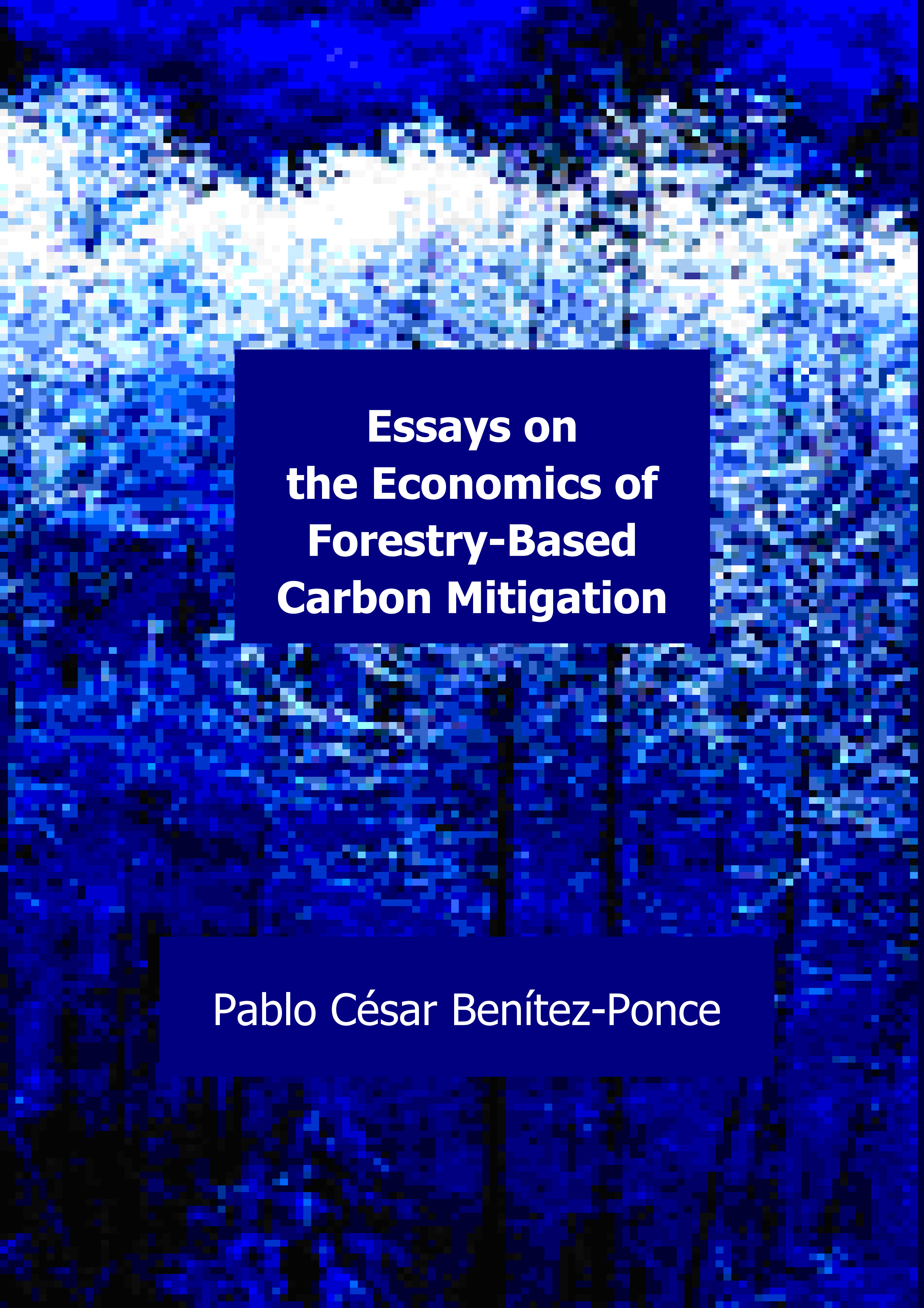

Essays on the Economics of Forestry-Based Carbon Mitigation

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To Liliana

Abstract

This thesis is a collection of articles that deal with the economics of carbon sequestration in forests. It pays special attention to the comparison of forestry alternatives for carbon sequestration, carbon supply curves at regional and global levels and the impact of risk on payments for ecosystem services. Case-studies in Ecuador and Latin America contribute to a better understanding of these issues. Policy implications of this research are: (1) Natural regeneration of secondary forests is a cost-efficient activity for carbon sequestration in the humid tropics and should be included as part of the Clean Development Mechanism of the Kyoto Protocol. (2) Country-risk is a relevant factor to be considered in climate change mitigation assessments. When accounting for country risk — associated with political, economic and financial risks — the potential carbon sequestration at a global level is reduced by more than half. (3) Potential carbon sequestration through afforestation ranges from 5% to 25% of the emission reduction targets of different policy scenarios for stabilization of atmospheric greenhouse gas concentrations, and therefore is relevant in a global context. (4) Farm-level decisions are influenced by risks associated to price and yield volatility of land-use alternatives. Efficient conservation policies that aim at enhancing carbon sequestration, biodiversity and other environmental services should look at both net revenues and risks. Combining payments for conservation with risk-hedging strategies is a policy option to be considered by conservation agencies worldwide.

Keywords: climate change, carbon costs, afforestation, risk, secondary forests, conservation payments, ecosystem services

Preface

This thesis summarizes my work during the last four years in the field of the economics of climate change. During this period I joint different research projects carried out in The Netherlands, Austria and Ecuador. The output of these research activities contributes to the different chapters of this thesis.

Although writing a thesis is a solitary task, you could hardly succeed without support from other people. My case is no exception from this rule.

To start with, I would like to thank my promotor Henk Folmer. Henk is not just a great professor who lets the student learning from him, but also a friend to whom to trust. I appreciate a lot his very broad knowledge and fresh perspectives on economics and his availability to revise my thesis on a day-to-day basis at a distance of more than 10.000 km away. I am also very grateful to my supervisor Roland Olschewski. I have worked under Roland's lead within two challenging research projects carried out in my home country, Ecuador. Thanks for his wise advices and for trusting my ideas. Without his continuous support, finishing this thesis would have hardly been possible. Many thanks as well to the help of Kees van Kooten and Timo Kuosmanen who shared their knowledge in the most relevant stages of this thesis. Also, I am grateful to the ECH Group for their valuable support in completing my PhD.

Much of this work had contributed to larger research projects. In Ecuador, I have worked for the Bio-Sys Project of Göttingen University and for the CO_2 Project of the Tropical Ecology Support Program of the German Agency of Technical Cooperation (GTZ). Within these projects, I had the excellent opportunity to learn from my colleagues Free de Koning and Magdalena López. While we have intensively worked in the rural areas of West Ecuador interviewing farmers and measuring carbon uptake in forests, I learnt from them about soil carbon sequestration, secondary forests and agroforestry systems. A special thanks goes to Allyson Tinney Rivera.

When I was in The Netherlands I worked for the Department of Policy Studies of the Energy Research Centre of the Netherlands (ECN), where I received the wise advice of Jos Sijm. Later on, I spent three months in the International Institute for Applied Systems Analysis (IIASA) in Austria. My best regards to my colleagues of IIASA and from the National Institute for Environmental Studies in Japan (NIES) who enthusiastically contributed to several co-authored publications. In particular, I gratefully acknowledge Michael Obersteiner, Ger Klassen and Ian McCallum from IIASA and Yoshiki Yamagata from NIES. Summer at IIASA was not only research, but also the time and the place to meet my wife Liliana. Three months was sufficient time for finding one's choice for life.

Writing a PhD thesis requires an adequate balance of one´s personal life and research. Those moments when I dedicated more time to Liliana and our sons Daniel and David (to be born) were those moments that I had the best output of my thesis. Without Liliana, none of this work would have been possible. She not only advised me on how to get funds for my research and finish my thesis in an efficient and joyful way, but she patiently and enthusiastically did the packing when those funds worked out. She was and always be my inspiration.

But, writing a PhD thesis is not just about science. Financial support from the German Ministry of Education and Science under the BioTEAM-Program, the Energy Research Centre of the Netherlands and the Tropical Ecology Support Program of the German Agency of Technical Cooperation is gratefully acknowledged.

Quito, November, 2004

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Chapter 1

General Introduction

1 The Impacts of Global Warming

There is plenty of scientific evidence that increases in anthropogenic emissions of greenhouse gases (GHG) are warming the Earth (IPCC, 2001a). Latest predictions of the International Panel of Climate Change (IPCC) suggest that by 2100, human-related GHG emissions would cause the global average surface air temperature to increase by 1.4 - 5.8 °C, and the average sea level to rise between 8 and 88 cm (IPCC, 2001a). This warming would vary between regions causing diverse impacts on agriculture, forestry, human health, infrastructure, water resources, energy supply, industry and biodiversity. Tropical regions would be more affected by a decrease in agricultural production, while temperate regions would face the expansion of vector-born diseases like malaria and dengue fever, and would confront higher temperatures and more frequent heat waves during summer. Natural systems like coral reefs, mangroves, tropical and boreal forests, polar and alpine ecosystems, and prairie wetlands are at risk of irreversible damage and the loss of vulnerable species (IPCC, 2001a).

Globally, increases in the occurrence of extreme weather events will result in high costs to society and higher insurance premiums, and it might happen that certain risks would be re-classified as uninsurable. The costs of weather events has increased rapidly during the last decades despite the efforts of fortifying infrastructure and enhanced disaster aid. Global economic losses from catastrophic events increased by a factor of 10 in four decades: from US$ 3.9 billion in 1950 to US$ 40 billion in 1990 (measured in constant US$ of 1999) (Munich Re, 1999). Part of this upward trend in catastrophic loss is linked to socioeconomic factors like population growth, migration, increase in wealth and urbanization in vulnerable areas, but another part is also linked to climatic factors like observed changes in precipitation and flooding events (IPCC, 2001a). Climate change is expected to increase actuarial uncertainty in risk assessment. Such changes would cause an increase in insurance premiums, slow the expansion of insurance services in developing countries and increase the demand of government-funded compensation after disaster. Whereas governments and financial institutions in more developed countries are usually able to cope with the impacts of disasters, in developing countries a substantial strain is posed on a country's resources after a catastrophe (Hochrainer et al., 2004). There, losses historically have been financed by diversions from the government budget and by already allocated loans, and the impact of a catastrophe could affect a larger proportion of the country's population and significantly affect economic growth.

Economic studies on global warming have attempted to estimate how costly its impacts would be (Darwin et al. 1995; Yohe and Schlesinger, 1998; Nordhaus, 1998). These studies have focused on some of the sensible areas like agriculture, sea-level rise, health, human settlements, ecosystems and catastrophic events. Table 1 shows a brief summary of the impacts of a 2.5 degree increase in the globally averaged air temperature (Nordhaus, 1998). The extent of global warming damages range between zero and 5% of GDP for different world regions. Most affected regions are the European Union within industrialized countries and India and Africa within the developing world. Also, catastrophic events would represent the highest share of global warming damages.

This chapter starts with a literature review on relevant climate change issues and then provides an outline of the thesis. The structure of the article is as follows: Section 2 deals with climate change policy and discusses aspects related to Integrated Assessment Models and the Kyoto Protocol of Climate Change. Section 3 provides a brief summary of major climate change mitigation options and Section 4 focuses on the economic aspects of forestry-based carbon sequestration. Section 5 describes the outline and main objective of the thesis.

Table 1. Impact of 2.5 Degree Warming Measured as Percent of Market Incomes.

Region /Country	Total	Non-catastrophic impacts	Catastrophic impacts
United States	0.45%	0.01%	0.44%
China	0.22%	-0.29%	0.51%
Japan	0.50%	0.06%	0.44%
EU	2.83%	0.92%	1.91%
Russia	-0.65%	-1.64%	0.99%
India	4.93%	2.66%	2.27%
Other high income (Canada, Australia, ..)	-0.39%	-1.33%	0.94%
High-income OPEC (Saudi Arabia, Libya, UAE, ..)	1.95%	1.49%	0.46%
Easter Europe (Poland, Ukraine,….)	0.71%	0.23%	0.48%
Middle income (Brazil, Korea, Taiwan, …)	2.44%	1.97%	0.47%
Lower-middle income (Mexico, Turkey, Iran, …)	1.81%	0.80%	1.01%
Africa (Nigeria, Zaire, …)	3.91%	3.51%	0.40%
Low income (Indonesia, Pakistan, …)	2.64%	1.55%	1.09%
Global average			
Output weighted (according to expected output in 2100)	1.50%	0.48%	1.02%
Population weighted (according to population in 1995)	2.19%	1.14%	1.05%

Source: Nordhaus (1998)
Note: Positive numbers indicate damages; negative numbers indicate benefits

2 Global Warming Policy

Facing the threats of global warming, the global society could set up policies aiming at adaptation or mitigation (or both). Adaptation means that humans would learn to live with global warming by protecting cities from sea-level rise, mobilizing human settlements out of areas vulnerable to extreme events, changing infrastructure and industry, and altering land use towards crops and forests more resistant to temperature rise. Mitigation consists of taking measures for reducing GHG atmospheric concentrations, so that global warming is prevented. A mixed policy would consider some mitigation efforts, but would require humans to adapt to global warming in some extent.

There is an ongoing debate on how to set a climate change policy. One option is to set *a priori* a target for GHG emissions or concentrations, based on what scientists or policy makers would consider to be appropriate. The problem of this alternative is that the choice for the target GHG emissions remains arbitrary and there is the risk of spending too much or too little for mitigating global warming. The Kyoto Protocol of Climate Change has followed this approach. A second option is to search for the optimum policy where marginal abatement costs equal marginal damages caused by global warming. This seems an obvious criterion for economists, but it is difficult to put into practice for a number of reasons, (i) there is wide uncertainty on the costs caused by global warming, (ii) the damages of global warming are unequal among regions where it appears that developing countries would be more vulnerable to climate change and they would be at risk of paying most of the costs associated with climate change, (iii) global warming could cause irreversible changes in ecosystems where unique species might simply disappear. A third option is adaptation to climate change. Having knowledge on what the impacts of global warming would be, human settlements could choose for adaptation. According to the IPCC (2001a) adaptive capacity in industrialized countries is much higher than that in developing countries. But, it is most likely that technological transfer and economic growth would enhance the adaptive capacity of developing countries.[1]

Regardless of the policy choice, it is desirable that any climate change policy be economically efficient, so that environmental objectives are attained in the least cost manner (Nordhaus and Boyer, 2000). This efficiency should consider both spatial (regional) and temporary aspects. This means that we should allocate resources across regions to minimize the costs of attaining the global emissions target, and also, the emission reduction path should be the one that minimizes the present value of the cost of emissions reductions subject to the policy's environmental goal. As an attempt to guide policy makers on the decisions surrounding global warming, integrated assessment models have been developed.

2.1 Integrated Assessment Models: A Guide for Policy Making

Integrated Assessment Models (IAM) combine the natural science and economic aspects of climate change in order to assess policy options. They have been used to describe inter-temporal optimization decisions, combining the economic macro-

[1] This thesis only deals with mitigation policies. Relevant issues concerning adaptation are kept for further research.

framework, energy models and environmental or climate change models (Carraro, 2002). In addition, IAM can incorporate uncertainties and risk in scenarios and climate policy. IAM have three major goals (Weyant et al, 1996), (i) assess climate change control policies, (ii) constructively force multiple dimensions of the climate change problem into the same framework, and (iii) quantify the relative importance of climate change in the context of other global problems. There exist more than twenty IAM developed worldwide. Examples of such models are, DICE (Nordhaus, 1993), IMAGE (Alcamo, 1994), MERGE (Manne et al., 1995) and RICE (Nordhaus and Bayer, 2000).

The literature often distinguishes between policy evaluation IAM and policy optimization IAM (Kelly and Kolstad, 1999). Policy evaluation models or simulation models consider the effect of a single policy option on the biosphere and climate and its economic impact. In contrast, policy optimization models seek to find the optimal policy which minimizes the costs of achieving a particular goal. Policy evaluation models have the advantage that they allow for much greater detail on the physical, economic and social aspects of climate change. They are also more flexible for taking actions by agents and governments as given and to freely assume growth rates in developing countries, which are often far from the optimum growth rates (Kelly and Kolstad, 1999). But, policy evaluation models are often as good as the modeler's ability to predict decisions and they are more like "black boxes" where the meaning of the results is not always easily interpreted. Policy optimization models are more economically founded and lead to endogenous estimates of climate policy (e.g. optimal carbon tax) and producers and consumer responses to such policies (e.g. producers and consumers determine endogenously the optimal mix of fossil fuels and renewables). However, policy optimization models might lack detail of relevant aspects of climate change.

DICE and RICE models

Throughout this thesis, we refer to the DICE (Dynamic Integrated model of Climate and the Economy) and RICE (Regional Dynamic Integrated model of Climate and the Economy) models which are among the most popular tools within economics for the study of climate change (Nordhaus and Boyer, 2000). Therefore we devote these paragraphs for describing these models and their major findings.

The RICE model is more elaborated than the DICE model in the sense that it divides the world in 8 regions. Each region has its own set of preferences, economic growth, consumption patterns and emission intensities. Meanwhile, the DICE model considers the world as one single economy. The approach of these models is to view climate change in the context of economic growth theory. In the neoclassical growth model, society invests in tangible capital goods, thereby abstaining from consumption today, in order to increase consumption in the future. Using the neoclassical growth model, emissions and interactions between economic activities and climate are incorporated. In the RICE model, the world is composed of several regions, where each region has a well-defined set of preferences represented by a "social welfare function". In order to maximize the social welfare function each region finds optimal paths of consumption, investment in tangible capital, and climate investments, i.e. reductions of GHG emissions. The RICE/DICE models contain a climate sub-model that includes a number of geophysical relationships that link together the different forces affecting climate change. This part contains a carbon cycle, a radiative forcing equation[2], climate-change equations, and a climate-damage relationship.

Within the RICE and DICE models different scenarios have been studied including: (i) No controls for GHG emissions or baseline scenario. (ii) Optimal policy. This scenario finds the optimal trajectory for the world carbon tax and global industrial emissions that balances current abatement costs against future environmental benefits of carbon abatement. (iii) Stabilize global emissions at 1990 levels. (iv) Stabilize carbon dioxide (CO_2) concentrations at two times pre-industrial levels. (v) Stabilize temperature rise at 2.5 ˚C. Results of the RICE model in terms of costs and benefits of emission abatement for the different scenarios are shown in Table 2.

[2] The carbon cycle provides the balance of GHG between sources (emissions) and sinks (carbon uptake in land and oceans). GHG accumulation in the atmosphere is the difference between both. This accumulation of GHG leads to global warming by increased radiation. The radiative forcing equation provides a relationship between GHG accumulation in the atmosphere and radiative force, F(T). Having knowledge of F(T), temperature changes for each year could be estimated.

With respect to the DICE model, the net economic impacts of policy scenarios are different than those of the RICE, but the ranking of the alternatives is maintained. For example, the optimal policy scenario of the DICE model leads to net benefits of 254 billion US$, about 30% larger than the predictions of the RICE model.

Table 2. Costs and benefits of emission abatement for different policy scenarios of the RICE model.

Policy Scenario	Carbon tax in 2005 (1990 US$/tC)	Costs and Benefits in billions of 1990 US$ Abatement Costs	Environmental Benefit	Net Economic Impact
Optimal Policy	9.1	-98	296	198
Optimal Policy with 10 years delay	9.1	-92	283	192
Limit CO_2 emissions at 1990 levels	52.5	-4533	1512	-3021
Limit CO_2 concentrations at two times pre-industrial levels	3.8	-1365	681	-684
Limit temperature rise at 2.5 °C	11.8	-3553	1139	-2414

Source: Nordhaus and Boyer (2000)

From Table 2 we see that the choice of non-optimal policies might lead to huge losses. With respect to the carbon tax at present times, the optimal policy proposes a modest tax of $9.1/tC which would cause no harm to the world economy. Comparing the different scenarios, limiting CO_2 emissions as in the case of the Kyoto Protocol might be too expensive in the long-term and it would be better to limit atmospheric concentrations rather than emissions. Also, a 10-year delay in the optimal policy has small impact, suggesting that there are no needs to rush for the implementation of climate change policies.

Further Improvements of IAM

There are several aspects in which IAM need to be improved. Besides the need for better data on expected economic damages of climate change, future research on IAM should consider:

- Economic modeling in developing countries. Most current IAM do not match the economic and social organization of developing countries well (Carraro, 2002). This leads to biases in global assessments where climate change mitigation and impacts are evaluated in developing countries as if their economies work like those of developed countries.

- Endogenous Technical Change. Most IAM models have considered technical change as an exogenous variable, where emission intensity of output is expected to decrease based on historical records (Kelly and Kolstad, 1999). But, technical change might be critically important in GHG mitigation scenarios. For example, the development of inexpensive electric automobiles or solar power might reduce significantly GHG emissions at low cost. Further research is needed in order to incorporate endogenous innovation in climate models.
- Specifying Regulation Instruments (Kelly and Kolstad, 1999). Most IAM calculate optimal carbon taxes for achieving emission reduction targets. But, the impact of recycling such tax revenues needs to be evaluated. Also, regulation instruments have associated monitoring costs and penalties for non-compliance which would reduce the overall efficiency of mitigation strategies.
- Adjustment to Climate Change (Kelly and Kolstad, 1999). Agents within the economy would respond to global warming in order to reduce its impacts. For example, given changes in rainfall and precipitation, farmers could modify crop choice in order to reduce the losses caused by climate change. Also, migration patterns and urbanization in developing countries might be modified in such a way that areas highly vulnerable to climate change would limit their growth.
- Include carbon mitigation in sinks. One of the major drawbacks of IAM is that they mainly focus on mitigation in the energy sector. For example, the RICE and DICE models consider emissions from land use as exogenous. But, GHG emissions from land use and current terrestrial uptake are significant (see Table 4 in the next section), so including GHG mitigation in sinks is something to be considered within IAM. This thesis works towards this direction by studying relevant economic aspects of carbon sequestration in forests.

