Tropical Ecology Programme of the German Agency of Technical Cooperation (GTZ), Eschborn, Germany.

Brown, S., J. Sathaye, M. Cannell and P. Kauppi (1996). Mitigation of Carbon Emissions to the Atmosphere by Forest Management. *Commonwealth Forest Review*, 75, 80–91.

Callaway, J.M. and B. McCarl (1996). The Economic Consequences of Substituting Carbon Payments for Crop Subsidies in US Agriculture. *Environmental and Resource Economics*, 7, 15–43.

CAN (2002). Submission by CAN on Issues Related to Modalities for Including Afforestation and Reforestation under Article 12 [of the Kyoto Protocol]. Climate Action Network, Brussels, Belgium, 20 August.

CIESIN (2000). Gridded Population of the World (GPW), Version 2. Center for International Earth Science Information Network (CIESIN), Columbia University, New York, USA. Available on the Internet: http://www.ciesin.org/datasets/gpw/globldem.

Creedy, J. and A.D. Wurzbacher (2001). The Economic Value of Forested Catchment with Timber, Water and Carbon Sequestration Benefits. *Ecological Economics*, 38(1), 71–83.

de Jong, B.J., R. Tipper and G. Montoya-Gómez (2000). An Economic Analysis of the Potential for Carbon Sequestration by Forests: Evidence from Southern Mexico. *Ecological Economics*, 33, 313–327.

de Koning, G. A. Veldkamp and L. Fresco (1999). Exploring Changes in Ecuadorian Land Use for Food Production and Their Effects on Natural Resources. *Journal of Environmental Management*, 57, 221–237.

de Koning, G., R. Olschewski, E. Veldkamp, P. Benítez, P. Laclau, M. López, M. Urquiza and T. Schlichter (2002). Evaluation of the CO_2 Sequestration Potential of Afforestation Projects and Secondary Forests in Two Different Climatic Zones of South America. Report TWF-37e. Tropical Ecology Programme of the German Agency of Technical Cooperation (GTZ), Eschborn, Germany.

den Elzen, M.G.J. and A.P.G. de Moor (2001). The Bonn Agreement and Marrakesh Accords: An Updated Analysis. Report No. 728001017/2001. National Institute of Public Health and the Environment (RIVM), Bilthoven, Netherlands.

Dixon, R.K, J.K. Winjum, K.J. Andrasko, J.J. Lee and P.E. Schroeder (1994). Integrated Land-Use Systems: Assessment of Promising Agroforest and Alternative Land-Use Practices to Enhance Carbon Conservation and Sequestration. *Climatic Change*, 27, 71–92.

EcoSecurities (2002). Baseline Determination for Plantar: Evaluation of the Emissions Reduction Potential of the Plantar Project. Prototype Carbon Fund, The World Bank, Washington DC, USA.

EROS (2002). Global Land Cover Characterization (GLCC), Version 2. Land Processes Distributed Active Archive Center, US Geological Survey, Earth Resources Observation Systems (EROS) Data Center, Sioux Falls, South Dakota, USA. Available on the Internet: http://edcdaac.usgs.gov/glcc/glcc.html.

FAO (2001). Global Forest Resources Assessment 2000. Main Report. United Nations Food and Agriculture Organization (FAO), Rome, Italy.

FAO (2002). Faostat Agricultural and Forestry Data. United Nations Food and Agriculture Organization (FAO), Rome, Italy. Available on the Internet: http://apps.fao.org.

Fearnside, P.M. (1995). Global Warming Response in Brazil's Forest Sector: Comparison of Project-Level Costs and Benefits. *Biomass and Bioenergy*, 8, 309–322.

Frumhoff, P.C., D.C. Goetze and J.J. Hardner (1998). Linking Solutions to Climate Change and Biodiversity Loss Through the Kyoto Protocol's Clean Development Mechanism. Briefing Paper, UCS Reports Series, Union of Concerned Scientists(UCS), Cambridge, Massachusetts, USA, October.