2.2 Uncertainty in Policy Decision Making

A major challenge for defining an efficient climate change policy is dealing with uncertainties. Uncertainty is one of the most frequently appearing words in any climate change debate. Decisions are made for a problem affecting 3 or 4 generations beyond with limited knowledge on how costly the climate change damages would be, where such damages would occur, the emissions path to be expected in a business-as-usual scenario, and the cost-effectiveness of a large number of GHG mitigation strategies. For policy-decision making it is important to classify uncertainty in the following categories:

- Parametric uncertainty with known probabilities. This consists of known effects that we can not estimate exactly, but only provide confidence intervals (Aaheim and Bretteville, 2001). This uncertainty is often found in known geo-physical interactions like the impact of GHG concentrations on temperature changes (radiative forcing equation). In this case, the estimate of temperature changes for a given concentration of GHG has a lower and higher confidence interval. Analysis of this type of uncertainty is relatively well-developed and could be dealt with simple sensitivity analysis or with more comprehensive approaches like Montecarlo simulations. Also, the development of more precise geo-physical models might lead to reducing this type of uncertainty.
- The occurrence of possible extreme events. This category refers to impacts that might occur as a consequence of climate change, like droughts, floods, hurricanes and diseases (Aaheim and Bretteville, 2001). These events have a small probability of occuring in a certain region, but a large impact if they occur. Decision-making and evaluation of impacts in such cases is much more complex than in the case of parametric uncertainty (Hochrainer et al., 2004).
- The baseline emission scenario. Forecasting world emissions and atmospheric GHG concentrations in the baseline scenario (scenario without control of GHG) for a 100-yr period is complex. Emission paths are strongly influenced by technological innovation and political factors such as: openness for trade, institutions and economic policies in developing countries, wars and terrorism. The IPCC in their special report of emission scenarios (IPCC, 2000a) evaluated up to 40 possible scenarios (or possible baseline scenarios) that include a range of socioeconomic assumptions influencing population and GDP growth. The implications of these scenarios on climate change are summarized in Table 3. The uncertainties in population and GDP growth cause uncertainties in future CO_2 emissions and atmospheric concentrations. As a consequence, predicted temperature changes for 2100 relative to situations where

there are no GHG controls (baseline) would be between 1.4 and 5.8 ˚C and global sea-level rise would be between 9 and 88 cm. Unfortunately, it is not easy to reduce this type of uncertainty as in the case of parameter uncertainty in geo-physical models. Waiting a few decades would reveal more concrete patterns in economic growth and emissions throughout the globe.

Table 3. Uncertainty levels in population and GDP growth and its climate change implications.

Year	Global population (billions)	Global GDP (10^{12} US$/yr)	CO_2 atmospheric concentration (ppm)	Global Temperature Change (˚C)	Global Sea-Level Rise (cm)
1990	5.3	21	354	0	0
2000	6.1-6.2	25-28	367	0.2	2
2050	8.4 - 11.3	59-187	463-623	0.8 -2.6	5- 32
2100	7.0 -15.1	197-550	478-1099	1.4 -5.8	9-88

Source: IPCC (2001a)

- The relationship between abatement costs and environmental benefits. Ultimately, what matters for policy makers is the comparison of costs and benefits of climate policy. The uncertainty in this comparison is the aggregated impact of the unknown information on the geo-physical and socioeconomic aspects of climate change and it is strongly influenced by how much we know about future extreme events and its damages. There is still a long way to go for providing sensible estimates of the costs and benefits of climate change policy.

Within this framework of unknowns, climate change policy is very debatable. On one hand, when the benefits of climate change mitigation are uncertain it might be too risky to spend billions of dollars on a project which might never pay back. On the other hand, we could claim for the "precautionary principle" to govern, and reduce emissions as much as possible so as not to leave future generations facing possible irreparable damages. As a compromise, climate policy could follow small mitigation measures in the next decades until more information is available. As shown by the RICE model (Table 2), policy delay is not so costly. If we start now with modest climate abatement measures we could learn more about the real costs of mitigation and establish GHG emission trading schemes for use in the future. The Kyoto Protocol of Climate Change in its current stage might lead to these benefits.

2.3 The Kyoto Protocol and Other Agreements

Despite the uncertainty surrounding the climate change problem, we have experienced interesting developments in climate change policy during the last decade, particularly the ratification of the Kyoto Protocol.

The United Nations Framework Convention on Climate Change (UNFCCC) was established with the aim of stabilizing atmospheric GHG concentrations at "*safety levels*". The Kyoto Protocol (KP) of the Convention was proposed in 1997 and sets GHG emission caps for industrialized countries (the so-called Annex-I countries) for the period 2008-2012 with the aim to have further emission limitations in subsequent commitment periods (UNFCCC, 1998). The emission caps set at Kyoto for the fist commitment period were based on political agreements. Since the withdrawal of the United States, implementation of the KP has been mostly pushed by the European Union. After the ratification of the KP by the Russian Federation in November, 2004, the KP has the sufficient number of Annex-I countries participating and it is expected to enter into force by the 16th of February, 2005. Being the first global attempt towards the stabilization of GHG emissions, the KP introduced some novel elements aiming at cost-efficiency in mitigation. Particularly, the KP proposed a system for GHG emission trading that allows participation of developing countries through the so-called Clean Development Mechanism (CDM). The CDM includes project- based activities reducing GHG emissions in any type of energy-related activities and, regarding sinks, it includes afforestation and reforestation.

During the last decade, GHG emission trading activities have grown intensively through project-based mechanisms within the KP and voluntary agreements (de Coninck and van der Linden, 2003). Project-based mechanisms include the Prototype Carbon Fund, Biocarbon Fund, and Community Based Carbon Fund of the World Bank; the Dutch funds ERUPT and CERUPT for projects with European and developing countries respectively; and the Singapore ASEAN fund. The market for voluntary emission trading includes the participation of US-based programs like the Chicago Climate Exchange, and the Dutch system of trees for travel, where companies or individuals compensate the GHG emissions of air travelling by paying for carbon sequestration projects.

3 Climate Change Mitigation

Mitigating measures aim to reduce current trends of GHG accumulation in the atmosphere. Therefore, mitigation aims to influence the global carbon balance or CO_2 budget summarized in Table 4. There are two major sources of greenhouse gases where CO_2 is the most important: emissions from fossil fuel combustion and cement production (item A in Table 4) and, emissions from land-use change (item B). Part of these emissions is taken up in the biosphere, either by ocean uptake (item C) or by residual terrestrial uptake (item D). Since the total emissions are larger than ocean and terrestrial uptake, there is net accumulation of CO_2 in the atmosphere (item E) and this causes global warming.

Table 4. Average annual budget of CO_2, expressed in GtC /yr (error limits correspond to an estimated 90% confidence interval).

Flow / Uptake / Storage	*1980 to 1989*	*1989 to 1998*
(A) Emissions from fossil fuel combustion and cement production	5.5 ± 0.5	6.3 ± 0.6
(B) Emissions from land-use change	1.7 ± 0.8	1.6 ± 0.8
(C) Ocean uptake	2.0 ± 0.8	2.3 ± 0.8
(D) Residual terrestrial uptake	1.9 ± 1.3	2.3 ± 1.3
(E) Storage in the atmosphere (A+B) – (C+D)	3.3 ± 0.2	3.3 ± 0.2

Source: IPCC (2000b)

It is desirable that climate change mitigation be cost-efficient. Finding least-cost GHG abatement strategies requires comparing costs in different sectors like energy, industry, transport, agriculture and forestry. GHG mitigation measures are classified in two broad categories: the reduction of GHG emissions associated with energy and industrial processes; and the enhancement of terrestrial carbon sinks and reduction of emissions from land-use change.[3]

Reducing GHG emissions associated with energy and industrial processes requires combined efforts across energy generation, transport, industrial development and waste management (including the reduction of methane emissions from landfills). Examples of these mitigation activities are: increased fuel switching toward lower carbon fuels; continued growth in the use of efficient gas turbines and combined heat and power systems; greater reliance on renewable energy sources like biomass, wind

[3] This second category is often called mitigation in sinks.

and hydropower; increased recovery of landfill methane for electricity production; and the development of more efficient vehicles such as those using fuel-cells (IPCC, 2001b). The costs for these activities have been well-documented in studies dealing with the energy sector (see for example Gritsevskyi and Schrattenholzer, 2003; Sijm et al., 2000).

Carbon mitigation in sinks is related to diverse land use, land-use change and forestry (LULUCF) activities focusing on carbon sequestration like: afforestation, reforestation, enhanced forest regeneration, deforestation prevention, agroforestry and cropland management. These activities are described as follows,

- *Afforestation* refers to planting trees in non-forested areas, which have been non-forested for a long time. The UNFCCC (2001) defines afforestation as the “direct human-induced conversion of land that has not been forested for a period of at least 50 years to forested land through planting, seeding and/or the human-induced promotion of natural seed sources”.
- *Reforestation* refers to planting trees in non-forested areas that were forested before. If the non-forested land was without forests for a period longer than 50 years, this activity is considered afforestation by the UNFCCC. Afforestation and reforestation have the advantage that in general they provide higher net carbon sequestration per hectare than other LULUCF activities. Their disadvantages are the relatively high costs for tree-planting at the initial phase of the project.
- *Forest Regeneration* is the act of renewing tree cover by establishing young trees naturally or artificially, generally within degraded and highly intervened forests. Forest regeneration includes practices such as changes in tree plant density, enrichment planting, reduced grazing of forested savannas, and changes in tree species (IPCC, 2001b). Forest regeneration has the advantage that it does not involve land-use change as in the case of afforestation and reforestation, so initial costs are lower.
- *Deforestation Prevention.* Emissions of GHG caused by deforestation are large, ranging between 1 and 2.2 GtC/yr for the last decade (IPCC, 2000b). Deforestation could be prevented by different means, such as the provision of economic incentives to farmers for forest conservation or the encouragement of sustainable forest management practices. The magnitude of the GHG emissions that could be reduced

by preventing deforestation is large. Also, preventing deforestation would lead to the protection of biodiversity. This activity has been criticized, however, because it rewards those countries that have high deforestation rates.

- *Agroforestry.* This is a management system that integrates trees on farms and in the agricultural landscape (IPCC, 2001b). Agroforestry encompasses a wide variety of practices, including crop-fallow rotations, complex agroforests (e.g. coffee mixed with fruit trees and cultivated under shade), simple agroforests (e.g. oil-palm plantations) and silvopastoral systems (grasslands combined with trees that are used for cattle ranching). The ecological relevance of agroforest systems in the tropics is often not only associated with carbon sequestration, but also with the provision of biodiversity services.
- *Cropland and Grazing Land Management.* This includes diverse activities within agricultural land-uses like converting croplands into grasslands, adopting conservation tillage, modifying crop rotations and improving fertilizing and irrigation management (Lewandrowski et al., 2004). This activity is of particular interest to those countries that have large areas used for agriculture like the US.

During the Seventh Conference of the Parties (COP 7) held in Marrakesh in 2001, an agreement was reached for including afforestation and reforestation activities under the CDM (UNFCCC, 2001). In this agreement, they also set a cap on 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 consequences of having this cap on carbon sinks is discussed in Chapter 3). This decision was made as a compromise to satisfy those that were against sinks within the CDM (Small Island Sates, European Union) and those who where in favor (Canada, Japan) (IISD, 2000). Developing countries had mixed opinions about sinks in the CDM. Some tropical countries (e.g. Bolivia) were in favor of including deforestation prevention in the CDM in order to benefit from payments for forest conservation. Other developing countries, however, feared including sinks (and specially those related to deforestation) in the CDM because it could cause permit prices to drop down and cut revenues from CDM activities. But, from a global perspective, restricting the use of sinks resulted in efficiency losses in climate change mitigation and this decision must be reviewed for the future commitment periods of the Kyoto Protocol.

4 Economic Aspects of Forestry-Based Carbon Sequestration

In this section we turn our attention towards the economic aspects of forestry-based carbon sequestration. Here we provide an overview of land-use economic models, discuss relevant aspects related to accounting carbon sequestration benefits and summarize results from the literature.

4.1 Land-Use Economic Models

There are different ways of estimating carbon sequestration costs. In general, carbon sequestration costs are estimated in the context of cost-benefit analysis, where the net benefits of afforestation programs are compared with the net benefits of current land-use practices (Richards et al., 1994; Parks and Hardie, 1995; de Jong et al., 2000). The level of the analysis (farmer, region, country and world) and the availability of data usually determine the methodological choice for estimating net benefits of land-use change. In this section we describe some of the methods that have been used in the literature for estimating net benefits of land-use change and carbon sequestration policies.

- *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; Sohngen and Mendelsohn, 2003). 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 given when they are applied to a single country or "small" region. When the studied region is large, these models evaluate changes on timber demand as a response to supply.

- *Equilibrium models.* Environmental policies aiming at the enhancement of carbon sinks by payments for tree-planting will change the relative prices of goods. When large afforestation programs are implemented, timber prices might become cheaper and prices for agricultural products might rise (assuming that afforestation occurs in land that is currently used for agriculture). This will have feedback effects on the economic structure and product mix, economic growth, the allocation of resources and the distribution of income (Zhang and Folmer, 1998). In the context of payments for carbon sequestration, general equilibrium models have been used in the US for evaluating the interaction of carbon payments with crop subsidies in the US agricultural sector (Callaway and McCarl, 1996).

- *Econometric models.* Econometric models are used for finding relationships between existing land use and observed variables that influence farmers´ land allocation decisions. For example, a typical econometric model would consider that the existing land use in a given plot would depend on a number of explanatory variables like: crop's expected revenues, farm size, distance to markets, labor availability (or population density), capital availability (or relative poverty) and soil properties (Blackman et al., 2002). By means of econometric models, afforestation programs could be simulated based on observations of actual decisions by landowners facing returns to alternative uses. Such approaches have been used by Stavins (1999) and Plantinga et al. (1999) for estimating the costs of carbon sequestration in the US. Their econometric models were tested using panel data on various explanatory variables such as agricultural rent, forestry rent and existing land-use.

- *Approaches considering risk.* Agricultural economists often point out that risk is a decisive factor for land use allocation decisions (Collender and Zilberman, 1985; Just and Pope, 2002). Carbon sequestration projects face risks and uncertainties associated with price volatility, forest growth, fires and pest attacks. Surprisingly, the literature on carbon sequestration has paid little attention to risk. In this section I provide a brief summary of two approaches considering risk that are applicable to estimating compensation costs for carbon sequestration: mean-variance analysis (M-V) and stochastic dominance.

The core elements for M-V are that investors care about expected net return and variance of return, and decision-making on portfolio choice only requires this information from portfolio assets (or farm land uses) (Markowitz, 1952). Given two portfolios of equal net return, investors will choose the one with the smaller variance; and given two portfolios of equal variance, they will choose the one with the higher net return. Thus, a portfolio is *mean-variance efficient* if it maximizes expected net return for a given variance and minimizes the variance for a given expected net return. Within climate change applications, the M-V approach has been used for evaluating portfolio diversification of investments in climate change mitigation (Springer 2003a, Springer 2003b).

While M-V provides a straight-forward solution for land-use allocation problems, one question remains: is M-V consistent with expected utility maximization, i.e. solutions of M-V problems are compatible with solutions led by direct utility maximization? This is certainly the case when some conditions are met: either investor has a quadratic utility function, or returns are normally distributed. When investors have a quadratic utility function, it implies that they have increasing absolute risk aversion, i.e. wealthy investors would be more risk averse than less-wealthy investors. This condition does not represent the preferences of many investors. The second assumption of normally distributed returns is a condition not always met when considering forests and other natural resource assets (Heikkinen and Kuosmanen, 2003). For example, when forests face the risk of fire, returns are non-normally distributed. Empirical research, however, has shown that M-V efficient portfolios are frequently portfolios that maximize expected utility (Kroll et al. 1984). This motivates the wide-application of M-V.

An alternative to M-V analysis is the choice rule based on stochastic dominance (SD), which has been widely applied in agricultural economics (Harris and Mapp, 1986; Johnson and Cramb, 1996; Williams et al., 1999). This technique sets minimum restrictions on landowners' utility functions and is valid for all types of return distributions (refer to Levy, 1992 and Levy, 1998, for an extensive description of SD rules).

The simplest SD criterion is the first order stochastic dominance (FSD), which ranks investment alternatives under the sole assumption that investors are non-satiated (with non-decreasing utility function, $U' \geq 0$). Assume that a landowner must decide whether to invest in land use f or g with cumulative net revenue distribution functions given by $F(x)$ and $G(x)$, respectively. Land use f dominates land use g *iff*,

$G(x) - F(x) \geq 0$, $\forall x \in$ R, with at least one strict inequality

When FSD holds, every non-satiated investor would choose land use *f* over *g*. FSD could be determined graphically by plotting G(x) and F(x). When F(x) is always below G(x), *f* dominates *g* in the first degree (Figure 1).

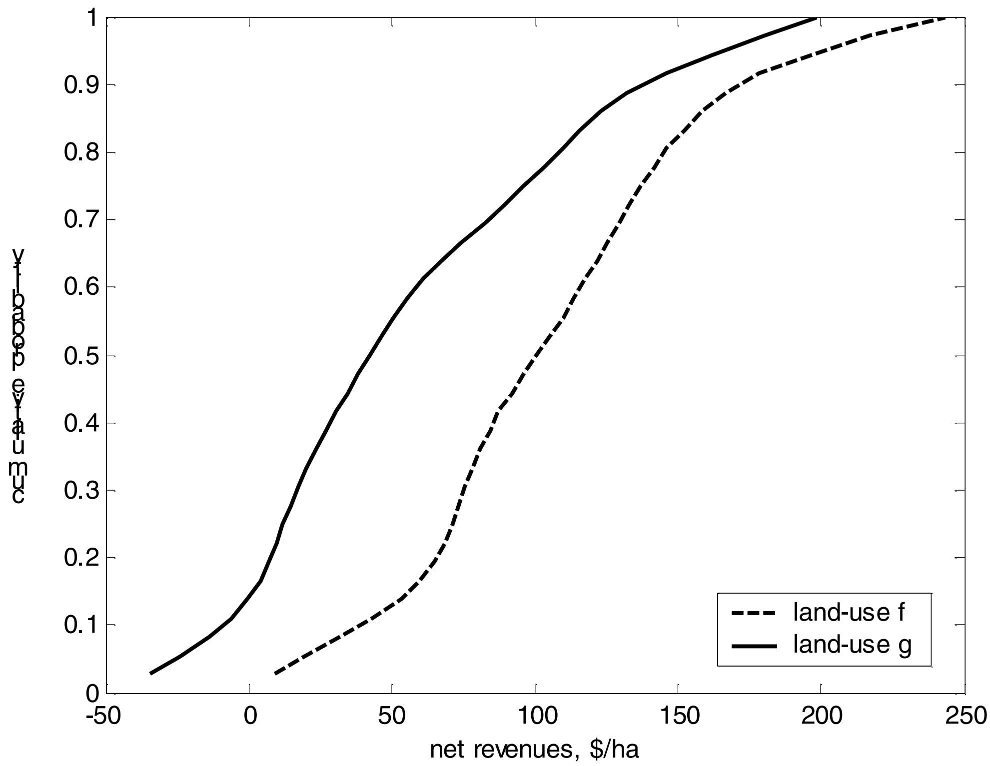

Figure 1. Situation where land use *f* dominates *g* under FSD.

While the FSD criterion seems reasonable, it is not very discerning. In practice, the cumulative distributions of net returns of the two investment alternatives often intersect, in which case FSD cannot discriminate between the alternatives.

If investors are risk averse in addition to insatiable (i.e., $U'' \leq 0$ and $U' \geq 0$), second-order stochastic dominance (SSD) could be used to choose between them. Formally, land use *f* dominates land use *g* in the SSD sense *iff,*

$$\int_{-\infty}^{x} \left(G(z) - F(z)\right) dz \geq 0 \ \forall x \in \mathrm{R}, \text{ with at least one strict inequality}$$

In other words, SSD requires that the area under the cumulative density function for *f* is always smaller than the area under the cumulative density function for *g*. Every risk-averse, non-satiable investor prefers the investment alternative that dominates by

SSD. Figure 2 shows a situation where *f* does not dominate *g* in first degree (the cumulative distributions cross), but it does in the second degree.

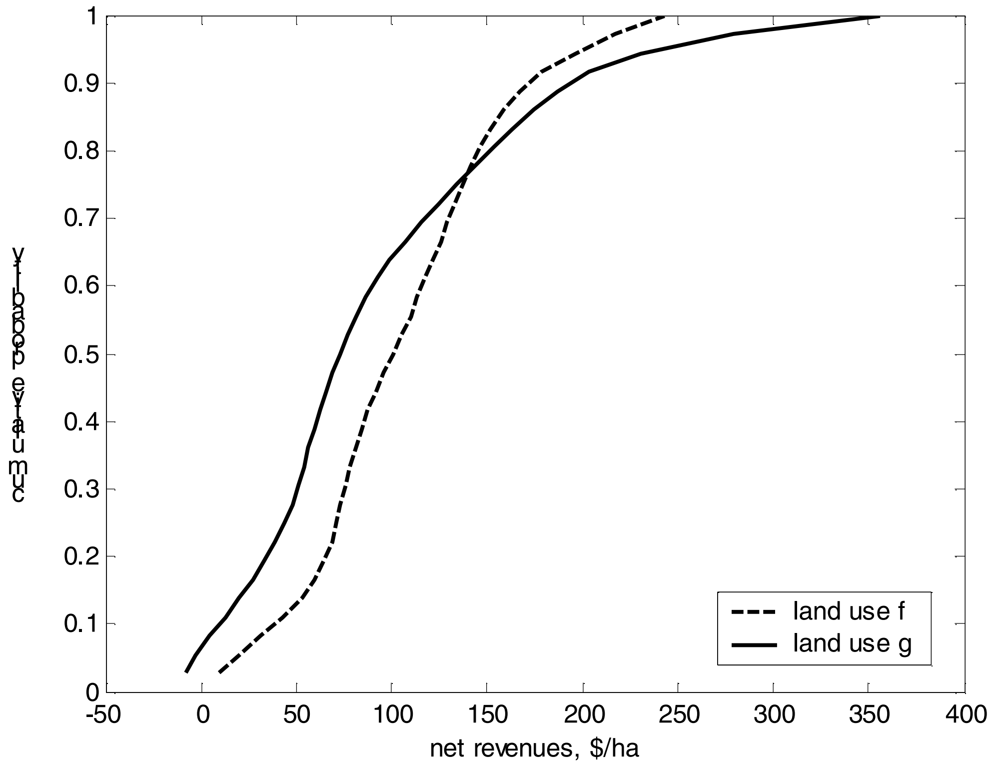

Figure 2. Situation where land use *f* dominates *g* under SSD, but not under FSD.

Both SSD and FSD have limited applicability when portfolios (or farms) are diversifiable. In such cases, there is need to use recent extensions of SD that have been used for analyzing portfolio allocation problems (Shalit and Yitzhaki, 1994; Kuosmanen, 2004 and Post, 2003).

So far, stochastic dominance rules have been used very little for climate change and carbon sequestration applications although it is well-known that uncertainties play a major role for climate change decision-making.

4.2 Accounting Carbon Benefits

A long debate has been held regarding carbon accounting in carbon sink projects (IPCC, 2000b). This section provides a brief summary of the alternative approaches for accounting carbon sequestration benefits in forests.