IISD (2002). Earth Negotiations Bulletin: Summary of the Eighth Conference of the Parties to the United Nations Framework Convention on Climate Change (UNFCCC), 23 October–1 November 2002. International Institute for Sustainable Development (IISD), Winnipeg, Manitoba, Canada. Available on the Internet: http://www.iisd.ca/linkages/climate/cop8/.

IPCC (2000). *IPCC Special Report on Land Use, Land-Use Change, and Forestry*. Intergovernmental Panel on Climate Change (IPCC), Cambridge University Press, Cambridge.

ITTO (2003). Tropical Timber Market Report, 16–31 March 2003. International Tropical Timber Organization (ITTO), Yokohama, Japan. Available on the Internet: http://www.itto.or.jp/market.

Kauppi, P. And R. Sedjo (2001). Technical and Economic Potential of Options to Enhance, Maintain and Manage Biological Carbon Reservoirs and Geo-Engineering. In: *IPCC Third Assessment Report*. Intergovernmental Panel on Climate Change (IPCC), Cambridge University Press, Cambridge.

Kolshus, H.H. (2001). Carbon Sequestration in Sinks: An Overview of Potential and Costs. Working Paper 11. Center for International Climate and Environmental Research — Oslo (CICERO), Norway.

Marland, G. and B. Schlamadinger (1999). The Kyoto Protocol Could Make a Difference for the Optimal Forest-Based CO_2 Mitigation Strategy: Some Results from GORCAM. *Environmental Science and Policy*, 2, 111–124.

Marland, G. and T. Bodden (2000). National CO_2 Emissions of Fossil-Fuel Burning, Cement Manufacturing and Gas Flaring: 1951–1997. Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA.

Marland, G., K. Fruit and R. Sedjo (2001). Accounting for Sequestered Carbon: The Question of Permanence. *Environmental Science and Policy*, 4, 259–268.

Martinez-Yrizar, A. and J.M. Maass (2001). NPP Tropical Forest: Chamela, Mexico, 1982–1995. Data set. Distributed Active Archive Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA. Available on the Internet: http://www. daac.ornl.gov.

Masera, O.R., M. Bellon and G. Segura (1995). Forest Management Options for Sequestering Carbon in Mexico. *Biomass and Bioenergy*, 8, 357–367.

Masera, O., M.R. Bellon and G. Segura (1997). Forestry Options for Sequestering Carbon in Mexico: Comparative Economic Analysis of Three Case Studies. *Critical Reviews in Environmental Science and Technology*, 27, S227–S244.

Masera, O., J.F. Garza-Caligaris, M. Kanninen, T. Karjalainen, G.J. Nabuurs, A. Pussinen and B.J. de Jong (2001a). Modelling Carbon Sequestration in Afforestation and Forest Management Projects: The CO_2fix V 2.0 Approach. European Forestry Institute (EFI), Joensuu, Helsinki.

Masera, O.R., A.D. Ceron and A. Ordoñez (2001b). Forestry Mitigation Options for Mexico: Finding Synergies between National Sustainable Development Priorities and Global Concerns. *Mitigation and Adaptation Strategies for Global Change*, 6, 291–312.

Mosnaim, A. (2001). Estimating CO_2 Abatement and Sequestration Potentials for Chile. *Energy Policy*, 29, 631–640.

Moura-Costa, P. and M.D. Stuart (1998). Forestry-Based Greenhouse Gas Mitigation: A Story of Market Evolution. *Commonwealth Forestry Review*, 77, 191–202

Nabuurs, G.J., J.F. Garza-Caligaris, M. Kanninen, T. Karjalainen, T. Lapvetelainen, J. Liski, O. Masera, G.M.J. Mohren, A. Pussinen and M.J. Schelhaas (2002). CO_2fix V2.0; Manual of a Modeling Framework for Quantifying Carbon Sequestration in Forest Ecosystems and Wood Products. Report 445. Research Institute for the Green Environment (Alterra), Wageningen, Netherlands.

Niles, J.O., S. Brown, J. Pretty, A. Ball and J. Fay (2001). Potential Carbon Mitigation and Income in Developing Countries from Changes in Use and Management of Agricultural and Forest Lands. Occasional Paper 2001-04. Centre for Environment and Society, University of Essex, UK.

Nilsson, S. and W. Schopfhauser (1995). The Carbon Sequestration Potential of a Global Afforestation Program. *Climatic Change,* 30, 267–293.

Noe, D. (1999). Costs and Potencial for Carbon Sequestration in the Forestry Sector of Chile. Pontificia Universidad Católica de Chile, Santiago, Chile.

Parks, P.J. and I.W. Hardie (1995). Least-Cost Forest Carbon Reserves: Cost-Effective Subsidies to Convert Marginal Agricultural Land to Forests. *Land Economics,* 71, 122–136.

Pereira, N. Y. Bonduki and M. Perdomo (1997). Potential Options to Reduce GHG Emissions in Venezuela. *Applied Energy,* 56, 265–286.

Ramankutty, N., J.A. Foley, J. Norman and K. McSweeney (2002). The Global Distribution of Cultivable Lands: Current Patterns and Sensitivity to Possible Climate Change. *Global Ecology and Biogeography,* 11(5), 377–392.

SAGE (2002). Atlas of the Biosphere. Data: Land Use, Suitability for Agriculture; Data: Ecosystems, Net Primary Productivity. Center for Sustainability and Global Environment (SAGE), Institute for Environmental Studies, University of Wisconsin, USA. Available on the Internet: http://atlas.sage.wisc.edu/maps.php.

Sathaye, J.A., W.R. Makundi, K. Andrasko, R. Boer, N.H. Ravindranath, P. Sudha, S. Rao, R. Lasco, F. Pulhin, O. Masera, A. Ceron, J. Ordoñez, X. Deying, X. Zhang and S. Zuomin (2001). Carbon Mitigation Potential and Costs of Forestry Options in Brazil, China, Indonesia, Mexico, the Philippines and Tanzania. *Mitigation and Adaptation Strategies for Global Change,* 6, 185–211.

Sedjo, R. (1999). Potential for Carbon Forest Plantations in Marginal Timber Forests: The Case of Patagonia, Argentina. Discussion Paper 99-27. Resources for the Future, Washington DC, USA.

Sedjo, R. and E. Ley (1995). Argentina: Carbon and Forests. Report prepared for the Global Environmental Facility of The World Bank. Resources for the Future, Washington DC, USA.

Sedjo, R., B. Sohngen and R. Mendelsohn (2001). Estimating Carbon Supply Curves for Global Forests and Other Land Uses. Discussion Paper 01-19. Resources for the Future, Washington DC, USA.

Sijm, J. (2000). Kyoto Mechanisms: The Role of Joint Implementation, the Clean Development Mechanism and Emissions Trading in Reducing Greenhouse Gas Emissions. Energy Research Centre of the Netherlands (ECN), Petten.

Sohngen, B. and R. Sedjo (2000). Potential Carbon Flux from Timber Harvests and Management on the Context of a Global Timber Market. *Climatic Change*, 44, 151–172.

Sohngen, B., R. Mendelsohn and R. Sedjo (1999). Forest Management, Conservation, and Global Timber Markets. *American Journal of Agricultural Economics*, 81, 1–13.

Stavins, R.N. (1999). The Costs of Carbon Sequestration: A Revealed-Preference Approach. *The American Economic Review*, 89, 994–1009.

Trexler, M. and C. Haugen (1995). Keeping It Green: Evaluating Tropical Forestry Strategies to Mitigate Global Warming. World Resource Institute, Washington DC, USA.

UNFCCC (1999a). Uniform Reporting Format: Activities Implemented Jointly under the Pilot Phase. Klinki Forestry Project, Costa Rica. United Nations Framework Convention on Climate Change (UNFCCC), Bonn, Germany.

UNFCCC (1999b). Uniform Reporting Format: Activities Implemented Jointly under the Pilot Phase. Scolel Té: Carbon Sequestration and Sustainable Forest Management in Chiapas. United Nations Framework Convention on Climate Change (UNFCCC), Bonn, Germany.

UNFCCC (2001). The Marrakesh Accords and the Marrakesh Declaration. Version: 10-11-01; 5:29. United Nations Framework Convention on Climate Change (UNFCCC), Bonn, Germany, 68–71.