The Faustmann-Hartman rotation model has been the traditional approach for accounting externalities in forests (van Kooten and Folmer, 2004). This model considers that forests provide commercial timber and non-timber (spillover) forest amenities and the forest manager seeks to maximize the net present value of this production over an infinite planning horizon. Examples of forest amenities are carbon uptake, watershed protection and recreational values. The rotation age that maximizes this present value is called the Faustmann-Hartman rotation. It might happen that for some standing forests the spillover amenity benefits might be so great that it would not be economically feasible to harvest the forest at any time in the future. This would be represented by an infinite Faustman-Hartman rotation length.

The application of the Faustmann-Hartman rotation model for carbon sequestration in forests is described in van Kooten et al. (1995). Externality benefits associated to carbon sequestration are a function of the change in forest biomass (and hence timber volume) over time. As trees grow and biomass accumulates they sequester carbon, but once carbon has been sequestered and a stable level is reached, there are no further benefits. The present value (PV) of carbon uptake benefits over a rotation of length R is,

$$PV = \int_0^R p_c \alpha \, v'(t) e^{-rt} dt \qquad (1)$$

where r is the discount rate, v' (t) is the rate of change of timber volume, p_c is the "price" or implicit social value of carbon and α is a constant depending on the tree specie measuring the tons of carbon per m^3 of timber.

In a similar fashion, the negative externality of carbon release in a forest could be accounted. If the forest biomass is totally burnt after harvest the term $-p_c \alpha \, v(t) e^{-rt}$, should be added to equation (1) in order to account for the external costs of carbon release to the atmosphere. In the case when part of the harvested timber goes into long-term storage in structures and landfills, the amount of carbon released into the atmosphere would depend on the fraction of carbon in long-term storage, θ, or "pickling" factor (van Kooten et al., 1995). In such a situation, the present value of carbon benefits is,

$$PV = \int_{0}^{R} p_c \alpha \, v'(t) e^{-rt} dt - (1-\theta) p_c \alpha \, v(t) e^{-rt} \qquad (2)$$

In order for forest companies to correctly take into account the external benefits and costs of their decisions, they should receive an annual subsidy equal to the value of carbon sequestered each year. Likewise, they should face a tax levied at harvest time that equals the external cost of the carbon released to the atmosphere. This method has been used for quantifying carbon sequestration benefits in forests in Alberta and British Columbia, Canada (van Kooten et al., 1995) and eucalyptus plantations in Portugal (Cunha-e-Sá and Rosa, 2004). Extensions of this method are used in Chapters 3 and 4 of this thesis.

The above-described carbon accounting method, although consistent with forest economic models, is controversial when applied to the CDM of The Kyoto Protocol, which allows carbon trading from afforestation projects in developing countries. The major problem for putting this method into practice is that it might become difficult to tax forest owners in developing countries when carbon is released during harvest (IPCC, 2000b). Since developing countries have no commitments in the Kyoto Protocol, they have no need to control their emissions. At the time when forests are harvested it would be to the benefit of developing countries not to report these emissions. Only strong enforcement rules and long-term contracts could force them to account for these emissions. But, this would introduce another controversial issue to be negotiated within the UNFCCC.

Different carbon accounting methods have been proposed during the recent years. These methods suggested different ways for estimating the amount of Certificates of Emission Reductions (CER) that are ascribed for afforestation and reforestation projects within the CDM. CER are certificates of greenhouse gas emission reductions obtained from project activities in developing countries and include emission reductions through emission avoidance and carbon sequestration, and are measured in tons of CO_2. These certificates, which have to be verified by an independent entity, could be used by industrialized countries for fulfilling their commitments to the Kyoto Protocol.

The stock-change method and the average-storage method are the carbon accounting methods that appeared first (they are described in the IPCC Special Report on Land Use, Land-Use Change and Forestry - IPCC, 2000b). Later, the idea of having expiring CER was proposed by the Colombian government in the Sixth Conference of the Parties (COP6) (IISD, 2000). This lead to a decision in December 2003 by the Ninth Conference of the Parties (COP9) that CER arising from CDM sink projects would be considered as non-permanent and two ways for accounting CER would be valid: temporary and long-term crediting (tCER and lCER respectively). While presently, only tCER and lCER methods are valid within the CDM, I describe the others in order to have a better understanding of this debate.

- The stock-change method. This method estimates net changes in carbon stocks within a given time-period. It is applicable when forests are planted only for the purpose of sequestering carbon and they are never harvested. 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 (IPCC, 2000b). Payments for carbon uptake take place until the forest reaches a stable level. This method has the drawback that it excludes possible carbon release when trees are burnt or die. Figure 3a illustrates how to account carbon credits using the stock-change method. The amount of credits for the project in the figure is the difference between the carbon stock in the forest at the end of the project (105 tCO_2) and the carbon stock in the baseline at the end of the project (0).
- The average-storage method. When forests are planted, harvested, and re-planted again, the average-storage method is applicable. This method entails averaging the amount of carbon stored in a site over the project time (T) according to the following equation (IPCC, 2000b),

$$\text{Average carbon storage} = \frac{\sum_{t=0}^{T} \text{carbon stored in the forest}_t - \text{carbon stored in the baseline}_t}{T} \tag{3}$$

Payments for carbon uptake take place until the forest reaches the average storage level. Figure 3b shows an example of this accounting method were the average carbon storage for a 50-year project is 46 tCO_2.

- tCER and lCER. Under these accounting systems, CER arising from CDM sink projects would be considered non-permanent, i.e. CER would have an expiration date after which, the country that owns the certificate must acquire a new one or replace this certificate with one that is permanent in nature (e.g. buy CER obtained from energy-related projects). A temporary credit (tCER) is defined as a CER issued for an afforestation project activity under the CDM, which expires at the end of the commitment period following the one when it is issued (UNFCCC, 2003). A long-term credit (lCER) is similar to a tCER, but it expires at the end of the crediting period for the afforestation project. The duration of commitment periods is five years for the first one (2008-2012), but still needs to be decided for the next ones. The crediting period for an afforestation project under both accounting systems should be either, (i) a maximum of 20 years that can be renewed twice or, (ii) a maximum of 30 years. The main difference between tCER and lCER is the expiration date: the first ones expire at the end of commitment periods and the latter expire at the end of crediting periods. In most cases, lCER credits would have longer expiration periods than tCER. In addition to the accounting rules, in COP9 it is decided that both tCER and lCER must be verified and certified every five years. Figure 4 shows examples of the tCER and lCER accounting methods.

Figures 3 and 4 provide a graphical representation of the different carbon accounting methods. Figure 3 shows the "old" methods for carbon accounting (before COP-9) that are the stock change and average storage method. Figure 4 shows the permitted methods for carbon accounting under the CDM: tCER and lCER.

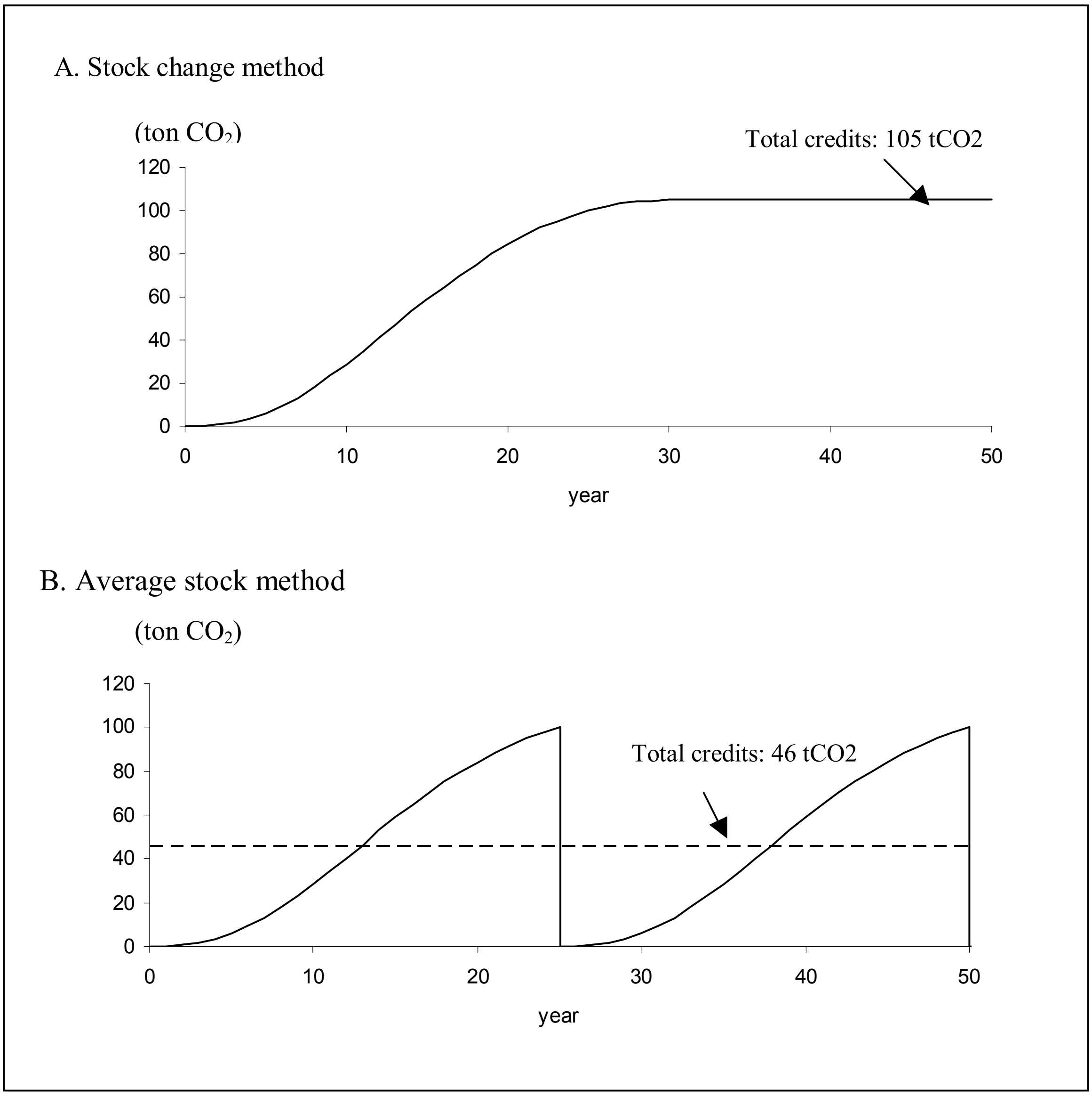

Figure 3. Systems for carbon accounting before COP-9: the stock-change and average-storage method.

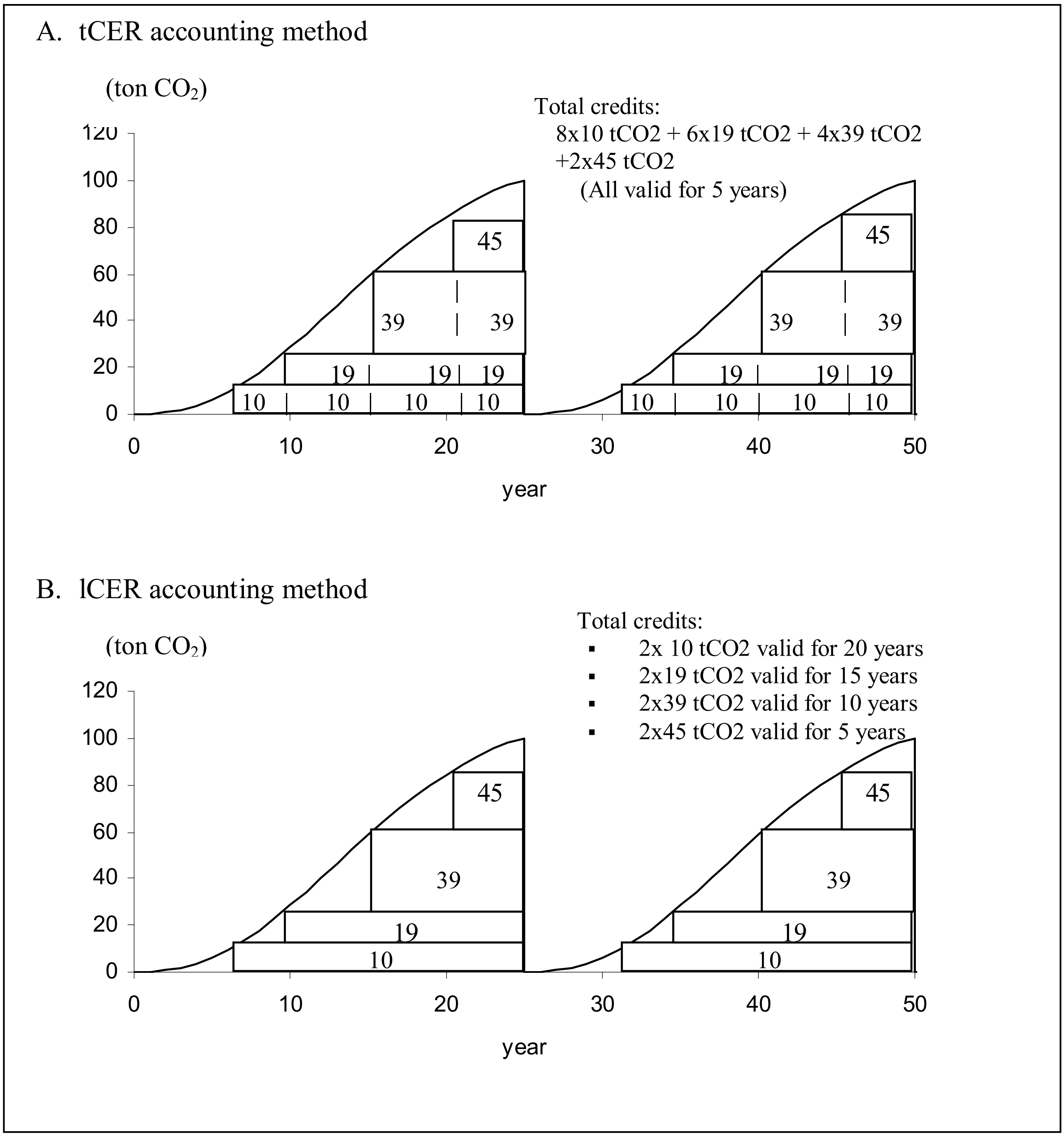

Figure 4. Carbon Accounting Methods Decided in COP9, 2003.

4.3 Cost Estimates for Carbon Sequestration in Forests

Researchers have been analyzing the costs of carbon sequestration for more than a decade (Richards and Stokes, 2004). For industrialized countries, particularly the US, cost curves for carbon sequestration have been derived. In developing countries, most economic studies have provided point estimates of carbon sequestration costs for particular countries and regions. Such analyses have been carried out in countries like China (Xu, 1995), Brazil (Fearnside, 1995), India (Ravindranath and Somashekhar, 1995), Mexico (de Jong et al., 2000) and Argentina (Sedjo, 1999). At a global level, research has been very limited, where the study of Sohngen et al. (1999), and Sohngen and Mendelsohn (2003) seem to be pioneer. By using optimal control and timber supply models, they evaluated the interaction of timber markets and carbon fluxes. As a limitation, they performed the analysis using high aggregation levels for representing relevant world regions.

Current economic studies on carbon sequestration have several methodological differences. This restricts the comparison of carbon costs among countries and regions. In Table 5, a summary of costs studies for carbon sequestration in Latin America and their differences is provided. Major differences among these studies are the following,

- *Carbon pools.* Afforestation projects lead to carbon storage in three major pools: (i) biomass, i.e. the carbon stored in trees, (ii) soils and, (iii) timber products, i.e. carbon stored in furniture, paper, wood materials for construction and buildings (IPCC, 2000b). In addition, afforestation could lead to substitution of fossil-fuels when the forest biomass is used for energy production and when timber products replace energy intensive materials like aluminium and steel in the construction sector (Marland and Schlamadinger, 1999). As shown in Table 5, some studies only consider biomass while others include biomass, soils and products.
- *Including relevant cost and benefits of projects.* Several studies have omitted relevant costs and benefit of projects, particularly land opportunity costs and timber benefits (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.

- *Discounting carbon benefits.* Carbon uptake in forests occurs during long time periods. According to Nilsson and Schopfhauser (1995), typical rotation intervals in the tropics are 20 years while in temperate regions, 30 years. This means that a forest owner providing carbon sequestration benefits by tree-planting should be rewarded according to the dynamics of tree growth, and such benefits should be discounted. Surprisingly, discounting carbon benefits has often been excluded from previous studies as shown in Table 5.

Regardless of the methodological differences, carbon sequestration in Latin America could be achieved at low costs (often below $10/tC) and therefore, it is a policy alternative that deserves further study. Note that the literature provides mostly point estimates of carbon costs, while information on supply-curves with price vs. quantity relationships is not available. Such supply-curves need to be developed and should consider a uniform accounting system.

Table 5. Point estimates of carbon sequestration costs through afforestation in Latin America.

Country or Region	Cost (US$/tC)	Carbon pools included	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)
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)
Mexico	10–35	B, S, P	Y	N	N	Masera et al. (2001)
Mexico	10	B, S, P	n/a	n/a	N	IPCC (2000b)
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/a	n/a n/a	N 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)

Abbreviations: B = Biomass; S = Soils; P= Products; Y = Yes; N = No; n/a = not available.

5. Main Objective and Outline of the Thesis

The main objective of this thesis is to provide a better understanding of the economics of carbon sequestration in forests with particular attention to carbon supply curves at regional and global levels and the incorporation of risk in carbon mitigation assessments. In order to achieve this objective, this thesis includes four articles dealing with relevant aspects related to forestry-based carbon sequestration and illustrates the analysis with case studies in West Ecuador and Latin America.

The previous sections provide an overview of the recent literature on the economics of climate change and carbon sequestration in forests. Economists have explored different topics within these themes like the assessment of climate change impacts, the cost evaluation of diverse carbon mitigation options, and the development of Integrated Assessment Models that link economic and natural science aspects of climate change. Regarding carbon sequestration in forests, there are several studies that provide estimates of average sequestration costs in different countries and regions. In addition, in countries like the US, carbon supply curves have been estimated. Current literature, however, is missing some key issues that motivate this thesis and could contribute to the decision-making process within the climate change debate. These missing issues, to be dealt within this thesis are,

- Economic comparison of carbon accounting methods and forestry alternatives for carbon sequestration. Most of the economic literature related to carbon sequestration refers to tree-planting as an option for carbon uptake. However, natural regeneration of secondary forests has been evaluated in a limited extent. This alternative might result in being economically attractive due to its combination of low investment costs and considerable rates of carbon uptake. Therefore, it is desirable to have a comparison of carbon sequestration costs in secondary forests and tree-plantations. With respect to carbon accounting, a long debate has been held during the recent years. In December 2003, it was decided that two ways for accounting carbon are possible under the CDM: temporary crediting (tCER) and long-term crediting (lCER). Presently, there are no economic studies dealing with this aspect. Chapter 2 of this thesis compares the costs and benefits of secondary forests and tree plantations under the tCER and lCER accounting methods using Northwest Ecuador as a case-study.

- Aggregated supply for carbon sequestration at regional and global levels. Researchers throughout the world have estimated costs for carbon sequestration by tree-planting for more than a decade. But still, there is little information on what the aggregate carbon supply throughout the world would be. This supply curve is important in order to quantify the relevance of afforestation as a climate change mitigation option. When dealing with global assessments of carbon mitigation, country-risk considerations that determine differences in country attractiveness for investing throughout the globe have been excluded from the literature. This motivates an evaluation of what is the impact of country-risk in the global supply for carbon sequestration. Chapter 3 of this thesis provides a methodology for estimating carbon supply curves through afforestation and uses Latin America as a case-study. In Chapter 4 this methodology is modified in order to account for country-risk and to be applied globally.

- Farm-level risk. Agricultural economists have pointed out that risk is a decisive factor for land-use allocation decisions. Also, carbon sequestration projects face risks and uncertainties associated with price and yield volatility. Surprisingly, the literature on carbon sequestration has paid little attention to risk. This motivates the need to evaluate how risk influences farmers' land-use choices and the associated supply of ecosystem services (e.g. carbon sequestration, biodiversity services, watershed protection). Chapter 5 of this thesis deals with the problem on land allocation under risk. In this Chapter, I describe how to estimate payments for forest conservation when landowners' decisions are influenced by net revenues and risk. West Ecuador is used as a case-study.

This thesis consists of separate articles dealing with specific research questions. In the following paragraphs I describe the aspects that each of these articles deals with, and the topics and specific research questions involved in each article.

Chapter 2. Cost-Benefit Analysis of Forestry- Based Carbon Sequestration in Northwest Ecuador

This article deals with two research questions referring to a case-study in Northwest Ecuador: (1) what is the economic potential of secondary forests and tree plantations for carbon sequestration? (2), what is the economic impact of carbon accounting methods for emission trading under the Clean Development Mechanism of the Kyoto Protocol?

In developing countries forestry is often not competitive with agricultural land uses like pasture for cattle ranching. This situation might change when payments for carbon sequestration exist. A cost-benefit analysis is used for determining what the minimum payment for carbon sequestration should be in different zones of Northwest Ecuador. In contrast to previous studies that estimate the costs for carbon sequestration by tree-planting (Winjum et al., 1993; Dixon et al., 1994; Masera et al., 1997; and Sedjo, 1999), the option of carbon sequestration in secondary forests is evaluated. Although not included in the CDM during the first commitment period (UNFCCC, 2003), this alternative could result in being attractive due to its combination of low investment costs and a considerable potential for carbon sequestration.

This article considers the recent rules pertaining to afforestation and reforestation under the CDM that allow two possible ways to account for carbon sequestration in forests: temporary and long-term credits (UNFCCC, 2003). These different accounting procedures have an impact on the potential carbon sequestration benefits for landowners in Northwest Ecuador and this is a subject of discussion in this article.

Chapter 3. Site Identification for Carbon Sequestration in Latin America: A Grid-Based Economic Approach

This article deals with two aspects: (i) what is the carbon supply through afforestation for Latin America and what are the potential gains of carbon trading, and (ii) where are the least-cost sites for carbon sequestration in Latin America.

Latin America harbors a large potential for carbon sequestration and biomass production and has been chosen as a study region due to its land-availability and ecological conditions favoring forestry projects, as well as its active participation in the implementation of carbon sequestration projects in the early stage of the Kyoto process (IPCC, 2000b). As discussed in the previous section, most economic studies on carbon sequestration in Latin America have so far provided single point estimates of sequestration costs associated with particular sequestration levels. They provide information on average costs of carbon sequestration for particular regions, but do not assess how these costs increase when large-scale afforestation programs are implemented. In contrast to these studies, we evaluate how the heterogeneity of prices (e.g. land and timber prices), and the heterogeneity in land attributes (e.g. net primary productivity and suitability for agriculture) influence sequestration costs and determine carbon-supply patterns. In addition, we provide a framework for identifying least-cost sites for carbon sequestration by means of a grid- based analysis that scrutinizes all the available area for plantations in the region.