USCSP (1999). Climate Change: Mitigation, Vulnerability, and Adaptation in Developing and Transition Countries. US Country Studies Program (USCSP) support for climate change studies, plans, and technology assessments, New York, USA.

van der Linden, N.H. (1999). Potential and Cost of Clean Development Mechanism Options in the Energy Sector. Energy Research Centre of the Netherlands (ECN), Petten.

van Kooten, G., C. Binkley and G. Delcourt (1995). Effect of Carbon Taxes and Subsidies on Optimal Forest Rotation Age and Supply of Carbon Services. *American Journal of Agricultural Economics*, 77, 365–374.

Verweij, H.J.A. and I.M. Emmer (1998). Implementing Carbon Sequestration Projects in Two Contrasting Areas: The Czech Republic and Uganda. *Commonwealth Forestry Review*, 77, 203–208.

Winjum, J.K., R.K. Dixon and P.E. Schroeder (1993). Forest Management and Carbon Storage: An Analysis of 12 Key Forest Nations. *Water, Air, and Soil Pollution*, 70, 239–257.

World Bank (2000). World Development Indicators. The World Bank, Washington DC, USA.

Xu, D. (1995). The Potential for Reducing Atmospheric Carbon by Large-Scale Afforestation in China and Related Cost Benefit Analysis. *Biomass and Bioenergy*, 8, 337–344.

Appendix: Data Comparison and Sensitivity Analysis

As usual in empirical studies, the final legitimacy of the outcomes for the Latin American case study is dependent on the input parameters and datasets. Therefore, it is necessary to compare the data used in the model with existing data from the literature and extend the discussion on the sensitivity analysis developed in Section 4.3.5. We focus on four major parameters, namely timber price, land price, rate of carbon uptake, and discount rate.

Timber Price

The analysis considered a stumpage timber price of US\$5/m^3 for the less accessible areas and US\$35/m^3 for areas with the highest access. It is assumed that accessibility is represented by population density, noting that more populated areas have a higher road infrastructure. The distribution of timber prices across grids is given in Figure A1, which shows that in most grids, the timber price is below US\$10/m^3. For comparison, the latest International Tropical Timber Organization (ITTO) market information for Brazil, mentions mill yard prices of US\$21/m^3 for soft wood logs and US\$57/m^3 for hard wood logs (ITTO, 2003). Subtracting US\$15/m^3 for felling and transportation to the mill yard (50 km), stumpage timber prices are US\$6/m^3 for soft wood and US\$42/m^3 for hard wood (note that generally, tree plantations produce soft and medium density wood). Masera *et al*. (1997) proposed US\$55/m^3 at the mill site in Mexico (about US\$40/m^3 stumpage), and Sedjo (1999) proposed US\$15/m^3 for stumpage timber in Patagonia, Argentina. Compared with our data, we have similar prices although we have no precise information on the accessibility of the forests mentioned in the literature.

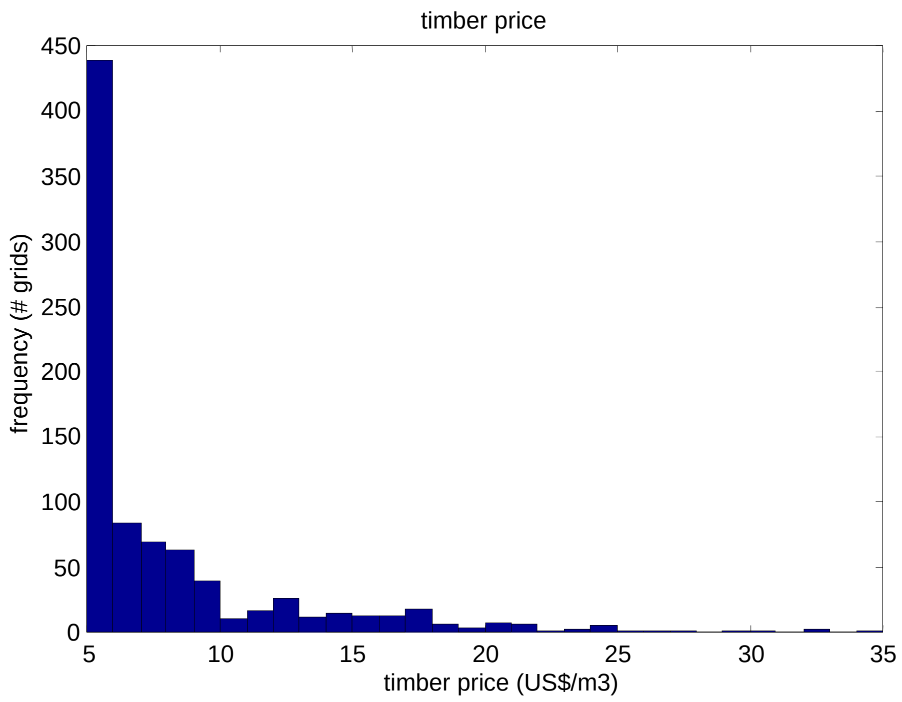

Figure A1: Distribution of timber price across grids.

If we consider 50% changes on timber prices compared with our basic scenario, we obtain the supply curves shown in Figure A2. Taking a cumulative sequestration level of 165 MtC that corresponds to the demand for CDM sinks without US participation, the carbon price ranges between US$16/tC and US$35/tC (the price for the main scenario is US$26/tC).

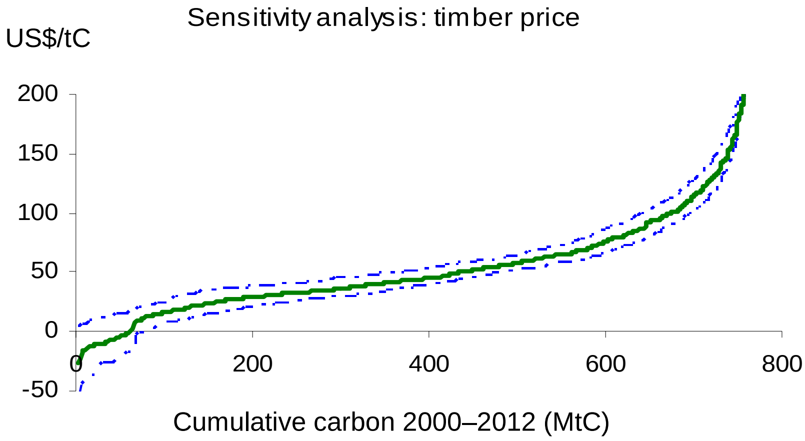

Figure A2: Sensitivity analysis for timber price. Dotted lines show supply curves with ± 50% of the timber price for each cell.

Land Price

First, we test the 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. Table A1 shows that the impact on the supply curve is small. This surprising result is explained by two factors: (i) suitability for agriculture and population density are not totally independent since the correlation coefficient between the two parameters is 0.24, and (ii) when the production function changes, the land price for some grids rises while for other grids diminishes, leading to a small aggregate effect on the supply curve. For example, if we take a threshold carbon price of US$100/tC and we change the production function, some grids that at the beginning were below US$100/tC, will later be over US$100/tC and vice versa. Thus, when grids are aggregated in the supply-curve, the effect of changing the production function has been reduced.

Table A1: Effect of the function for the land price on the carbon supply curve.

	Cumulative carbon sequestration 2000–2012 (MtC)		
Land price function: $L = \upsilon \cdot S^{\alpha} \cdot D^{\gamma}$	***Carbon price: US$20/tC***	***Carbon price: US$50/tC***	***Carbon price: US$100/tC***
α = *γ(main scenario)*	*127*	*434*	*675*
α = 2γ	123	419	656
2α = γ	135	460	681

Note: upper and lower bounds for the land price remain the same.

As discussed in Section 4.2, there is little information on land prices, but experience in Latin America shows that an acceptable range for land prices is between US$100/ha and US$2500/ha depending on the quality and accessibility of the site (EcoSecurities, 2002; de Jong *et al*., 2000; Benítez *et al*., 2001; Sedjo, 1999). Land prices in our model are in a similar range (Figure A3). We test the impact on the supply curve for 50% changes on the land price for each grid (Figure A4). Under this uncertainty range, the required carbon price for a cumulative sequestration level of 165 MtC is between US$20/tC and US$32/tC.