Chapter 4: Global Supply for Carbon Sequestration: Geographical Distribution, Country Risk and Policy Implications

This article deals with three research questions, (i) what is the global carbon supply through afforestation, (ii) how do country considerations associated with political, financial and economic risks influence the global carbon supply, and (iii) what are the policy implications in terms of including afforestation as a GHG mitigation option at a global scale.

Based on global datasets, the carbon supply of afforestation throughout the globe is estimated. Being aware that country considerations related to political, financial and economic risks are a crucial factor for investors we incorporate this aspect in the analysis by using extensions of the Capital Asset Pricing Model (CAPM). Results are presented in a spatially explicit fashion that allows cross-country comparison.

Results of this study are compared with emission abatement scenarios in the energy sector from IAM models (RICE model) in order to quantify how much afforestation is worth in terms of global emission abatement.

Chapter 5: Conservation Payments under Risk: A Stochastic Dominance Approach

This article focuses on two issues: (i) how to estimate risk-efficient payments for ecosystem services (like carbon sequestration); and (ii) what should be the level of such payments in order to maintain shaded-coffee areas in West Ecuador that provide carbon sequestration and biodiversity services.

This article deals with setting efficient payments for forest conservation under revenue risk. Such payments could be used for carbon sequestration or any other environmental service of forests like biodiversity protection. Stochastic Dominance (SD) is used for ranking risky land-use investments. In this article, SD is used for situations with and without diversification possibilities. In the first case, first and second order stochastic dominance is used, and in the second case, marginal conditional stochastic dominance is used. Findings of this article include theoretical aspects related to the problem of land allocation under risk and policy recommendations for the case-study on shaded-coffee in West Ecuador.

Structure of the Thesis

This thesis consists of four articles that deal with the outlined objectives and a conclusion section summarizing major findings. The thesis is organized in such a way that each article could be read independently. If the thesis is read as whole, some aspects need to be taken into account,

- References are included at the end of each article. The formatting of references differs among articles since they follow journal requirements.
- Each article has its own numbering of sections, tables and figures.
- Carbon units are measured in tons of CO_2 in Chapter 2 and in tons of carbon in Chapters 3 and 4.
- The location of case-studies in Ecuador for Chapters 2 and 5 is shown in the Appendix of this Chapter.

Throughout this thesis the terms afforestation and reforestation are used indistinctively.

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Appendix: Case studies in West Ecuador

Chapters 2 and 5 refer to two different areas of West Ecuador. Both areas are in the lowlands of Ecuador but differ in their land use practices. In the first area (Northwest), natural forests represent more than 50% of the area while in the second area (West) natural forests have almost disappeared, while large areas of coffee cultivated under tree- shade exist. In both regions pasture is a major land use. Northwest Ecuador is used for the case of reforestation by natural regeneration of secondary forests (Chapter 2) and West Ecuador is used for the case of payments for conservation under risk (Chapter 5). Figure A1 shows the location of the case-study regions.

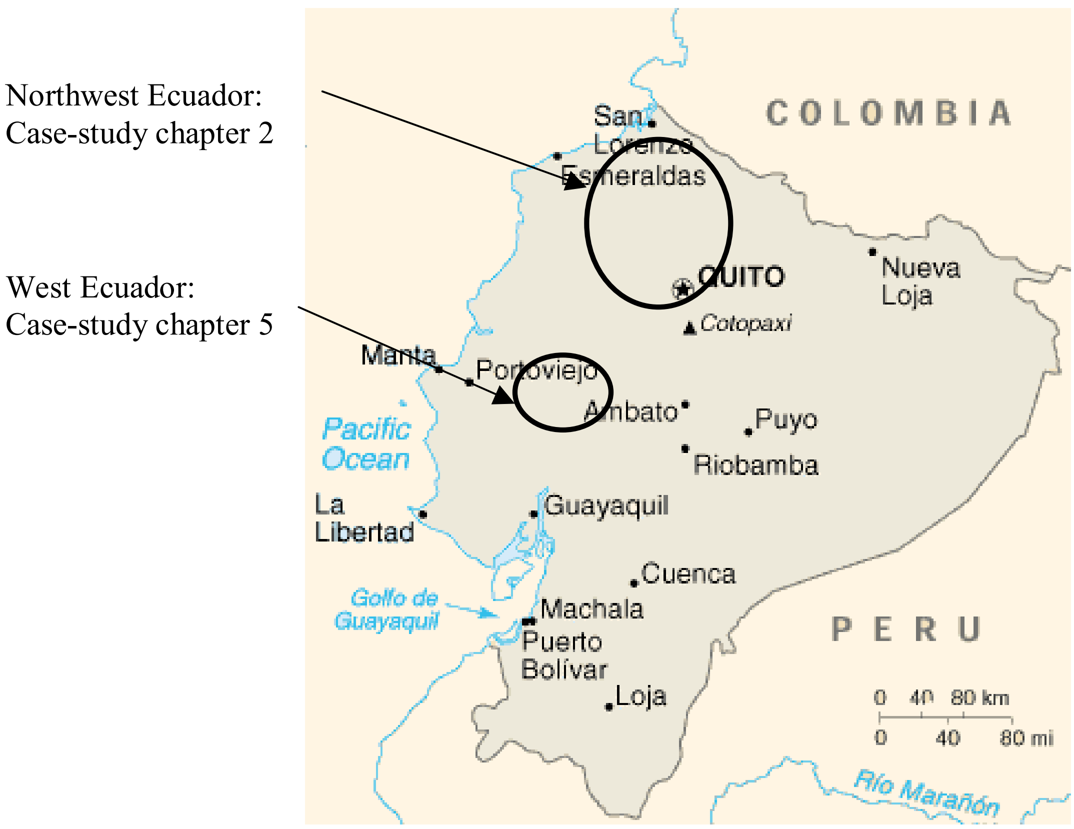

Figure A1. Location of case-study regions in Ecuador.

Chapter 2

Cost-Benefit Analysis of Forestry-Based Carbon Sequestration in Northwest Ecuador

This chapter is based on:

Benítez, P.C., R. Olschewski, G.H.J de Koning and M. López, 2001. Análisis Costo-beneficio de Usos del Suelo y Fijación de Carbono en Sistemas Forestales de Ecuador Noroccidental. p.90. Report TÖB TWF-30s of the German Agency for Technical Cooperation (GTZ), Eschborn, Germany.

Olschewski, R. and P.C. Benítez. Secondary forests as temporary carbon sinks: The Economic Impact of Accounting Methods on Reforestation Projects in the Tropics. *Ecological Economics* (accepted for publication).

Abstract

Tropical forestry is often not competitive with agricultural land uses like pasture for cattle ranching. Additional revenues from carbon sequestration generated by the Clean Development Mechanism (CDM) of the Kyoto Protocol may change this situation. We determined minimum compensation payments for carbon sequestration through tree planting and natural regeneration of secondary forests necessary to make forestry a more attractive land use than pasture in Northwest Ecuador. For estimating carbon benefits, we considered the accounting regimes for CDM sinks defined in the Ninth Conference of the Parties, where Certified Emission Reductions could be either temporary or long-term. A comparison of afforestation alternatives showed that secondary forest is a better option because of its low establishment costs and relatively early timber revenues. Minimum payments for making secondary forests economically attractive in the most appropriate zone for carbon sequestration require about \$6/tCO_2 (\$22/tC) whereas for forest plantations, \$9/tCO_2 (\$33/tC) are needed. In both cases, the results are within the margins of prices that were forecasted by various institutions for the first commitment period of Kyoto. The presented methodology is meant to support the decision making process on the supply side of carbon sequestration. As not all zones are suitable for carbon sequestration from the economic point of view, opportunity costs of land use changes have to be analyzed carefully before deciding in favor of long binding forestry projects. Assigning non-permanent credits to naturally re-grown secondary forests could - although excluded from CDM during the first commitment period - combine the advantages of a flexible accounting regime with the positive economic and ecological effects of this competitive land use.

Keywords: cost-benefit analysis, afforestation, carbon sequestration, carbon accounting methods, clean development mechanism

1. Introduction

In tropical countries forestry is often not competitive with agricultural land uses like pasture for cattle ranching. This situation might change, if additional income for carbon sequestration services is taken into account. Payments for such services within the Clean Development Mechanism (CDM) of the Kyoto Protocol could be an incentive for landowners in developing countries to switch from pasture to forestry.

Relevant economic literature has discussed extensively the potential of tree plantations for storing carbon. Sequestration costs through tree planting have been estimated for different world regions in early studies such as Winjum et al. (1993) and Dixon et al. (1994) and in more recent publications like Masera et al. (1997) and Sedjo (1999). These studies showed that tree plantations can provide considerable carbon and timber yields, but have the disadvantage of high investment costs and the need for access to long-term financing. An alternative to tree plantations in the humid tropics is the natural regeneration of secondary forests. Although not included in the CDM during the first commitment period (UNFCCC, 2001), this land use could result economically attractive due to its low investment costs and significant rates of carbon uptake.

The potential carbon revenues depend on the future market for Certified Emission Reductions (CER). CER are certificates of greenhouse gas emission reductions obtained from project activities in developing countries and include emission reductions through emission avoidance and mitigation of emissions by means of carbon sequestration, and are measured in tons of CO_2.[1] These certificates, which have to be verified by an independent entity, are expected to be traded like any commodity: directly on a commodity exchange, through forward contracts or by options.

In December 2003 the Ninth Conference of the Parties (COP9) came with a final decision on the accounting rules for CER of afforestation projects.[2] This

[1] When the target GHG is not CO_2, emission reductions should be converted in CO_2 equivalents using the global warming potential for each gas.

[2] Throughout this paper we used the term afforestation for both afforestation and reforestation activities.

decision states that CER arising from CDM sink projects would be accounted as non-permanent, i.e. CER would have an expiration date and thereafter the country that owns the certificate must acquire a new one or find a permanent solution to fulfill the emission reduction commitments. There are two possible ways to account for non-permanent CER in forests: temporary and long-term crediting (UNFCCC, 2003).

A temporary credit (tCER) is defined as a CER issued for an afforestation project activity under the CDM, which expires at the end of the commitment period following the one when it is issued (UNFCCC, 2003). A long-term credit (lCER) is similar to a tCER, but it expires at the end of the crediting period for the afforestation project. The duration of commitment periods is five years for the first one (2008-2012), but still needs to be decided for the next ones. The rules pertaining tCER/lCER state that the crediting period for an afforestation project under both accounting systems shall be either, (i) a maximum of 20 years which may be renewed at most two times (so the project lifetime could be up to 60 years) or, (ii) a maximum of 30 years without renewal (UNFCCC, 2003). The main difference between tCER and lCER is the expiration date: the first ones expire at the end of commitment periods and the later expire at the end of crediting periods. In most cases, lCER credits would have longer expiration time than tCER. In addition to the accounting rules, in COP9 it was decided that both tCER and lCER must be verified and certified every five years.

These different types of accounting procedures have impact on the amount and value of CER generated by afforestation projects. Given the temporary nature of tCER/lCER arising from afforestation projects, the price of these credits will probably be lower than the price of credits arising from carbon mitigation in the energy or industrial sector. In this situation it is useful for Non-Annex I countries to know how competitive they can be on the future CER market, what kind of forestry practices are appropriate (e.g. plantations vs. natural regeneration), and which monetary impact different accounting methods will have.

In the present study we contribute to a better understanding of the economics of the supply and demand for carbon sequestration taking Northwest Ecuador as a case study. In Section 2 of this Chapter we briefly describe the study area consisting of three distinct zones. In Section 3 we explain the methodologies we used to estimate carbon sequestration costs, to calculate net present value of forest and pasture land uses, and to compute carbon sequestration rates of plantations and secondary forests. In Section 4 we show the results and discuss major findings of our study. This includes the comparison of net benefits of land use alternatives, an analysis of carbon sequestration costs and the evaluation of potential revenues for landowners in Northwest Ecuador if CER are indeed traded. Furthermore, we compare advantages and disadvantages of different carbon accounting regimes based on the latest Kyoto Protocol developments. Conclusions are in Section 5.

2. Study Area

We selected an area of about 15000 km^2 in the northwestern part of Ecuador, covering the provinces of Esmeraldas and part of Pichincha. Land use is very dynamic with the highest deforestation rates within the country due to timber extraction and conversion to agricultural land (Sierra and Stallings, 1998; de Koning et al., 1999). According to government statistics, pasture areas have doubled between 1974 and 1995, becoming the main agricultural land use of the region with more than 300 thousand hectares being used for cattle ranching (INEC, 1995). Primary and secondary forest cover is estimated between 50% and 73% (CLIRSEN-PATRA, 1998; INEC, 1995). Only few forest plantations have been established in the project region, but existing pasture areas in Northwest Ecuador are suitable for larger afforestation projects. This area is considered one of the world´s hot-spots for biodiversity (Myers et al., 2000) and afforestation might lead to ecological gains while providing additional income for landowners when a system of carbon sequestration payments is implemented.

The large variation in economic conditions such as infrastructure, market access and productivity prompted to do calculations independently for three zones (see Table 1). Zone 1 (in the north) is characterized by a high percentage of forest land, low to medium accessibility to roads, low population density, and low land prices. Zone 2 (coastal strip) has large areas of extensively managed pastures, medium to high accessibility to major roads, and intermediate land prices. Zone 3 (the area nearest to the capital, Quito) has the highest percentage of agricultural crops such as oil palm and banana plantations, good road access, and high land prices. According to the different characteristics, opportunity costs of land vary between these zones.

Table 1. Characteristics of major zones of Northwest Ecuador.

Zone	Main Towns	Area*, thousand ha	Land price, $/ha	Population density, persons/km^2	Land use shares		
					Pasture	Crops	Forests, others
1:north	San Lorenzo, Eloy Alfaro	490	150 - 500	4	5%	2%	93%
2:coastal strip	Muisne, Atacames, Río Verde, Esmeraldas	420	400 - 1000	20	37%	10%	53%
3:closest to capital	Quinindé, Puerto Quito	450	800 - 2000	14	28%	25%	47%

*Excludes ecological reserves protected by the government

3. Methodology

3.1 Costs of carbon sequestration

The economic analysis focuses on the costs of sequestration, i.e. the costs that occur on the supply side of CER (Sedjo et al., 1995; Sedjo, 1999; Stavins, 1999). Note that these costs cannot be estimated solely from cost data of forest establishment and management, because forests are used for a joint production of both timber and carbon sequestration and it is not possible to separate the costs associated with each of these activities. Also, opportunity costs exist because new forests are established on land which otherwise would have been used for cattle grazing or agriculture. When deciding to switch from non-forest to forest the landowner loses the opportunity to get revenues from the land-use alternative. Therefore, we define the opportunity costs of carbon sequestration as the minimum financial compensation per ton of CO_2, which a landowner would have to receive for changing existing non-forest land into forests.

Costs and benefits of the different land-use types are calculated to determine this compensation using the Net Present Value criterion (NPV). For our particular region we assume that the relevant land-use alternative is pasture. We excluded more productive land uses (e.g. oil palm plantations) from our analysis since they provide much higher net revenues than those of pasture and the cultivated area suitable for those land uses is much smaller. For example, we estimated NPV for oil palm plantations in medium-quality sites and our results showed that NPV for oil palm plantations is about 3 times higher than those for pasture.

A profit-maximizing and risk-neutral landowner would switch from pasture to forest, if the NPV of forestry (NPV_F) is higher than the NPV of pasture (NPV_P),

$$NPV_F \geq NPV_P \tag{1}$$

Equation (1) could be influenced by payments for carbon sequestration under tCER or lCER accounting systems.

tCER accounting

We start our analysis with the case of tCER accounting. Assuming a joint production of timber and carbon sequestration, revenues for carbon sequestration can be added to the forestry alternative as follows,

$$NPV_F + B^{\tau} \geq NPV_P \tag{2}$$

where B^{τ} is the present value of carbon revenues when the tCER accounting method is used. For estimating carbon revenues we follow CDM rules that require carbon verification and certification every five years (UNFCCC, 2003) and assume that credits are synchronous with the commitment periods of Kyoto: they are issued towards the end of the respective commitment period and expire at the end of the following commitment period. Therefore, plantation projects starting in 2007 would have their carbon verified in 2012 (the end of the first commitment period) and tCER would expire in 2017 (this would hold if the Kyoto Protocol continues with 5-year commitment periods). Given these assumptions, tCER would always be valid for 5 years. Similar assumptions have been made by Dutschke and Schlamadinger (2003).

Under these considerations, we estimate the present value of carbon revenues for a 30-year afforestation project. We denote C_t the cumulative carbon in the forest at time t, which is measured in tons of CO_2 and refer to net carbon accumulation, i.e. the project baseline corresponding to the carbon stock in the without-project scenario has been subtracted. [3] The first credits of the afforestation project are generated at year 5

[3] According to the UNFCCC mandate (UNFCCC, 1998), emission reductions need to be additional to those emissions occuring in the baseline scenario (or without-project scenario). For our case, the baseline scenario is pasture. Therefore, emission reductions need to be accounted as the difference between carbon uptake in the forest and carbon uptake in the pasture.

and equal the net cumulative carbon at this time, C_5. These credits expire at year ten but could be reissued together with the additional certificates obtained between years 5 and 10. Therefore, a total of C_{10} credits are assigned in year 10. The same holds for the following five-year periods until the last tCER are issued in year 25 which are equal to C_{25}. The present value of tCER revenues is,

$$B^{\tau} = \frac{\mathrm{ptCER}_5 \cdot C_5}{(1+\mathrm{r})^5} + \frac{\mathrm{ptCER}_{10} \cdot C_{10}}{(1+\mathrm{r})^{10}} + \ldots\ldots \frac{\mathrm{ptCER}_{25} \cdot \mathrm{C}_{25}}{(1+\mathrm{r})^{25}} \tag{3}$$

where ptCER_t is the price for one tCER unit at time t, and r is the discount rate in Ecuador. When we assume that the price for tCER remains constant in time, $\mathrm{ptCER}_5 = \mathrm{ptCER}_{10} = \ldots\ldots = \mathrm{ptCER}_{25,}$ we have,

$$B^{\tau} = \mathrm{ptCER}\left(\frac{\mathrm{C}_5}{(1+\mathrm{r})^5} + \frac{\mathrm{C}_{10}}{(1+\mathrm{r})^{10}} + \ldots\ldots\ldots \frac{\mathrm{C}_{25}}{(1+\mathrm{r})^{25}} \right) \tag{4}$$

If we set both sides of equation (2) equal, replace B^{τ} and solve for ptCER, we get,

$$\mathrm{ptCER} = \frac{\mathrm{NPV_P} - \mathrm{NPV_F}}{\frac{\mathrm{C}_5}{(1+\mathrm{r})^5} + \frac{\mathrm{C}_{10}}{(1+\mathrm{r})^{10}} + \ldots\ldots\ldots \frac{\mathrm{C}_{25}}{(1+\mathrm{r})^{25}}} \tag{5}$$

Equation (5) determines the minimum compensation that is required for switching from non-forest to forest, measured in dollars per temporary CER. Note that the required compensation increases with higher $\mathrm{NPV_P}$ and with lower $\mathrm{NPV_F}$. When $\mathrm{NPV_F}$ is higher than $\mathrm{NPV_P}$ the forestry alternative could be realized even without carbon payments.

In practice, the Kyoto Protocol states that Annex-I countries must reduce emissions which are permanent in nature. Also, emission trading schemes are based on permanent emission reductions. Therefore, there is need to have a relationship between tCER prices and permanent CER prices so we could evaluate the competitiveness of afforestation projects in Ecuador within global markets for carbon emission reductions - refer to Subak (2003) and Chomitz and Lecocq (2003) for a more extensive discussion on this issue.

In a competitive market, the potential buyers of CER from Annex-I countries would be indifferent between (i) buying a permanent credit today and (ii) buying a non-permanent credit (tCER) today and replacing it by a permanent one when the initial credit expires. This indifference is represented by equation (6), where T denotes the expiring time of temporary credits, the index "0" refers to credits bought today and r* is the discount rate in Annex-I countries (Subak, 2003),

$$ptCER_0 = pCER_0 - \frac{pCER_T}{(1+r^*)^T} \tag{6}$$

According to equation (6), the temporary CER price increases with higher discount rates and longer expiring times. If we assume that CER prices are constant in time ($pCER_0 = pCER_T = pCER$) we have,

$$ptCER = pCER\left(1 - \frac{1}{(1+r^*)^T}\right) \tag{7}$$

Based on this equivalence between temporary and permanent CER prices we are able to estimate the minimum price for a permanent CER that is required for switching from non-forest to forests. For this, we combine equation (7) and (5) and use T=5, which leads to,

$$pCER^{\tau} = \frac{NPV_P - NPV_F}{\left(1-\frac{1}{(1+r^*)^5}\right)\left(\frac{C_5}{(1+r)^5} + \frac{C_{10}}{(1+r)^{10}} + \ldots\ldots\ \frac{C_{25}}{(1+r)^{25}}\right)} \tag{8}$$

where the superindex "τ" is used for indicating that we are using the tCER accounting method.

lCER accounting

In the case of lCER accounting, equation (2) holds in a similar fashion as for tCER,

$$NPV_F + B^L \geq NPV_P \tag{9}$$

where B^L denotes the present value of carbon revenues when the lCER method is used. For accounting carbon revenues in lCER we take into account that credits do not expire until the end of the crediting period. The first lCER are produced at year 5 and remain valid for 25 years. At year 10 the additional credits generated between year 5 and 10 are issued, which have a duration of 20 years. The last lCER units are issued in year 25 with a duration of five years only. Therefore, the present value of lCER revenues is,

$$B^L = \frac{plCER_5(C_5)}{(1+r)^5} + \frac{plCER_{10}(C_{10}-C_5)}{(1+r)^{10}} + \ldots\ldots\ldots \frac{plCER_{25}(C_{25}-C_{20})}{(1+r)^{25}} \tag{10}$$

Long-term CER have variable expiration periods. For example, certificates issued in year 5 have 25 years validity, while certificates issued at year 20 have only 10 years validity. For that reason, prices for lCER are dependent on their expiration period and it is not possible to factor them out of the equation because, $plCER_5 \neq plCER_{10} \neq \ldots$ $plCER_{25}$. This also implies that it is not possible to estimate a minimum plCER price, but just an equivalent permanent CER.

Finding the equivalent permanent CER price for lCER follows a similar approach as for tCER. Equation (7) can be used by replacing tCER by lCER and considering the appropriate expiration time, T. Combining (7) and (10) gives,

$$B^L = \left(1 - \frac{1}{(1+r^*)^{25}}\right)\left(\frac{pCER_5 \cdot C_5}{(1+r)^5}\right) + \left(1 - \frac{1}{(1+r^*)^{20}}\right)\left(\frac{pCER_{10}(C_{10}-C_5)}{(1+r)^{10}}\right) + \ldots$$
$$\ldots + \left(1 - \frac{1}{(1+r^*)^{5}}\right)\left(\frac{pCER_{25}(C_{25}-C_{20})}{(1+r)^{25}}\right) \tag{11}$$

In equation (11), permanent prices are constant in time, so pCER can be factored out of the equation. When we combine (11) and (9) and set both sides of the equation equal, we get the minimum permanent price that is required for switching from non-forest to forest when the lCER method is used (this price is denoted as $pCER^L$),

$$pCER^{L} = \frac{NPV_P - NPV_F}{\left(1 - \frac{1}{(1+r^*)^{25}}\right)\left(\frac{C_5}{(1+r)^5}\right) + \left(1 - \frac{1}{(1+r^*)^{20}}\right)\left(\frac{C_{10}-C_5}{(1+r)^{10}}\right) + .. + \left(1 - \frac{1}{(1+r^*)^{5}}\right)\left(\frac{C_{25}-C_{20}}{(1+r)^{25}}\right)} \qquad (12)$$

In summary, equation (5) serves for finding the minimum tCER price that allows forestry being more profitable that non-forest. A minimum lCER could not be estimated, however, because lCER prices within one afforestation project are different (due to different expiration times). Equations (8) and (12) serve for estimating the minimum price for (equivalent) permanent CER under tCER and lCER accounting respectively. These equations allow comparing the costs for afforestation projects in the general context of emission reductions in the energy sector and emission trading schemes that are based on permanent credits.

3.2 Net present value of pasture

Pasture in Northwest Ecuador is used for double-purpose cattle ranching, i.e. meat and milk producing cattle. Estimating NPV_P requires knowledge of yearly revenues for meat and milk production and opportunity costs, management costs and administrative costs. For our case-study, most data on costs, prices and milk production is obtained directly from interviews. However, data on meat production is estimated indirectly using the model described below.

Cattle herd consists of three categories: young cattle or calves up to two years that are grown and sold for slaughtering, cows that are used for milk production and breeding, and bulls that are used for breeding. For obtaining yearly net revenues of pasture we assume that farms are in equilibrium so cattle stock per hectare remains constant over time.[4] This allows estimating benefits from meat production (growth of

[4] Pasture areas in Northwest Ecuador have been cultivated for 18 years in average (according to interviews to 36 farmers). This suggests equilibrium conditions. Farmers ususally start their cattle-ranching activities by buying cows and bulls for breeding. Then, new calves are born (about one calf per cow per year) which are sold at an age below 2 years. Since cattle-ranching activities have existed for much longer periods, the equilibrium assumption is a good approximation. In addition, when we look at cattle-ranching activities at a macro level, we observe little changes in the average cattle stock per hectare. For example, between 1974 and 2000 average cattle stock in the province of Esmeraldas varied around 7% (INEC, 1975; INEC, MAG and SICA, 2001).

calves) based on existing stock without inquiring cattle purchases and sales over the cattle lifetime. In addition to the equilibrium conditions, we consider that the price per kg of standing cattle is constant and independent on gender and age. This approximation is valid for typical *mestizo* or *criollo* cattle which are the most common herd populations in the study region (Torres and Izquierdo, 1991).

For estimating the number of calves that are sold every year we account for the dynamics of the herd population. In one year, the amount of calves born (G_b) is,

$$G_b = C \cdot g \qquad (13)$$

where C is the number of cows and g is the reproduction rate for cows. Some of these calves die during the first year and other survive. Therefore, the number of calves that reach an age of one year (G_1) is,

$$G_1 = s_1 \cdot G_b \qquad (14)$$

where s_1 is the survival rate for calves having an age of 0-1 years. In a similar fashion, we estimate the number of calves that reach an age of 2 years (G_2),

$$G_2 = s_2 \cdot G_1 \qquad (15)$$

where s_2 is the survival rate for calves having an age of 1-2 years. Since all the calves that reach an age of 2 are sold, the number of calves sold per year (G_s) equals G_2.

The net meat production per year (M) equals G_s times the weight per calf at the age they are sold, W_{sold}. Therefore, we have,

$$M = G_s \cdot W_{sold} \qquad (16)$$

For estimating the yearly production of meat we use the following procedure: (i) Determine on the basis of interviews the number of cows per hectare, C. (ii) Find data on reproduction rate of cows and survival rate of calves. Based on this, estimate the number of calves sold per year, G_s. (iii) Find data on weight of calves for an age of 2 years. (iv) Estimate meat production using equation (16). Appendix A provides an example of these calculations.

3.3 Net present value of forestry

The net present value for a plantation project that considers one harvest period is,

$$NPV = p_w \cdot V(t) e^{-r \cdot t} - c \tag{17}$$

where p_w is the stumpage price of wood (timber price minus harvest costs), t is the length of a harvesting rotation (time between planting and harvesting), V(t) is the timber volume that is a function of t, c is the present value of planting and maintenance costs, and r is the discount rate. The optimum financial rotation or Faustmann rotation is obtained by maximizing the NPV for an infinite number of rotation periods (van Kooten and Folmer, 2004),

$$\underset{t}{\text{Max}}: \quad \text{NPV} = \frac{p_w \cdot V(t) \cdot e^{-r \cdot t} - c}{1 - e^{-r \cdot t}} \tag{18}$$

We estimated the timber volume function, V(t), for plantations following the model described in Alder and Montenegro (1999) for *Cordia alliodora* (laurel) in Northwest Ecuador. The first model equation is the estimation of stand height (h) as a function of age (t),

$$h = h_{max} \exp(\beta \cdot t^{-k}) \tag{19}$$

where h_{max} is a theoretical asymptotic height and β and k are parameters. These parameters were estimated by Alder and Montenegro (1999) using data of 562 plots of laurel plantations located in Northwest Ecuador,

$$\beta = 0.073\, S - 3.496 \tag{20}$$
$$k = 0.25$$
$$h_{max} = S / \exp(10^{-k} \beta)$$

where S is the site index that determines the suitability of the site for tree growth and it equals stand height at an age of 10 years.

Based on stand height, timber volume per hectare (ha) is estimated using the following equations (Adler and Montenegro, 1999) which are valid for an age above 5 years,

$$V_{10}=0.0000411h^{3.152}N^{0.889} \quad (21)$$

$$V_{20}=0.0187(h-13.5)^{1.961}N^{0.7527} \quad (22)$$

where N is stocking in trees per ha, V_{10} is timber volume per ha with diameter at breast height (dbh) larger than 10cm, and V_{20} is timber volume per ha with dbh >20cm that corresponds to commercial timber volume. V_{10} and V_{20} are used for different purposes. V_{10} provides timber volume data that is required for estimating forest biomass (next section). V_{20} corresponds to the commercial timber volume for laurel (used for the Faustmann model).[5]

In the case of secondary forests, we consider "managed" systems where forests are regenerated naturally, but combined with human intervention aimed at encouraging the growth of valuable species. Under this system light harvests of commercial timber occur each year and a clear cut takes place when the project ends.

3.4 Carbon uptake in forests

Carbon uptake in forests is estimated using the methodology described in Brown (1997) that allows estimating biomass density based on existing volume per ha data. The primary data needed for this approach is volume inventories per ha that include all trees, whether commercial or not, with a minimum diameter of 10 cm at breast height (V_{10} for our case). The general equation for estimating biomass in forests is (Brown, 1997),

$$\text{Aboveground biomass per hectare, B (t/ha)} = V_{10} \cdot \delta \cdot \text{BEF} \quad (23)$$

where above-ground biomass per hectare (B) in a forest (either plantation or secondary forest) includes the dry weight per ha of stem, branches and leaves for all trees in the forest; δ is the wood density (tons of dry biomass per m^3 of green volume), BEF is the biomass expansion factor (ratio of aboveground biomass of trees to biomass of inventoried volume) and V_{10} is timber volume per ha with dbh >10 cm.[6]

[5] In practice, laurel timber volume in Ecuador with dbh < 20 cm has no economic value because it is too thin to be processed. That is why we use V_{20} for the commercial timber volume.

[6] Note the difference between V_{10} and δ. The first one is the amout of timber that exists in one hectare of land and the later is the weight in tons of one cubic meter of wood.

According to Brown (1997), the biomass expansion factor is a function of the weight of the stem, $V_{10} \cdot \delta$, and it is estimated as follows,

$$BEF = exp(3.213-0.506 \cdot ln(V_{10} \cdot \delta)) \quad \text{for } V_{10} \cdot \delta < 190 \tag{24}$$
$$BEF = 1.74 \quad \text{for } V_{10} \cdot \delta \geq 190$$

Carbon accumulation measured in tC/ha, is the biomass density (B) divided by 2 according to IPCC guidelines (Houghton et al., 1996). For having it in tCO_2/ha units, it should be multiplied by 3.667.

In the case of laurel plantations timber volume, V_{10}, is estimated using equation (21) and this data serves for calculating biomass with equations (23) and (24). Wood density for laurel, δ, is 0.45 ton/m^3 (López et al., 2002).

For estimating biomass in secondary forest, we used data from López et al., (2002) who used the following procedure for finding a biomass/age relationship: (i) select 34 plots of secondary forests of different ages that were pasture before, (ii) for each plot, measure V_{10} for all trees and estimate above-ground biomass, (iii) perform a regression analysis that relates above-ground biomass with age. The results of the regression are (López et al., 2002),

$$B = \underset{(25.8)}{-9.28} + \underset{(9.6)}{62.587 \cdot ln\,(t)}, \quad \text{with } R^2=0.58 \tag{25}$$

where the figures in brachets are standard errors. Finally, data of soil organic carbon in Northwest Ecuador is obtained from de Koning et al. (2002) and de Koning et al. (2003). Carbon fixed in timber products is not included in our analysis according to IPCC guidelines (Houghton et al., 1996). Carbon storage in products is dealt with in Chapter 3 of this thesis.

4. Results and Discussion

We calculated NPV_P of typical pasture for meat and milk producing cattle, and NPV_F of tree plantation and secondary forests in the three zones of Northwest Ecuador. We used an interest rate of 7% corresponding to the average rate on savings and borrowing in Ecuador (BCE, 2004). The project duration is 30 years in accordance with CDM requirements (UNFCCC, 2003), and based on our findings that the optimum financial rotation interval of laurel plantations in medium sites is 15 years (refer to section 4.2 and Appendix C). Thus, we compared pasture land-use with forest plantations of two cutting cycles and with secondary forest harvested after 30 years. All costs and benefits are calculated in US dollars, the official Ecuadorian currency.

4.1 Net Present Value of Pasture

Major data for the cost benefit analysis is obtained from a set of 40 interviews performed in year 2000 and secondary sources (INIAP, 2000; Torres and Izquierdo, 1991) (refer to Appendix A for details). Based on these data we find that milk and meat productivity varies across zones (Table 2). Cattle stock is between 0.8 and 1.1 animal units per ha, milk production between 135 and 365 liters per ha, and meat production between 132 and 152 kg per ha. Meat and milk prices are relatively homogenous with meat prices between \$0.8 and \$0.9 per kg, and milk prices between \$0.21 and \$0.24 per liter. These differences among regions lead to significant differences in net revenues per hectare, where the zone closest to the capital is the one with highest profits. For comparison with forestry systems, yearly net revenues are converted into 30-year net present values, resulting in \$756/ha, \$812/ha and \$1301/ha for zones 1, 2 and 3, respectively (Table 2).

Table 2. NPV of pasture used for meat and milk producing cattle in Northwest Ecuador.

Zone	Cattle stock[a] (AU/ha)	Total costs[b] (\$/ha/yr)	Meat production (kg/ha/yr)	Milk production (liters/ha/yr)	Net revenues of meat and milk[c] (\$/ha/yr)	Net present value of pasture for a 30-yr period (\$/ha)
1: North	0.84	99	132	238	57	756
2: Coastal strip	0.79	93	135	135	61	812
3: Closest to capital	1.09	127	152	365	98	1301

a. One animal unit (AU) equals 454 kg of cattle. b. Includes opportunity costs of cattle stock, pasture maintenance, fences, vaccines, cattle replacement, cattle losses, milking costs and administrative costs. c. Considers farm-gate prices for standing cattle of \$0.9/kg for zones 2 and 3, and \$0.8/kg for zone 1. Milk prices are \$0.24/l for zones 2 and 3, and \$0.21/l in zone 1.

4.2 Net present value of forestry

We choose *cordia alliodora* (laurel) as the specie for tree-planting. Laurel is a valuable medium-density specie native from the region used for furniture and construction. Generally, laurel is saw-milled on site and sold in nearby villages or large cities. Therefore, for estimating stumpage timber prices we use market prices and subtract felling, processing and transportation costs. Appendix B shows the detailed estimation of stumpage timber price. A value of $20/m^3 is used for this study, both for the case of plantations and secondary forests. Later we test the impact of timber prices by means of sensitivity analysis.

Regarding laurel plantations, establishment costs are $408/ha and the present value of further maintenance between year one and ten sums up to $376/ha (Appendix C). Commercial timber volume is calculated for medium-quality sites (S=22) and stocking (N) of 400 trees/ha. Applying this data and a timber price of $20/m^3, we found that 15 years is the optimum financial rotation according to the Faustmann rotation model. Given these values, the estimated NPV_F for laurel plantations corresponds to $77/ha in all three zones (Appendix C).

Regarding secondary forests, timber production is estimated on the basis of tree inventories measured by López et al., (2002). We determined NPV_F for "managed" systems which have on average 78% of medium-density species (e.g. laurel), 8% of low-density species and 14% of shrubs. From these species, only medium-density species have commercial value. According to inventory data, mean annual increment (MAI) of commercial timber volume is 2.5m^3/ha/yr. In accordance to observed practices, we considered that timber extraction starts at year 10 and extraction is kept below the MAI (a value of 2 m^3/ha/yr is used). Annual costs of such systems are low and sum up to $15/ha. Considering the stumpage timber price of $20/m^3, the NPV for secondary forests for all three zones is $264/ha (see Appendix D).

Two things are worth noting. First, in our study region secondary forest generates higher net revenues than forest plantations. This can be explained by the high costs of plantation establishment that are superior to those of secondary forests, where growth of valuable species naturally occurs due to the existence of large areas of natural forests in the surroundings. Based on these findings, we included natural regrowth of secondary forests in the further analysis - although currently not accepted as a human induced activity within CDM - to analyze its potential for carbon sequestration. Second, in comparison to both forestry alternatives pasture generates a higher net present value, indicating that - without payments for carbon sequestration - neither of both forestry alternatives is competitive to pasture land use.

4.3 Carbon sequestration in forests

For plantations, carbon sequestration in biomass is estimated using the laurel growth model described in section 3.4. For secondary forests, we used the regression model of López et al. (2002) (equation 26). Regarding soil organic carbon storage we used data from de Koning et al. (2003) and assumed that reforestation takes place on old pastures. In this case, carbon accumulation in soils occurs during the first 15 years of forest growth and reaches a stable level of about 60 t CO_2/ha. Due to lack of data we assumed that carbon accumulation in soils is linearly dependent on time in secondary forests as well as plantations.[7] Since carbon sequestration in soils is based on simplifying assumptions, we test the impact of including this pool (section 4.7). Finally, with respect to the baseline that is the carbon level in pasture, a value of 18 tCO_2/ha is used.[8]

Figure 1 shows the net carbon sequestration in the forest and in its components (biomass and soils) for secondary forests and laurel plantations. Net cumulative sequestration in secondary forests reaches a level of 420 tCO_2/ha in 30 years. For laurel plantations, 460 tCO_2/ha are sequestered after 15 years. Note that for plantations, net carbon storage after harvest (year 15) does not go to zero because soil carbon is retained.

[7] We assume that soil carbon in the plantation is kept at the same level after harvest takes place. But in practice, soil carbon increases after harvest due to decomposition of leaves and branches (Mohren et al., 1999). This effect is excluded due to lack of data.

[8] Tropical pastures contain some 3 tC/ha (Palm et al., 1999). In addition, on average there are about 6 shadow trees per hectare that contain in total 2 tC/ha. Therefore total carbon in the baseline is 5tC/ha or 18tCO_2/ha.

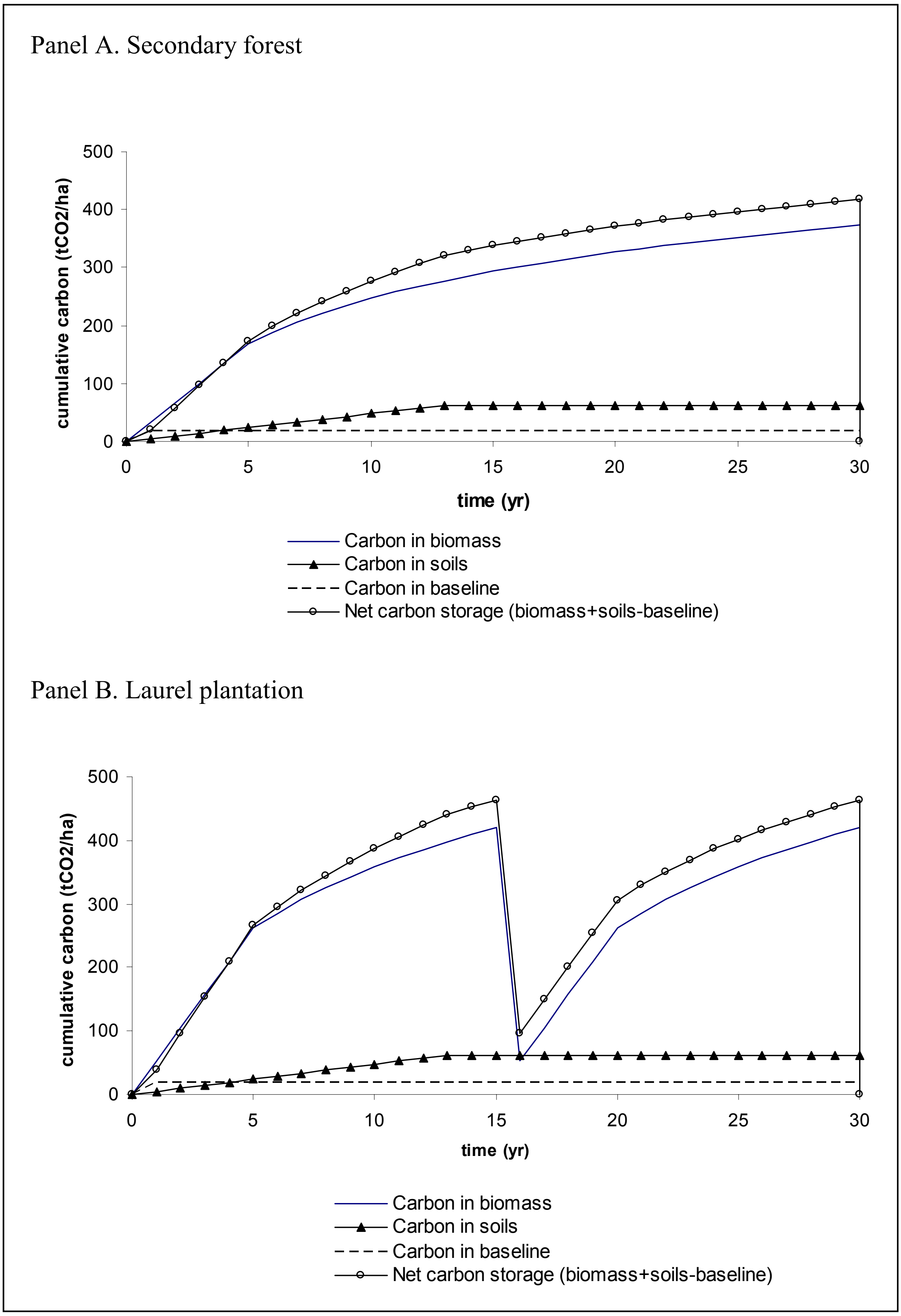

Figure 1. Carbon sequestration in forest biomass and soils.

4.4 Accounting for temporary and long-term CER

Figure 2 (panel A) illustrates how temporary CER are assigned to secondary forests. During the first 5 years of growth, the cumulative carbon storage is 173 tCO_2/ha, thus, 173 temporary CER are assigned. They expire after 5 years, but could be reissued together with additional 104 tCER corresponding to the carbon accumulation between years 5 and 10. In year 15 additional 61 certificates are generated. Together with the still existing 277 they add up to 338 credits available until year 20. During the following 5-year periods further 33 and 25 credits are produced so that during the last project period 396 temporary CER can be provided before the final timber harvest takes place in year 30. During the whole project a total of 1555 temporary credits is issued, which is roughly equivalent to the area below the cumulative sequestration curve divided by five (note that credits are valid for five years).

In a similar way we account temporary CER for the plantation project. After the first 5 years, 266 temporary CER are generated (Figure 2, panel B). From these credits, 242 correspond to biomass and 24 to soils. In year 10, additional 123 credits are produced (99 in biomass and 24 in soils), so a total of 389 tCER are available until year 15, when the first clear cut takes place. When the stand is harvested, biomass carbon is either released to the atmosphere or stored in products, but because carbon storage in products is excluded from the CDM, this additional sequestration is excluded. Regarding soil organic carbon, it remains at the same level after harvest as discussed in the previous section. For the second rotation, 304 temporary credits are produced until year 20 of which 242 are in biomass and 62 in soils. After expiring in year 25 they are reissued together with additional 99 tCER (99 in biomass and zero in soils). After 30 years the project is finished by a final clear cut and all carbon is released. Applying the temporary credit approach leads to a total of 1362 tCER for the plantation project.