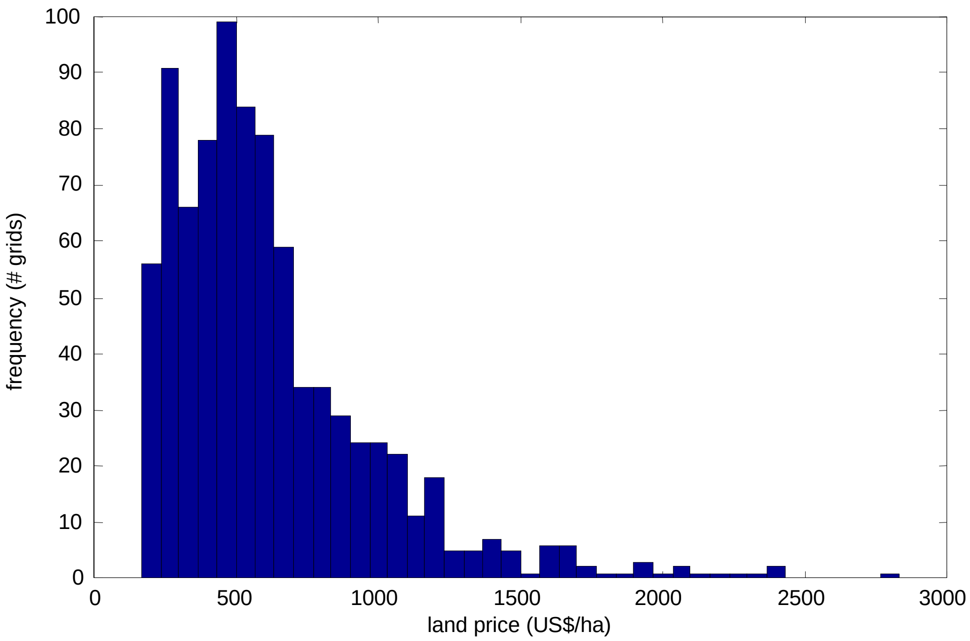

Figure A3: Distribution of land prices across grids.

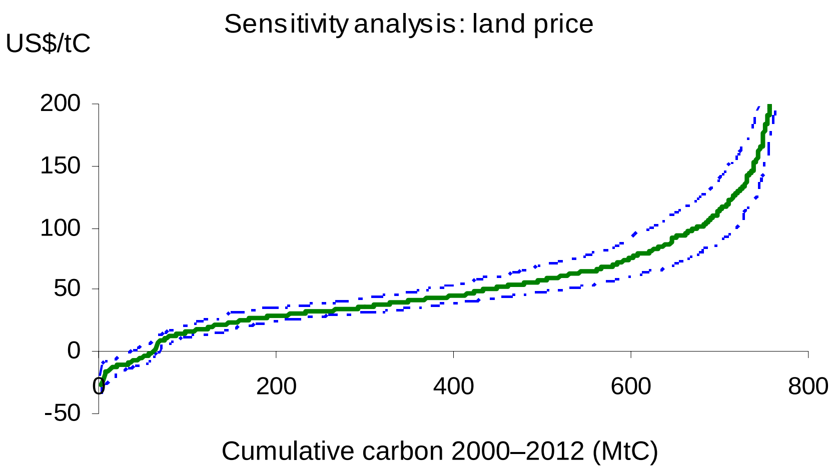

Figure A4: Sensitivity analysis for land price. Dotted lines show supply curves with ± 50% of the land price for each cell.

Rate of Carbon Uptake

One of the most sensitive parameters is the rate of carbon uptake since it influences both the carbon sequestration potential and timber productivity. The rate of carbon uptake across grids ranges from 0.6 tC/ha/yr to 6.2 tC/ha/yr (Figure A5). The average for tropical regions is 3.2 tC/ha/yr and for temperate regions, 1.8 tC/ha/yr. In the literature, we find values of 0.3–1.5tC/ha/yr for the dry tropics and 6–12 tC/ha/yr in the wet tropics (Trexler and Haugen, 1995), 3.8 tC/ha/yr for Patagonia, Argentina (de Koning *et al*., 2002), and 4.5 tC/ha/yr for temperate South America[17] (Brown *et al*., 1996). This comparison suggests that the values used in this analysis are conservative, but conservative values are appropriate due to the sustainability requirements for CDM projects that suggest excluding fast growing tree species. In our calculations, we used a conversion factor of 50% for converting NPP to carbon accumulation rates. Uncertainties in soil respiration, humus depletion, biomass decomposition, fires and baseline might affect this conversion factor. Figure A6 shows supply curves using a conversion factor 25% above and 25% below our estimate (a conversion factor of 62.5% and 37.5%, respectively). Under this range of uncertainty, the required carbon price for a cumulative sequestration level of 165 MtC is between US$12/tC and US$41/tC.

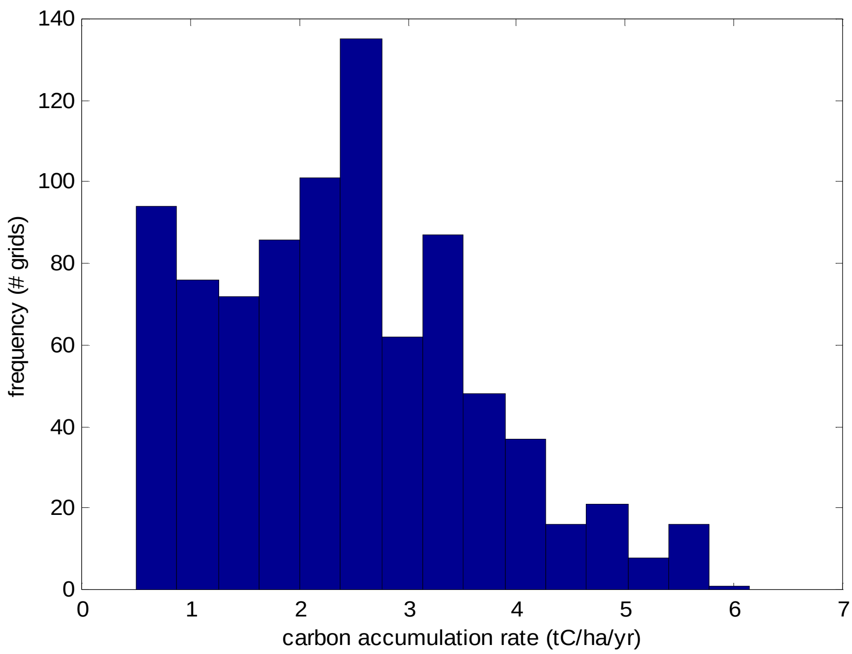

Figure A5: Rate of carbon uptake across grids.

[17] Estimated from MAI, considering a carbon density of 0.3tC/m^3.

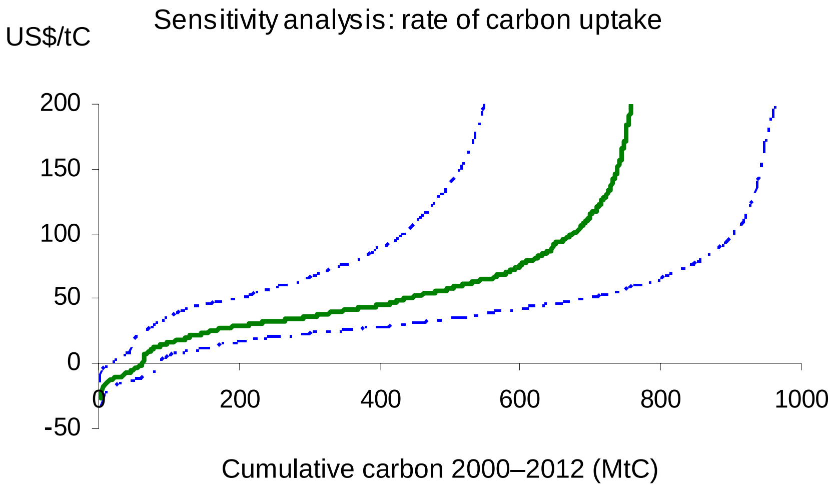

Figure A6: Sensitivity analysis for rate of carbon uptake. Dotted lines show supply curves with ± 25% of the rate of carbon uptake for each cell.