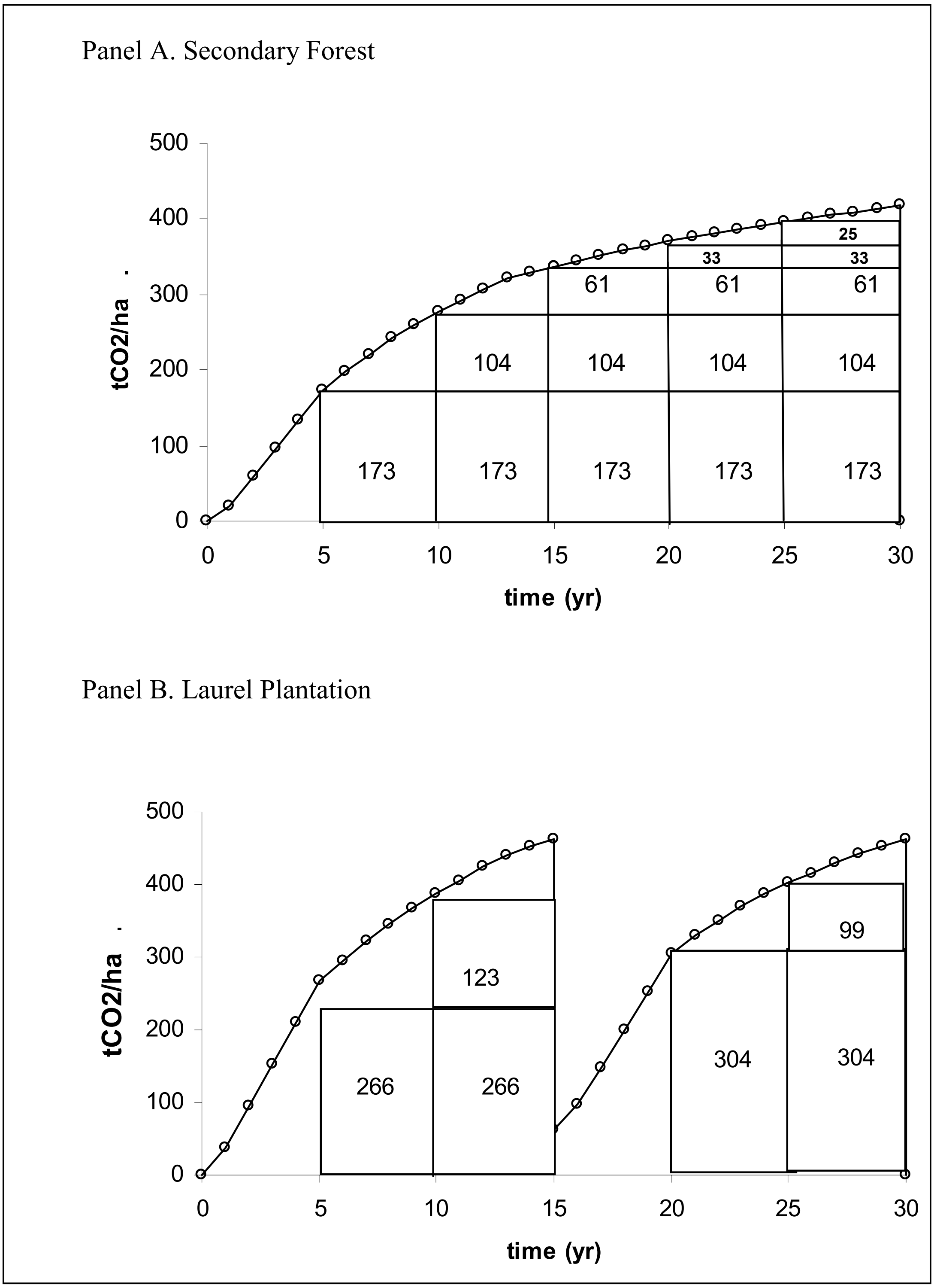

Figure 2. tCER accounting in forests.

Note: for the case of plantations (panel B), the curve does not go down to zero in year 15 after harvest, because carbon in soils is retained.

Accounting long-term CER is similar to temporary CER with the only difference that credits last longer than 5 years. In the case of secondary forest, at year five 173 long-term CER are assigned, which are valid till the end of the project - 25 years - (Figure 3, panel A). In year 10, additional 104 lCER are produced, which last for 20 years. In the following five-year periods 61, 33 and 25 lCER are provided with a validity of 15, 10 and 5 years respectively.

For accounting lCER in plantations we first divide the project in two crediting periods, one for each rotation (this is needed since lCER requires that credits expire at the end of the crediting period). Then, we estimate lCER in a similar fashion as in secondary forests. As shown in Figure 3 (panel B), 266 lCER are issued at year 5 with a duration of ten years. Additional 123 credits are generated in year ten, which are valid for 5 years only. During the second rotation 304 credits are produced at year 20 which are valid for 10 years and finally, 99 credits are produced in year 25 which are valid for 5 years. It is important to note that long-term certificates have short validity: a maximum of 10 years instead of the 25 years for secondary forests. These findings show a problematic aspect of accounting lCER for afforestation projects in the tropics: due to fast growing tree species with short cutting cycles, forest plantations will generate "long-term" certificates of "short-validity".

By comparing the dynamics of tCER and lCER crediting (figures 2 and 3), we find that under the lCER system more credits are assigned in the early stage of the project. This implies that carbon revenues with lCER accounting would be received earlier than with tCER accounting and this makes lCER more attractive.

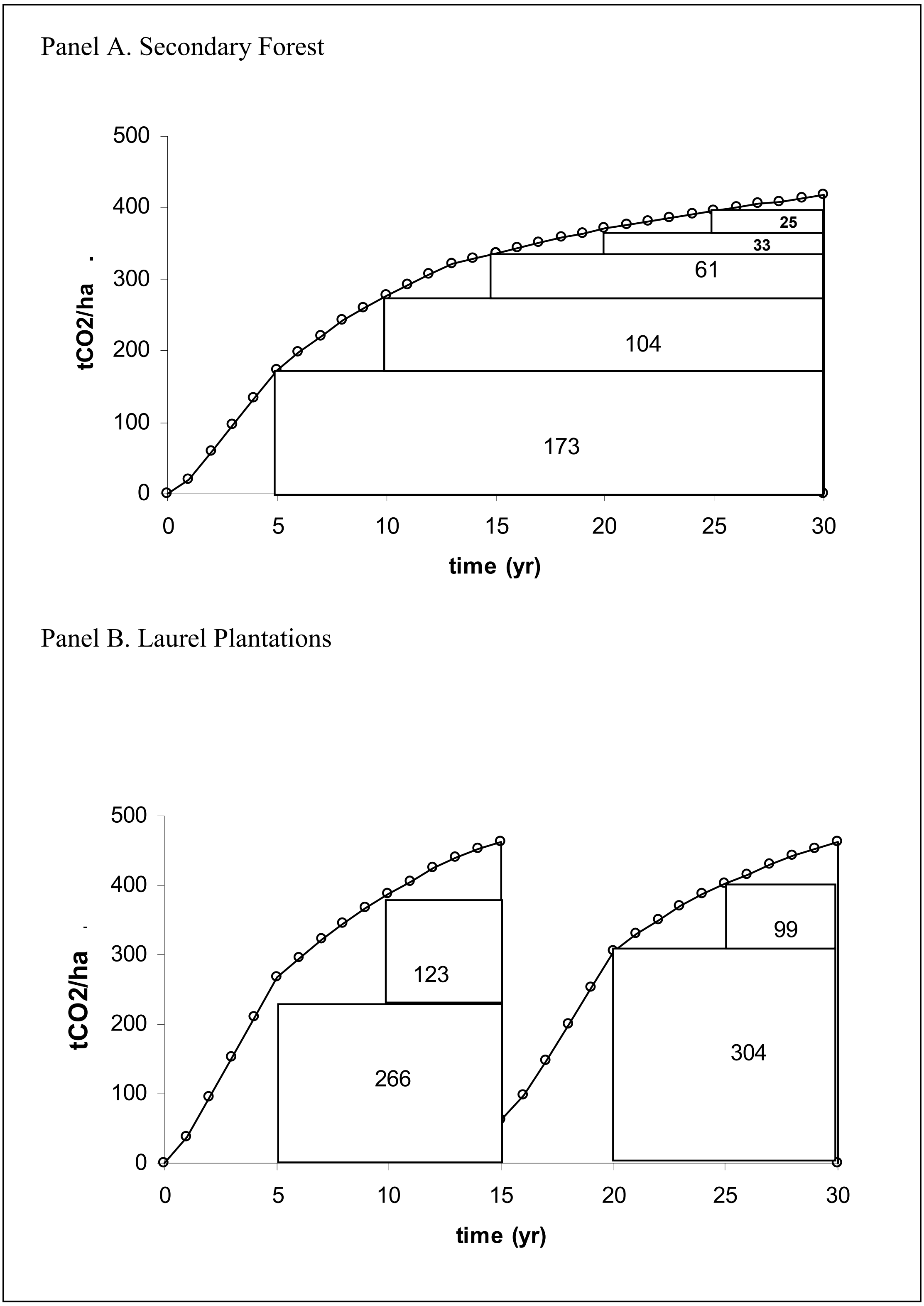

Figure 3. lCER accounting in forests.

4.5 Minimum carbon prices

Based on the tCER estimations, we determined the minimum compensation that would have to be paid to landowners in order to make forestry an economically attractive land-use alternative. We first estimate the minimum tCER price according to equation (5) (see Table 3). The lowest costs of carbon sequestration are found in the northern part of the study area (zone 1) where minimum payments for secondary forest and forest plantation are \$0.9/tCER and \$1.3/tCER respectively. This is mainly caused by the low productivity of the extensive pasture in this zone, resulting in a low NPV_P. At the same time only five percent of the area is used for pasture, so there is only a small area available to switch from pasture to forestry. In zone 3 the opportunity costs of sequestering CO_2 are relatively high due to the higher productivity of the pasture alternative. Zone 2 has the largest pasture areas, and the minimum price that would have to be paid to landowners in order to switch from pasture to forestry is \$1.0/tCER in case of secondary forests and \$1.4/tCER in case of tree plantations.

Table 3. Minimum compensation per temporary CER in Northwest Ecuador.

Zone	Pasture area (km^2)	Secondary forest (\$/tCER)	laurel Plantation (\$/tCER)
1: northern	250	0.9	1.3
2: coastal strip	1550	1.0	1.4
3: closest to capital	1260	1.9	2.3

In order to evaluate how competitive afforestation projects would be in emission trading schemes based on permanent credits and for comparing tCER accounting against lCER accounting, we estimate prices for non-permanent credits. For this, we use equation (8) for tCER and equation (12) for lCER. The results are shown in Table 4, where a discount rate in Annex-I countries of 3% is used for the calculations (Deutsche Bundesbank, 2004).

Table 4. Equivalent prices for permanent CER under different accounting systems ($/t$CO_2$).

	Secondary Forest		Laurel Plantation	
	tCER accounting	lCER accounting	tCER accounting	lCER accounting
Zone 1	6.4	5.0	9.1	8.5
Zone 2	7.2	5.6	9.9	9.2
Zone 3	13.6	10.5	16.5	15.3

The prices shown in Table 4 need to be compared with market prices for permanent credits. The BioCarbon Fund proposed a lower limit for a price margin of $3/t$CO_2$ (The World Bank, 2003). Den Elzen and de Moor (2002) analyzed the potential effects of the Bonn Agreement and the Marrakesh Accords on the CER market price and estimated an equilibrium price of about $4.5 to $5.5 per t$CO_2$. The International Emission Trading Association forecasts CER prices that range from $9.9 to $13.7 per t$CO_2$ (IETA, 2003). The OECD Global Forum on Sustainable Development expects prices from $9 to $22 per t$CO_2$ referring to emission allowance trading within the European Union (Grubb, 2003), whereas PointCarbon estimates come to an expected average price of $10 per t$CO_2$, including potential price effects of the latest agreement on the German National Allocation Plan (PointCarbon, 2004). By comparing these prices with our findings in Northwest Ecuador, minimum CER prices in zone 1 and 2 are most likely to be under market prices and therefore, afforestation projects in these zones would be attractive. But, for zone 3 minimum prices are most likely to be above market prices, so afforestation is not economically viable.

As shown in Table 4, secondary forests always require less compensation costs per ton of carbon than forest plantations. Also, lCER accounting requires lower payments than tCER accounting. In the case of secondary forest, for example, lCER accounting requires prices for permanent credits about 20% lower than tCER accounting for the three zones. Therefore, afforestation through secondary forests and under lCER accounting is the most attractive alternative for carbon sequestration in Northwest Ecuador.

4.6 Net revenues for carbon sequestration

Given the range of prices for permanent credits provided in the previous section, we estimate what the net revenues for afforestation would be in zone 2. We consider both secondary forests and laurel plantations under the two accounting regimes. For this analysis, we first convert permanent prices into non-permanent prices, then estimate the present value of carbon revenues and finally estimate net revenues of afforestation, which is the difference between net present value of forestry including payments for carbon sequestration and net present value of pasture.[9] Results are shown in Figure 4.

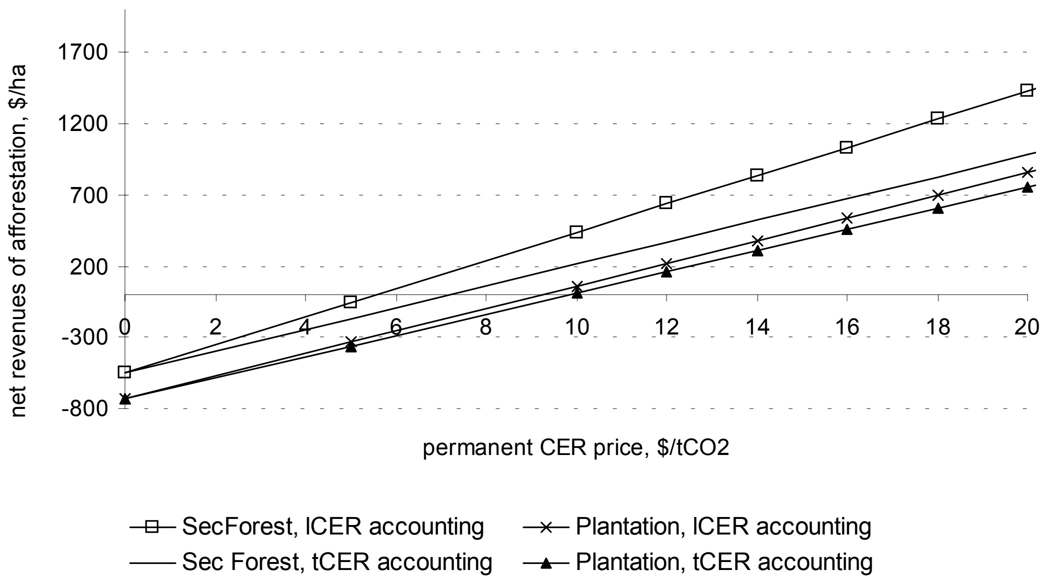

Figure 4. Net revenues of afforestation in zone 2 depending on permanent CER prices and accounting method.

Note that, no matter which price and accounting regime is chosen, secondary forests always generate higher net revenues than forest plantations. Furthermore, due to the extended expiring time, long-term carbon credits generate higher net revenues for afforestation. In secondary forests payments for carbon uptake under lCER method are 20% higher than those of the tCER method. When we take as a reference

[9] In the case of tCER accounting we convert CER prices into tCER prices using equation (7) and then estimate the present value of carbon revenues with equation (3). For lCER accounting, we use equation (11) for determining the present value of carbon revenues.

a carbon price of \$10/tCO_2 that corresponds to one of the latest forecasts (Point Carbon, 2004), landowners in zone 2 from Northwest Ecuador could benefit from up to \$440/ha (secondary forests under lCER accounting), which means that they would earn 50% more than what they currently earn with pasture. Therefore, assigning long-term credits to naturally regrown secondary forests could - although excluded from CDM during the first commitment period - combine the advantages of the accounting regime with the positive economic and ecological effects of this competitive land use.

4.7 Price trends and sensitivity analysis

In our analysis we considered that opportunity costs of land use, i.e. NPV_P, remain constant over the whole 30-year project cycle. If these costs are time-dependant, the compensation payments estimated before would change. For getting an insight into possible price trends, we performed diagnostic tests concerning producer price series for milk and meat in Ecuador, between 1967 and 2002 (Whitaker, Colyer and Alzamora, 1990; SICA, 2003). These series are corrected for inflation using the consumer price index (BCE, 2004). We tested for trends with an Ordinary Least Squares (OLS) regression based on the functional form, $p_t = a + bt + e_t$, where p_t denotes price at time t; a and b are regression coefficients, and e_t is the error term. The regression results showed that milk and meat price have no trends, i.e., b is not significantly different from zero at a 5 percent confidence level (details for this regression are found in Chapter 5 of this thesis). Nevertheless, the meat price varies notably and has a standard deviation of 27 percent (relative to the mean), whereas the milk price standard deviation is smaller (7 percent).

Taking uncertainty related to price developments into account, we simulated a price change of 30 percent for meat, milk, and timber prices as well as for the interest rate. In addition to these variables we evaluated the sensitivity of our results towards the inclusion of certification costs and soil carbon storage. The resulting changes for temporary CER prices in zone 2 are given in Table 5. Note that for lCER accounting, similar percentage changes would be obtained.

The minimum price of carbon sequestration in secondary forests is more sensitive to changes of meat and milk prices than in tree plantations. But, the estimated minimum price in plantation projects is more sensitive to changes of timber price than in secondary forests. This is because plantations provide more commercial timber than secondary forests, so timber price has a larger impact in the NPV of plantations. Therefore, uncertainty regarding opportunity costs of land has a larger impact on the profitability of secondary forests and uncertainty on forest revenues has a larger impact on tree plantations.

Table 5. Sensitivity Analysis.

	Change in minimum price for tCER in zone 2	
	Secondary forests	Laurel plantation
Stumpage timber price. Benchmark scenario: $\$20/m^3$		
$26/m3 (30% higher)	-25%	-34%
$14/m3 (30% lower)	+25%	+34%
Meat price. Benchmark scenario: $0.9/kg		
$1.17/kg (30% higher)	+58%	+43%
$63/kg (30% lower)	-58%	-43%
Milk price. Benchmark scenario: $24/l		
$0.17/l (30% higher)	+24%	+18%
$0.31/l (30% lower)	-24%	-18%
Discount rate Ecuador. Benchmark: 7%		
9% (30% higher)	+6%	+26%
5% (30% lower)	-11%	-28%
Soils. Benchmark scenario: including carbon uptake in soils		
Without soils	+20%	+15%
Certification costs. Benchmark scenario: no costs		
$50/ha every 5 years	+28%	+20%
$100/ha every 5 years	+55%	+41%

Transaction costs of carbon certification are often neglected when estimating sequestration costs. Nevertheless, they may play an important part in overall costs. We included certification costs by adding their present value with a positive sign in the numerator of equation (5) and assumed that these costs are paid every five years when carbon verification and certification by an official verifier takes place (UNFCCC, 2003). Table 5 shows that the impact of certification costs of $50/ha every 5-years, increases minimum prices with up to 28%. Finally, our study included estimates on carbon storage in soils. The impact on the minimum price when neglecting carbon uptake in soils is smaller than 20%.

As an overall result of our sensitivity analysis it can be stated that, in spite of the high volatility, changes within the assumed range do not lead to compensation requirements much higher than those prices forcasted by different institutions. For example, in the case of secondary forests minimum prices might increase in 58% with increasing meat prices. This would reqiure minimum prices for permanent credits of about \$11/tCO_2 in zone 2, which remains close to the forecasted price of PointCarbon (2004). But, of course, this minimum price increase would take a large proportion of the revenues from carbon trading perceived by landowners.

5. Conclusions

This study focused on the competition between forestry and pasture land uses. We provided a framework for the economic comparison of these land use systems and the evaluation of compensation payments that are required for landowners choosing forestry as a land-use alternative. We applied the method for the case of carbon sequestration payments within the clean developing mechanism (CDM) of the Kyoto Protocol in order to estimate what the minimum prices for certificates of emission reductions (CER) would be. Major advantages of our approach are, (i) it uses farm-level information on cattle production in order to capture heterogeneity of land opportunity costs across zones, (ii) it integrates economic and ecological aspects of carbon sequestration, (iii) it considers the latest and definitive decisions on carbon accounting under the CDM, and (iv) provides an easy-to-reproduce approach for estimating carbon sequestration costs that could be used as a standard procedure for CDM project assessment.

The comparison of land-use alternatives in three distinct zones of Northwest Ecuador showed that without payment for carbon sequestration pasture is always a better option than forestry. Therefore, for afforestation to be viable always requires payments associated with the environmental services of forests. Our comparison also showed that secondary forest is economically more attractive than tree plantations (laurel), and afforestation programs should consider this option that has been excluded from the CDM for the first commitment period of Kyoto. Secondary forests are more cost-efficient than plantations due to the low establishment costs and the relatively early timber revenues from the “managed” secondary forests. Compensation costs per ton of CO_2 are lower for secondary forests than for plantations. Natural regrowth of secondary forest - once accepted within the CDM - could play an important role as an effective and efficient project activity. This finding is even strengthened when further additional benefits of secondary forests are taken into account, such as soil and water protection or biodiversity conservation.

Given the decision of the Conference of the Parties (COP9) for assigning non-permanent credits for afforestation projects under the CDM, we compared the two possible systems for carbon accounting: temporary CER and long-term CER. Our results showed that long-term crediting is economically more favorable since it provides larger revenues. This advantage is particularly evident in the case of secondary forests where the carbon stock in the forest is monotonically increasing, without clear-cuts within the project cycle (only at the end). But, lCER could be less attractive for landowners due to the long-biding character of these certificates.

The presented methodology is meant to support the decision making process on the supply side of a future CER market. Focusing on the *development* aspect of CDM means that forestry projects within this mechanism should generate higher income than the status quo. As shown in this research, not all zones of northwest Ecuador are economically apt for afforestation and only in some regions landowners would be better off via this mechanism. Thus, developing countries should carefully analyze the opportunity costs of land-use changes before taking a decision in favor of long-binding forestry projects. In addition, transaction costs should be kept low in order not to strongly reduce the revenues for landowners in developing countries.

Our sensitivity analysis showed that uncertainties associated to timber and meat prices have a strong impact on the outcome. Therefore, CDM project developers must take measurements to reduce current uncertainty levels. It would be important, for example, that project developers assist landowners in finding appropriate markets for their wood within domestic and international timber markets.

Something ignored throughout this Chapter is the impact of risk and uncertainty in land-use decision making. This problem is dealt into detail in Chapter 5 of this thesis.

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Appendix

A. Cost and benefits for pasture

In this appendix we present the details for the cost-benefit analysis of pasture. Data is obtained by means of 40 interviews to farmers in 2000, from INIAP (2000) and from Torres and Izquierdo (1991). Table A1 presents general data needed for the analysis and Table A2 provides the age/weight relationship for *mestizo* cattle in Northwest Ecuador. *Mestizo* cattle have its origins in the Brahman race that was introduced in West Ecuador several hundred years ago. These cattle are used throughout the 3 zones.

Table A1. Data for the cost-benefit analysis.

	Zone 1	**Zone 2**	**Zone 3**
Labor costs ($/day)	3	3	3
Labor requirements for pasture cleaning, day/(ha*yr)	10	10	10
Reproduction rate of cows, g, calves/(cow*yr)	0.8	0.8	0.8
Survival rate of calves in their first year, s_1 (%)	90%	90%	90%
Survival rate of calves in their second year, s_2 (%)	97%	97%	97%
Milking costs ($/liter)	0.04	0.04	0.04
Losses of cattle due to robbery (%)	2%	2%	2%
Administrative costs (% of total costs)	15%	15%	15%
Total heads per ha	1.2	1.2	1.6
Cows per ha (C)	0.53	0.54	0.61
Bulls per ha (B)	0.13	0.02	0.05
Calves per ha (G)	0.54	0.64	0.94
Farmgate price for standing cattle ($/kg)	0.8	0.9	0.9
Milk production, liters/(cow*yr)	450	250	600
Farmgate milk price, ($/l)	0.21	0.24	0.24
Cattle vaccines, pests control and other cattle maintenance($/head/yr)	6	6	10

Table A2. Age / Weight relationship for cattle.

Age (years)	*Weight (kg)*
0.5	125
1.25	215
1.75	310
2.5 or more	455

Here we illustrate how cost and benefits are estimated using zone 1 as an example.

We start by solving the cattle model for meat production.

<u>Meat production and meat revenues</u>

- Calves born per year, $G_b = C \cdot g$ = 0.53cow/ha · 0.8 calf /cow/yr = 0.424 calf/ha/yr
- Calves with age 0-1, $G_1 = s_1 \cdot G_b$ = 0.9·0.424 = 0.381 calves/ha
- Calves with age 1-2, $G_2 = s_2 \cdot G_1$ = 0.97·0.381 = 0.37 calves/ha
- Calves sold per year, $G_s = G_2$ = 0.37 calves/ha/yr
- Weight of calves sold. We use the age/weight relationship of Table A2. For an age of 2 years, the weight of cattle lies between 310 kg and 455 kg. By linear interpolation, we get that the weight of calves sold is, W_{sold} = 358 kg/calf.
- Meat production, $M = G_s \cdot W_{sold}$ = 0.37·358 = 132 kg/ha/yr
- Meat revenues. For a farmgate price of \$0.8/kg; meat revenues are: **\$105.7/ha/yr**

<u>Milk production and revenues</u>

- Milk production = (0.53 cow/ha) · (450 l/cow/yr) = 238 l/ha/yr
- Milk revenues. For a farmgate price of \$0.21/l, milk revenues are: **\$49.9/ha/yr**

<u>Costs</u>

- Opportunity costs of cattle stock (c_o). This equals the rental value of the cattle stock for one year, $c_o = r \cdot W_{total} \cdot pm$; where r is the discount rate, W_{total} is the weight of all the stock (calves + cows + bulls), and pm is the meat price. The average weight of calves is: $(W_{sold} + W_{born})/2$. We have W_{sold} = 358 kg (see above) and W_{born} = 75 kg; so the average weight of calves is: 216 kg. For cows and bulls their weight is 455 kg (Table A2). Based on these data we estimate total weight:

W_{total} = 0.53 cow/ha · 455kg/cow + 0.13 bull/ha · 455kg/bull + 0.54 calf/ha · 216kg/calf

W_{total} = 417 kg/ha or 0.92 AU/ha - one AU (animal unit) is 454 kg -

→ c_o = 0.07· (417 kg/ha) · (\$0.8/kg) = \$23.3/ha/yr

- Replacement of old cows and bulls (c_r). When cows and bulls loose their breeding capacity by aging, they are replaced by younger ones (they are sold to a slaughterhouse and new cattle is bought). This replacement costs about 20% of the original value of cows and bulls. Considering that 10% of cows and bulls are replaced each year, we have,

$c_r = 0.1 \cdot 0.2 \cdot \$0.8/\text{kg} \cdot (0.53\text{cow/ha}+0.13 \text{ bull/ha}) \cdot (455\text{kg/head}) = \$4.8/\text{ha/yr}$

- Cattle losses (c_l). Since 2% of the cattle is lost each year, the total weight of cattle is 380kg/ha and the price of meat is $0.8 kg, $c_l = 0.02 \cdot 417 \text{ kg/ha} \cdot \$0.8\text{kg} = \$6.7/\text{ha/yr}$
- Vaccines and pest control in this zone costs $6/head; therefore these costs are: $7.2/ha/yr
- Milking costs. We have $0.04/l. Since milk production is 238 l/ha/yr; these costs are: $9.5/ha/yr
- Pasture cleaning. Labor for pasture cleaning requires 10 days/ha/yr. Since labor costs $3/day, these costs are: $30/ha/yr.
- Fence costs. These depend on parcel size. For a parcel size of 3ha, the costs for new fences sums $52/ha. If we consider an amortization period of 30 years, and 7% discounting, fence costs are, $4.2/ha/yr.
- Administrative costs. They are 15% of costs. Since the above described costs sum $83.1/ha/yr, administrative costs are: $12.9/ha/yr
- Total costs. Summing all cost items leads to: **$98.6/ha/yr.**

Net revenues and NPV

Net revenues per year equal revenues for meat and milk production minus costs. Therefore, net revenues are: 105.7 + 49.9 – 98.6 = **$57.0/ha/yr.**

For estimating NPV for a 30-year period, we sum the discounted value of 30 payments of $28.9/ha/yr using a 7% rate. This leads to **NPV = $756.3/ha**

Costs and revenues for the 3 zones

The summary of costs and revenues for the three zones is shown in Table A3.

Table A3. Costs and Revenues for Cattle Production in Northwest Ecuador.

Costs	**Zone 1**	**Zone 2**	**Zone 3**
Opportunity costs of cattle stock, $/ha/yr	$23.4	$24.8	$31.7
Replacement of old cows and bulls, $/ha/yr	$4.8	$4.6	$5.4
Cattle losses due to robbery $/(ha*yr)	$6.7	$7.1	$9.1
Vaccines and pest control $/(ha*yr)	$7.2	$7.2	$16.0
Milking costs	$9.5	$5.4	14.6
Pasture cleaning $/(ha*yr)	$30.0	$30.0	$30.0
Fence costs $/(ha*yr)	$4.2	$1.6	3.2
Administrative costs $/(ha*yr)	$12.9	$12.1	$16.5
Total costs	***$98.6***	***$92.8***	***$126.5***
Revenues	**Zone 1**	**Zone 2**	**Zone 3**
Meat			
Meat production: kg/(ha*yr):	132.1	135.1	152.1
Revenues for meat production $/(ha*yr):	$105.7	$121.6	$136.9
Milk			
Milk production liters/(ha*yr):	237.6	135.0	364.8
Revenues for milk production $/(ha*yr):	$49.9	$32.4	$87.6
Total revenues	$155.6	$154.0	$224.4
Net revenues, $/(ha*yr)	**$57.0**	**$61.2**	**$98.0**
NPV for a 30-year period	**$756.3**	**$812.4**	**$1300.7**

B. Stumpage timber price

For estimating stumpage timber price, we evaluate two available options for forest owners: (i) to sell sawnwood in nearby towns and (ii) to sell sawnwood in the country's capital, Quito. In both cases, stumpage timber price is estimated with the following equation:

$$p_w = (p_s - c_f - c_r - c_t - c_a) \cdot \eta$$

where, p_w is the stumpage timber price, p_s is the sawn wood price in the market, c_f are felling and sawmill costs, c_r are transport costs from the forest site to the side of the road, c_t are transport costs to the market, c_a are administrative costs and η is processing efficiency. These prices and costs are shown in Table B1.

Table B1. Stumpage timber price in Northwest Ecuador, 2000.

Price / Cost	sawnwood sold in nearby towns*	sawnwood sold in country´s capital (Quito)
p_s: sawnwood price	\$35 –\$65 /m^3	80 –100 \$/m^3
c_h: Felling and sawmill costs	\$10/m^3	\$10/m^3
c_r: transport costs till the side of the road (with animals) and lift over truck (by man)	16/m^3	\$16/m^3
distance from forest to market	100 km	400 km
Transport costs per km	\$0.06/km	\$0.06/km
c_t: transport costs	\$6/m^3	\$24/m^3
Subtotal: c_h+c_r+c_t	\$32 /m^3	\$50/m^3
c_a: Administrative costs (15%)	\$4.8/m^3	7.5/m^3
Total costs	\$36.8/m^3	\$57.5/m^3
Processing efficiency	0.7	0.7
Stumpage timber price	***\$0 –\$ 19.7 /m^3***	***\$15.8 -\$ 29.8/m^3***

*Nearby towns: Esmeraldas, Borbón, Quinindé, Esmeraldas.

From Table B1 it is clear that it is more favorable to sell timber in Quito. This option is considered for our study and a value of \$20/m^3 is used for the analysis.

C. Cost and benefits for plantations

In this Appendix we provide a summary of cost and benefits for laurel plantations. Table C1 shows costs per hectare at the start of a plantation project (year zero). Table C2 shows maintenance costs between year one and 10 and Table C3 shows the discounted value of total establishment and maintenance costs. These costs are the same for the three zones since it is a labor intensive activity and labor prices are uniform across all zones. Based on this data, the optimum rotation interval is estimated and the net present value for plantations is shown in Table C4.

Table C1. Establishment costs for plantation.

Activity	\$/ha
Land preparation (\$/ha)	30
Plant costs \$/ha:	176
Planting (\$/ha):	60
Replanting (30%):	71
Fences	18
Administrative and technical assistance (15%)	53
Total establishment costs	408

Table C2. Maintenance costs, years 1-10, \$/ha.

Year	Cleaning	Thinning	Administration	Total
1	90	0	14	104
2	90	0	14	104
3	48	0	7	55
4	36	0	5	41
5	27	0	4	31
6	27	60	13	100
7	9	0	1	10
8	9	0	1	10
9	9	0	1	10
10	9	0	1	10

Table C3. Total discounted establishment and maintenance costs (c).

	\$/ha
Initial costs	408
Discounted costs year 1-10 (7% discounting)	376
Total	784

Optimum rotation. An analytical solution of the maximization problem for the Faustman equation is not possible given the complexity of the equations that are used for estimating timber volume. Therefore, the problem is solved numerically with Solver/Excel. We estimate an optimal rotation of **15 years** and a **timber volume of \$116/m^3** given the following data: discount rate 7%, timber price \$20/m^3, plantation costs \$784/ha, stocking 400 trees/ha, site index 22.

Net present value. Combining the above described data, we estimate the NPV for laurel plantations:

Table C4. NPV for laurel plantations.

Discounted establishment costs	\$784/ha
Timber volume at year 15	116 m^3/ha
Timber price	\$20/m^3
Present value of timber revenues (tr)*	\$840/ha
Net present value for one rotation of 15 years (NPV_1)**	\$56/ha
Net present value for two rotations of 15 years each (NPV_2)***	\$77/ha

*$tr=pw/(1+r)^{15}$, where pw is the timber price and r the discount rate (7%)
**NPV_1=tr-c, where c are total discounted establishment and maintenance costs (\$784/ha)
*** $NPV_2= NPV_1 + NPV_1/(1+r)^{15}$

D. Cost and benefits of secondary forests

Table D1 summarizes the costs and benefits of “managed” secondary forests using a discount rate of 7% and a timber price of $\$20/m^3$. In the absence of more detailed data, such costs and benefits are the same for the three zones.

Table D1. Costs and benefits of managed secondary forests (per ha).

	Years 0 - 9	Years 10 - 29	Year 30*
Costs for specie selection and cleaning	$15	$15	0
Timber harvest, m^3/ha/yr	0	2.0	89
Revenues, $/ha/yr **	0	$40	$1770
Net revenues, $/ha/yr ***	-$15	$25	$1770
NPV, with 7% discounting	**$264/ha**		

* In year 30 the forest is completely harvested
** Revenues = (timber harvest)*(timber price), where timber price is $\$20/m^3$
*** Net revenues = revenues – costs for specie selection and cleaning

Chapter 3

Site Identification for Carbon Sequestration in Latin America: A Grid-Based Economic Approach

This chapter is based on:

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Abstract

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

Keywords: carbon sequestration, climate change, afforestation, Kyoto Protocol, clean development mechanism

1. Introduction

Global warming as a consequence of human-induced emissions of greenhouse gases (GHG) is perceived as a major environmental concern threatening future welfare. Scientists predict that by 2100 the globally averaged surface air temperature will increase by 1.4 - 5.8 °C leading to major disturbances for human settlements and natural ecosystems (IPCC, 2001). The Kyoto Protocol of Climate Change aims at capping GHG emissions from industrialized countries and allows emission trading between industrialized countries and developing countries through the Clean Development Mechanism, CDM (UNFCCC, 1998).

The CDM is applicable for energy-related projects as well as for afforestation and reforestation projects, where the latter are referred to as CDM-sinks. While for the first commitment period of Kyoto, 2008-2012, the market for CDM-sinks is limited (den Elzen and de Moor, 2002), the importance of CDM-sinks is in the large potential for afforestation[1] in developing countries that could be used beyond 2012. According to Nilsson and Schopfhauser (1995), the area available for plantations in the developing world is twenty-six times larger than in Europe, eleven times larger than in the US and three times larger than in the Former Soviet Union. Therefore, there is a need to develop methods for deriving cost-curves of carbon sequestration in these regions and identify areas where carbon sequestration is cost-efficient. We take Latin America as a case study because of its land-availability and ecological conditions favoring forestry projects, as well as its active participation for implementing carbon sequestration projects in the early stage of the Kyoto process (Brown et al., 2000). We estimate carbon supply-curves for afforestation, its potential benefits for carbon trading under the Kyoto agreement and provide a geographic representation of the distribution of carbon costs.

Economic studies on carbon sequestration in Latin America have so far provided single point estimates of sequestration costs associated with particular sequestration levels [e.g. Fearnside (1995) for Brazil, Pereira et al. (1997) for Venezuela, Masera et al. (1997) for Mexico and, Benítez et al. (2001) for Ecuador].

[1] We use afforestation for both afforestation and reforestation, noting that they correspond to the process of tree-planting in non-forest land and their difference relies on the land-history.

These studies provide information on average costs of carbon sequestration for particular regions, but do not assess how these costs increase when large-scale afforestation programs are implemented. In contrast to these studies, we evaluate how the heterogeneity of prices (e.g. land and timber prices), and the heterogeneity in land attributes (e.g. net primary productivity and suitability for agriculture) influence sequestration costs and determine carbon-supply patterns. In addition, we provide a framework for identifying least-cost sites for carbon sequestration by means of a grid-based analysis that scrutinizes all the available area for plantations in the region.

2. Methods

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

The analysis starts by creating a homogenous geographical grid (with a grid-cell size of 0.5 degrees) for the whole study area and selecting grid-cells that are suitable for afforestation, i.e. non-forest areas where tree-planting is viable and will not compromise food security of the region. We then estimate sequestration costs for each grid-cell[2] based on estimates for net primary productivity (NPP), plantation costs, expected timber and land prices, and carbon storage in products. Finally, we

[2] For ease on the reading we call “grid-cells” simply as “cells”.

obtain the cumulative sequestration cost-curve by aggregating cell results, taking into account that afforestation activities occur only in cells where the carbon price exceeds sequestration costs. Besides obtaining the cost-curve, the method allows identifying the geographic distribution of carbon costs and forest growth potentials throughout the region.

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

$$F_i \geq A_i \qquad (1)$$

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

$$f_i = -cp_i + pw_i \cdot V_i \cdot (1+r)^{-R_i} + B_i \qquad (2)$$

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

2.1 Carbon benefits

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

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

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

2.2 Forest products and their carbon benefits

In practice, not all the carbon removed from the forest is immediately released to the atmosphere, but there is a fraction, θ, that is stored for longer time periods outside the atmosphere (van Kooten et al., 1995). This storage after harvest can take place in a wide range of forest products including long-lived products like furniture, structures, construction materials and thick branches, and short-lived products like paper, leaves and thin branches. This broad definition for "forest products" is used throughout this study. Including forest products, the equation for carbon benefits is now[3],

$$B = pc\sum_{t=1}^{R} \omega \left(1+r\right)^{-t} \quad - \quad pc \cdot \omega \cdot R\,(1+r)^{-R} + pc \cdot \theta \cdot \omega \cdot R\,(1+r)^{-R} \tag{4}$$

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

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

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

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

where (t-R) is the time after harvest, ϕ is the fraction of the forest biomass stored in long-lived products and, k1 and k2 are rates of decay of long and short-lived products respectively. Carbon release from forest products, W'(t), is estimated by taking the first derivative of W(t) with respect to t,

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

Now we proceed to estimate the net benefits of the externalities associated with carbon uptake and release in forest products. At harvest time, all the biomass that was standing in the forest enters the products pool. Therefore, the initial carbon storage in products is ω·R. Then, carbon is released according to the exponential decay function of equation (6). The present value of carbon uptake/release in products (P) estimated over an infinite time period and using continuous discounting is,

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

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

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

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

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

and,

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

With lower decay rates and higher discount rates, the parameter θ is larger and so the present value of carbon benefits in products. This makes sense because low decay rates indicate that products remain in the atmosphere for a long time, and high discount rates reduce the present value of the social costs associated to carbon release when products are decomposed.

2.3 Baseline considerations

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

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

$$B_i = pc_i \cdot \omega_i (1-b_i) \left\{ r^{-1} \left[1-(1+r)^{-R_i} \right] - R_i (1-\theta_i)(1+r)^{-R_i} \right\} \tag{11}$$

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

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

2.4 Net present value for agriculture

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

$$y_i = \eta_i \cdot S_i^{\alpha_i} \cdot D_i^{\gamma_i} \tag{13}$$

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

$$A_i = \upsilon_i \cdot S_i^{\alpha_i} \cdot D_i^{\gamma_i} \tag{14}$$

where υ_i would also take into account the general price level existing in each country[4]. Equation (14) provides only an approximation for net present value of agriculture[5], but by using it we avoid relying on detailed land-use statistics and it also prevents underestimation of agricultural revenues in case the land is not well-managed. For practical reasons, we denote A_i as the land price, knowing that in the absence of risks and uncertainties, and having competitive markets, A_i will reflect the value that a farmer will be willing to accept in exchange of his land.

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

[5] More comprehensive approaches exist for predicting land prices, e.g. in Plantinga et al. (2002).

2.5 Costs for carbon sequestration

When we set A_i=F_i, we find the minimum carbon price (which we define as the carbon costs) that allows forestry to be as profitable as agriculture (derivation in footnote 6),

$$pc_i = \frac{A_i\left[1 - (1+r)^{-R_i}\right] + cp_i - pw_i \cdot V_i (1+r)^{-R_i}}{\omega_i (1-b_i)\left\{r^{-1}\left[1-(1+r)^{-R_i}\right] - R_i(1-\theta_i)(1+r)^{-R_i}\right\}} \tag{15}$$

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

2.6 Time-profile of carbon sequestration

In the previous equations we determined the (minimum) carbon price a landowner requires for converting non-forest land into forests. Now our interest is to know how

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6 Replace carbon benefits, B_i of (eq. 11) with net present value of forestry for one rotation, eq. (2):

$$f_i = -cp_i + pw_i \cdot V_i \cdot (1+r)^{-R_i} + pc \cdot \omega_i (1-b_i)\left\{r^{-1}\left[1-(1+r)^{-R_i}\right] - R_i(1-\theta_i)(1+r)^{-R_i}\right\}$$

Substitute f_i in (eq.12):

$$F_i = \frac{-cp_i + pw_i \cdot V_i \cdot (1+r)^{-R_i} + pc \cdot \omega_i (1-b_i)\left\{r^{-1}\left[1-(1+r)^{-R_i}\right] - R_i(1-\theta_i)(1+r)^{-R_i}\right\}}{1-(1+r)^{-R_i}}$$

Replace F_i in (eq. 1):

$$\mathrm{A_i} = \frac{-cp_i + pw_i \cdot V_i \cdot (1+r)^{-R_i} + pc \cdot \omega_i (1-b_i)\left\{r^{-1}\left[1-(1+r)^{-R_i}\right] - R_i(1-\theta_i)(1+r)^{-R_i}\right\}}{1-(1+r)^{-R_i}}$$

find the carbon price, pc, that satisfies $\mathrm{A}_i = F_i$ for each grid,

$$pc_i = \frac{A_i\left[1 - (1+r)^{-R_i}\right] + cp_i - pw_i \cdot V_i (1+r)^{-R_i}}{\omega_i (1-b_i)\left\{r^{-1}\left[1-(1+r)^{-R_i}\right] - R_i(1-\theta_i)(1+r)^{-R_i}\right\}}$$

much carbon is sequestered at any given time among all available cells, if the carbon price has a certain market value, pc*.

For estimating the time profile of carbon sequestration, we need to distinguish between cells and stands. Each cell has one carbon price, pc_i, but is divided in parcels that are planted at different times. Each of these parcels is one stand. While all stands within a cell have the same carbon price, the cumulative sequestration at a given time differs.

Figure 1 shows the time profile of carbon sequestration in forest biomass and forest products for one stand. Cumulative carbon in tree biomass accumulates until harvest takes place (year 20) and carbon biomass becomes zero. Afterwards, trees are re-planted and carbon in tree biomass increases until the second harvest (year 40), when the carbon level is reduced to zero again. The same holds for the subsequent cycles. Carbon in forest products (furniture, paper, dead leaves and branches), starts to accumulate after the first harvest (year 20). Then, products decay and carbon in products follows an exponential decrease. When a second harvest takes place (year 40), a new stock enters the products pool, summing up with the remaining stock from the first harvest. Total carbon accumulation is the sum of carbon in biomass and products.

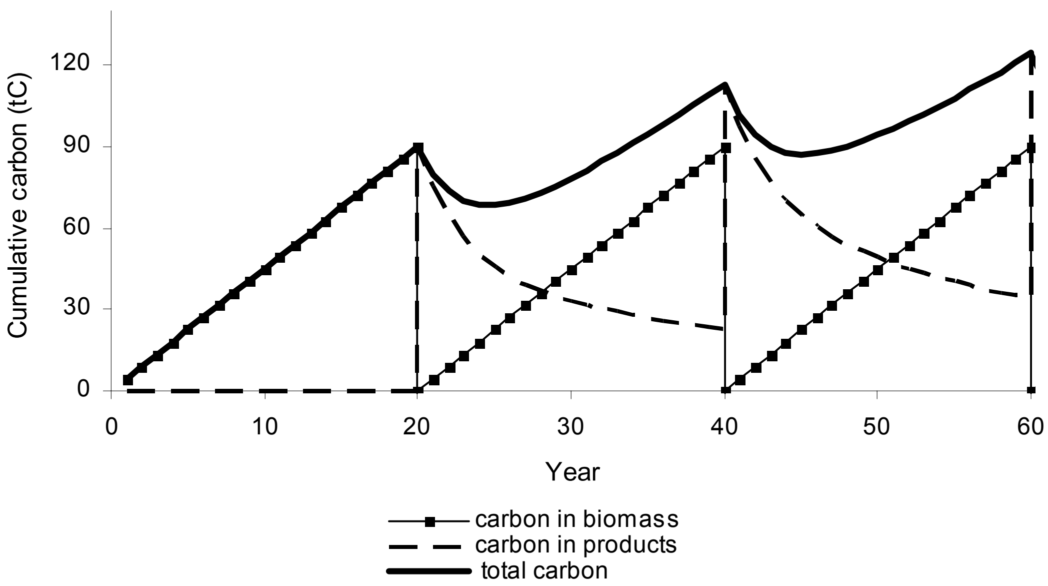

Figure 1. Carbon accumulation in forest biomass and forest products.