Discount Rate

This study used a discount rate of 5%. Other studies on Latin America have proposed higher discount rates like 10% in Mexico (Masera *et al*., 1995), 12% in Brazil (Fearnside, 1995) and 10% in Argentina (Sedjo, 1999). The reason for having such higher discount rates is the inclusion of a risk premium for investing in these countries. Environmentalists, however, propose that discounting rates for long-term climate change investments should be lower than current rates of interest. It is beyond the purpose of this study to extensively discuss the discount rate to be used, but our interest is to show the applicability of the method for evaluating different scenarios. Figure A7 shows supply curves using 3%, 5% and 8% discounting. Under this range, the required carbon price for a cumulative sequestration level of 165 MtC is between US$16/tC and US$38/tC.

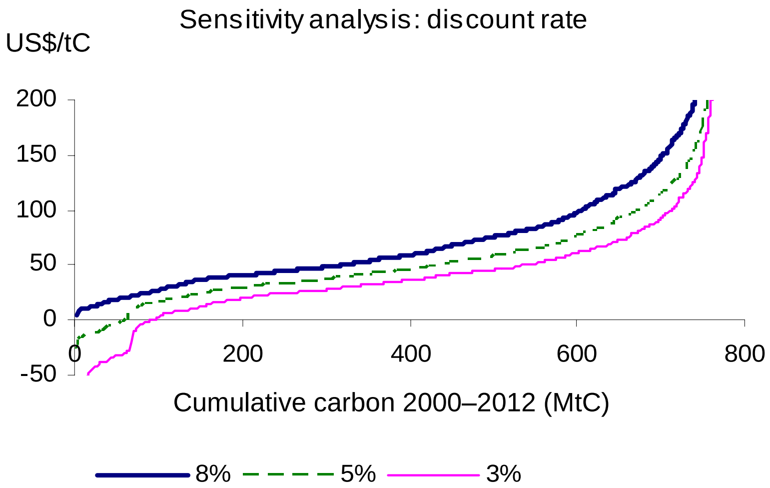

Figure A7: Sensitivity analysis for discount rate.

Concluding Remarks

Based on this sensitivity analysis, we conclude that Latin America could supply large quantities of carbon sequestration, which are comparable with the demand for CDM sinks for 2012, at prices between US$10/tC and US$45/tC. In addition, we comment on the following:

- The rate of carbon uptake is the most sensitive parameter, and more and reliable data sources on the basis of current ecological models and empirical databases should be used for more detailed analysis. Moreover, assumptions on technological learning of plantation management should be considered.
- 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 and attitudes of landowners.
- The carbon price has a strong influence on the sensitivity, i.e., the higher the price is, the more robust the results are. The more extensive the afforestation activities will be (which causes a higher carbon price), the more certain the results. Thus, risk aversion might call for paying a higher price for having more secure results.
- This analysis has tested the sensitivity of the supply curve that contains all grids, but not the sensitivity for individual grids. The range of uncertainty for particular grids is higher, since in the supply curve negative and positive effects of uncertainty cancel each other. In addition, we should be aware that this method could not substitute gathering project-level information for CDM investments.

Finally, the estimated supply curve could be compared with studies from the literature, but just at the left side of the curve (low cost) where information from previous studies is available. In tropical Latin America, we found zero cost and low cost options for carbon sequestration as suggested by Sathaye *et al*. (2001), Kauppi and Sedjo (2001), Frumhoff *et al*. (1998), Fearnside (1995), and Winjum *et al*. (1993). In temperate Latin America we did not find zero cost options as mentioned in Sathaye *et al*. (2001) nor costs below US$10/tC as mentioned in Kolshus (2001) and Masera *et al*. (1997). This difference for temperate regions relies on the conservative rates of carbon uptake used in the analysis and the different ways of carbon accounting.