Under a market price pc*, sequestration would take place only in the cells that have their minimum carbon price, pc_i, below pc*. Also we have stands of different ages within a cell. We use the subindex "k" for stands. Every stand of each cell has an area $A_{i,k}$. The net cumulative carbon sequestration up to time T is the sum of the carbon sequestered in the "*K*" stands of the "*I*" cells, minus the carbon in the baseline,

$$C_T = \sum_{i=1}^{I} \sum_{k=1}^{K} A_{i,k} \left(1-b_i\right)\left(C_{i,k,T}^{b} + C_{i,k,T}^{p}\right) \tag{16}$$

$$\forall i \mid \; pc_i < pc^*$$

$C_{i,k,T}^{b}$ measures the cumulative carbon sequestration per hectare in the biomass of stand k of cell i at time T. $C_{i,k,T}^{p}$ measures the cumulative carbon sequestration in forest products.

We estimate sequestration in biomass with,

$$C_{i,k,T}^{b} = \omega_i (T - tp_{i,k}) - h_{i,k,T} \cdot \omega_i \cdot R_i \tag{17}$$

and,

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

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

The cumulative carbon in products is estimated as,

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

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

Carbon supply curves represent the relationship between the carbon price and the amount of carbon sequestered. A problem with respect to the carbon supply is that the amount of carbon sequestered depends on the time-period for sequestration (see equation 19). Therefore, supply curves need to be specified for a given time, T.

2.7 Revenues for carbon trading

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

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

where $C_{i,t}$ and $C_{i,t-1}$ denote cumulative carbon levels at year t and t-1 in cell "i", including all K stands. The difference between these two values is the net carbon uptake at year t.

In order to solve the above described model a MATLAB algorithm is developed.

3. Data

The analysis considers 0.5 degree cells (about 50x50 km depending on latitude) and includes 8 countries that represent more than 90% of the Latin American region (FA0, 2001; FAO, 2002). The ecological and economic data used for the analysis are discussed below.

3.1 Land available for plantations

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. For estimating non-forest areas available for plantations, we used the International Geosphere Bioshpere Programme (IGBP) land-use classification systems (Belward, 1996). This classification uses 17 land classes as shown in Table 1. From these classes, only three are considered suitable for afforestation and reforestation: grasslands, savannas, and open shrub lands that sum up 22 % of the total Latin American area.[7]

[7] In practice, low productive croplands and woody savannas could also be considered suitable for plantations. But, for Latin America, this inclusion would not affect significantly its carbon supply.

Table 1. IGBP 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	Land with herbaceous type of cover. Tree and shrub cover: 0–10%	7.4%
Open Shrublands	Land with woody vegetation less than 2 meters tall. Shrub cover: 10–60%	8.5%
Savannas	Land with herbaceous and other understory systems. Forest cover: 10–30%	6.4%
Non-suitable for afforestation and reforestation		***77.7%***
Woody Savannas	Land with herbaceous and other understory systems. Forest cover: 30–60%	10.6%
Barren or Sparsely Vegetated	Land with exposed soil, sand, rocks, or snow. Less than 10% vegetation cover	2.7%
Closed Shrublands	Land 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).

From the pre-selected land classes shown in Table 1 we also exclude: (i) highly productive land where the indicator of suitability for agricultural is above 50%[8] (Ramankutty et al., 2002; SAGE, 2002), (ii) areas where the population density is over 100 hab/km^2 (CIESIN, 2002), (iii) areas where the net primary productivity of C is below 0.1 kg/m^2/yr like in deserts (SAGE, 2002) and, (iv) areas where the altitude is above 3500 m, so that the unique Andean ecosystem, Páramo, is kept untouched. Applying the above mentioned constraints, the area available for plantations is

[8] This indicator ranges from 0% (no suitable) to 100% (very suitable).

reduced to 237 million hectares or 13% of the total land area of Latin America. As shown in Table 2, Argentina and Brazil have the largest share of this land.

Table 2. Area suitable for plantations in the major Latin American countries.

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

3.2. Carbon Sequestration Parameters

Grid data on tree-growth is estimated as a function of net primary productivity (NPP), (SAGE, 2002). For converting NPP values to carbon uptake, a factor of 50% is used[9]. This leads to rates of carbon uptake between 0.6 - 6.2 tC/ha/yr across the region. These values are comparable with data from Trexler and Haugen (1995) who propose rates of carbon uptake from 0.3 - 1.5 tC/ha/yr for the dry tropics and 6 - 12 tC/ha/yr for the humid tropics.

Timber volume is proportional to biomass accumulation in the aboveground forest. We consider that 20% of the carbon uptake is in the roots, and the carbon content in the aboveground forest is in the range of 0.3 tC/m^3 for temperate regions and 0.4 tC/m^3 for tropical regions (Nilsson and Schopfhauser, 1995). This leads to a timber/carbon ratio of 2 m3/tC in the tropics and 2.6 m3/tC in temperate regions. Rotation intervals are 20 years for the tropics and 30 years for temperate regions (Nilsson and Schopfhauser, 1995). The baseline factors, b_i, described in the previous section are 5% for grassland and 20% for savannahs and open shrublands. This

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

assumption follows the IGBP definition of grasslands and savannahs mentioned in Table 1.

Regarding the parameters for the decay function of forest products, we consider that 50% of the forest biomass is stored in long-lived products with a half-life time of 20 years while the remaining biomass that consists of short-lived products has a half-life time of one year[10]. Finally, we assume that tree-planting in each cell requires 50 years for completion and that planting occurs at a constant rate as in Trexler and Haugen (1995). The assumption of a 50-yr period to complete planting in each cell, reflects the enormous effort that is required to start large-scale afforestation projects in areas where trees have never existed before.

3.3 Prices

As discussed in section 2, our model considers the price of land as a function of the suitability for agriculture and population density, following a Cobb-Douglas relationship. The level of aggregation for the suitability for agriculture is 0.5 degrees. For the population density, the level of aggregation is 3.5 degrees. This value is selected in order to capture the average population density in a radius of approximately[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.

For fitting the parameters of the land price function (A_i), we set minimum and maximum bounds, so that the upper bound corresponds to cells where suitability for agriculture and population density are the highest, and the lower bound corresponds to cells where these indicators are the lowest. In our benchmark scenario, we assign equal weights for both indicators[12], so that $\alpha_i = \gamma_i$ in equation (14), but we test the impact of this assumption with a sensitivity analysis. For Brazil, the higher bound for land prices is set at $2000/ha which is in agreement with data for sites of good quality in Latin America (de Jong et. al, 2000; Benítez et al., 2001). The lower bound is set to

[10] Decay rates are estimated on the basis of half-life time ($t_{1/2}$) using the following equation: $k=\ln(2)/t_{1/2}$.
[11] One degree is about 100 km depending on latitude.
[12] Since S and D could have a value of zero, we normalized them between 1 to 10, where 1 is the lowest outcome and 10 the highest.

\$200/ha. Plantation costs in Brazil are \$800/ha which is within the range provided by Ecosecurities (2002) and Fearnside (1995). Note that Brazil has been chosen as a reference country for prices, given its large potential for carbon sequestration. For estimating land prices and plantation costs in other countries, we correct prices with the price index which is the ratio between the purchasing power parity (PPP) conversion factor and official exchange rate (World Bank, 2001).

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

Table 3 shows the summary of the model parameters used for the Latin American case-study.

Table 3.Model parameters used for Latin America.

Parameter	Value / Source
Discount rate, r	5%.
Plantation Costs, cp	\$800/ha for reference country Brazil. Adjusted to other countries using price index.
Timber price, pw	Range reference country: 5–35 \$/m^3 depending on population density.
Land price, A	Range reference country: 200–2000 \$/ha depending on population density and suitability for agriculture.
Suitability for agriculture , S	Source: Ramankutty et al. (2001).
Population density, D	Source: CIESIN (2000).
Net primary productivity, NPP	Source: SAGE (2002).
Rotation interval, R	20 years in tropics, 30 years in temperate regions.
Timber/Carbon ratio	$2m^3$/tC in the tropics, $2.6m^3$/tC in temperate regions.
Planting scenario	2% of each cell is planted every year.
Carbon in long-lived products, ϕ	50%
Rate of decay long-lived products, k1	0.0347 yr^{-1}
Rate of decay short-lived products, k2	0.693 yr^{-1}
Baseline factor, b	5% for grasslands, 20% for open shrublands and savannahs.

4. Results

4.1. Cost curve for 2012 and 2020

Based on the model and data described in the previous sections, we estimated the Latin American carbon-supply for the years 2012 and 2020 considering 2000 as starting year. We consider 2012, since it is the end of the first commitment period of Kyoto and 2020 for providing insights into the post-Kyoto era. As shown in Figure 2, we find zero-cost options for carbon sequestration at the left-side of the curve (the carbon price appears to be negative), where timber benefits would provide sufficient incentive to convert non-forest land into timber production.

Small payments (0-15 \$/tC) have a small impact on carbon sequestration. But, starting from \$15/tC, the quantity of carbon sequestered increases rapidly and slows down with carbon prices over $100/tC, where most of the cells available for afforestation are already in use. The 2000-2020 curve provides 3 times more carbon sequestration than the 2000-2012 curve, illustrating that more forests have been planted and that trees have taken more time for growing.

When we look at the 2000-2012 curve and compare it with the cap of 165 MtC on sinks set under the Kyoto Protocol for the first commitment period (den Elzen and de Moor, 2002), we find out that Latin America on its own could satisfy the whole market for CDM-sinks at a price of $26/tC. This price is in the range of carbon prices estimated for the first commitment period of Kyoto (den Elzen and de Moor, 2002; Point Carbon, 2003; World Bank, 2003). As shown in Figure 1, the cap on sinks is located at the very left of the supply curve meaning that the CDM market is very small as compared to the Latin American potential. Since the curve is relatively flat around this sequestration level, much more sequestration is possible with little increases on the carbon price. Therefore, we conclude that the cap on sinks leads to efficiency losses, where sinks would have been able to provide more GHG emission reductions.

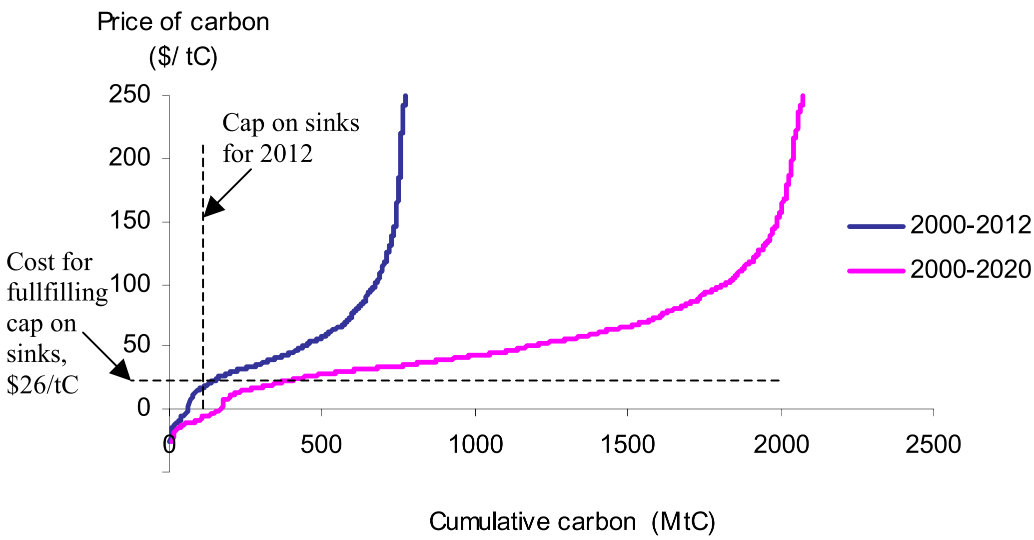

Figure 2. Supply-curve of carbon sequestration through afforestation in Latin America.

4.2. Net benefits of carbon sequestration

For the assessment of net benefits of carbon sequestration and trading we use equation (20). An important, yet not fully resolved, criterion for trading carbon offsets under the CDM is additionality (UNFCCC, 1998). An additional project is defined as a project that in the absence of carbon payments would not be implemented. If for example timber revenues provide sufficient incentive to convert non-forest land into forests, they might be excluded from the CDM because no carbon payments are needed. But, as it is discussed in Chomitz (2002), it is difficult to predict which projects will comply with the additionality criteria since it does not only depend on costs and benefits but also on perceived risks, information, legal constraints and institutional environment[13].

We evaluate net benefits for carbon sequestration for two situations: (i) an unconstrained scenario were carbon payments are possible in any case and, (ii) a constrained scenario that excludes carbon payments for situations in which timber revenues are sufficient for the conversion of non-forest areas into forests, i.e. “additionality” restrictions are taken into account. Net benefits are estimated for carbon prices of \$10, \$20 and \$30 per tC, and for the periods 2000-2012 and 2000-2020. This range of prices is consistent with estimates for the carbon price during the first commitment period of Kyoto given by den Elzen and de Moor (2002), Point Carbon (2003) and World Bank (2003). The results are shown in Table 4, indicating the area planted, the total amount of sequestered carbon and the net benefits of carbon sequestration. A carbon price of \$20/tC would allocate 8 million hectares for afforestation between 2000 and 2020, which corresponds to 3% of the suitable area for afforestation in the region. Emission trading under this price represents net benefits of 2.2 billion dollars in a 20 year period in the unconstrained scenario. But, with the additionality restrictions that exclude all zero-cost options, the planting area will be reduced by 44% and net benefits by 80%. Note that if the carbon price will be \$30/tC, the region could not sell all its emission offsets during the first commitment period since the cumulative sequestration will be above the cap on CDM sinks (165 MtC).

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[13] Yearly, about 0.5 million hectares of plantations are established in Latin America, part of them in non-forest areas (FAO, 2001). This shows the existence of non-additional projects. However, the problem of identification and verification of additionality will always remain.

Table 4. Net benefits of carbon sequestration in Latin America.

Period	Area planted in million hectares, and in (% of suitable area)			Cumulative carbon MtC			Present value net benefits, million US$		
	$10/tC	$20/tC	$30/tC	$10/tC	$20/tC	$30/tC	$10/tC	$20/tC	$30/tC
Unconstrained scenario									
2000-2012	2.5 (1%)	4.8 (2%)	9.1 (4%)	72	125	213	438	1075	2165
2000-2020	4.1 (2%)	8.0 (3%)	15.1 (6%)	192	337	574	926	2274	4576
Constrained scenario[a]									
2000-2012	0.4 (0.2%)	2.7 (1%)	7.0 (3%)	9	63	151	18	235	904
2000-2020	0.6 (0.3%)	4.5 (2%)	11.6 (5%)	25	170	406	38	497	1911

a. Excludes tree-planting in regions where afforestation is a better option than agriculture in the absence of carbon payments, so that the additionality criteria of the CDM is not necessarily met.

4.3 Long-term sequestration potential

Long-term predictions require strong assumptions on future rates of tree-growth and prices. If we assume constant prices and exclude effects affecting future net primary productivity, e.g. CO_2 fertilization and soil depletion, we get an impression of the long-term carbon sequestration for the region. Figure 3 indicates that a carbon price of $20/tC would lead to cumulative sequestration in year 2050 of some 1340 MtC and in year 2100 of some 2100 MtC (Figure 3). By comparison, carbon emissions in the energy sector for Latin America[14] amounted to about 320 MtC in 1997 (Marland and Boden, 2000), which leads to the conclusion that 100 years of carbon sequestration triggered by a carbon price of $20/tC compensate for 6.7 years of current fossil fuel emissions. A higher carbon price of $50/tC, will lead to sequestration levels that compensate 23 times the current emissions.

[14] Emissions of countries listed in Table 2.

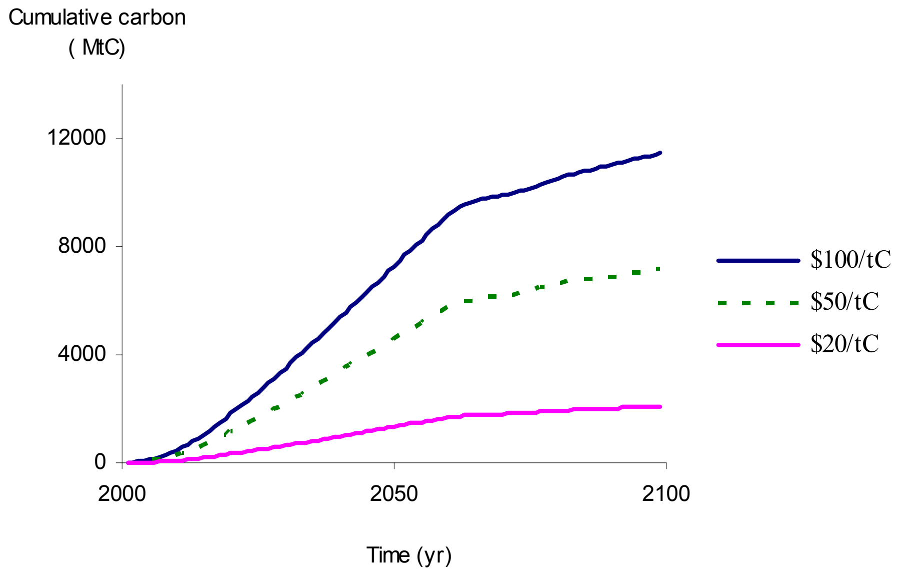


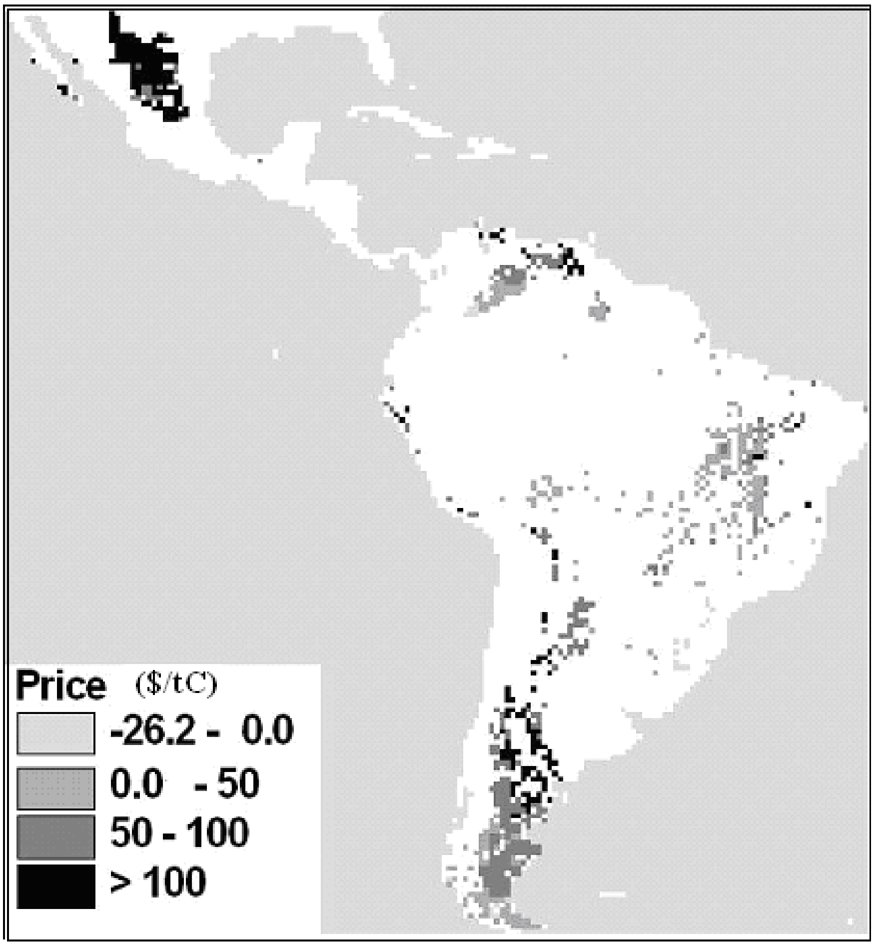
Figure 2. Time-profile of carbon sequestration through afforestation in Latin America.

In terms of policy implications, there are no doubts that Latin America could offset a substantial proportion of its emissions by tree-planting at low carbon prices[15]. Also, we show that the Latin American potential is much larger than the cap for CDM sinks under Kyoto. But, regarding global emissions in a more general context outside the Kyoto agreements, Latin American contribution through afforestation would still be limited. For example, a 100-year scenario considering a carbon price of $20/tC would only offset 20% of the global emissions of one single year (for 1997, global GHG emissions in the energy sector where 6650 MtC – Marland and Boden, 2000). Therefore, the present methodology should be applied globally, including other relevant regions for carbon sequestration such as Asia, Africa and the former Soviet Union.

[15] Whether a carbon price is low or high is debatable and depends on the policy choice for climate change mitigation. If the policy choice is to limit GHG emissions at 1990 levels, the average shadow price of carbon for a 100-year period is $312/tC (Nordhaus and Boyer, 2000). If the policy is optimal, meaning that mitigation costs equal global warming damages, the average carbon price for a 100-year period is $34/tC (Nordhaus and Boyer, 2000). Generally speaking a price of $20/tC for a 100 years scenario would be low.

4.4 Geographical distribution of carbon costs

High rates of carbon sequestration and low carbon costs are located mostly in the tropics, particularly Brazil and Colombia. Temperate regions exhibit relatively higher carbon costs due to lower rates of tree growth. Southern (temperate) Latin America (Argentina and Chile) provides economically more favorable afforestation conditions than northern (temperate) Latin America, Mexico, due to the higher NPP. On the basis of these considerations our country comparison suggests that Brazil, Colombia and Argentina are the most interesting countries for afforestation (see Map 1). Nevertheless, we should be aware that investors might account for social risks, which might put constraints on the implementation of afforestation projects. For example, investors might avoid afforestation projects in Colombia due to risks related to conflicts between government and revolutionary armed forces.



Map 1. *Geographical Distribution of Carbon Sequestration Costs in Latin America*
Note: Countries with land areas below 500000 km^2 are excluded

4.5 Sensitivity Analysis

There is a myriad of uncertainties in the assessment of carbon sequestration with respect to parameter choice and input data. We test the sensitivity for relevant factors like discount rate, land price, timber price and rate of carbon uptake. In testing the sensitivity for land-prices we evaluate our assumption for the Cobb-Douglas function for the land price by changing the relative weight of suitability for agriculture (S) and population density (D), i.e., change the relative ratios between α and γ. In addition, we evaluate transaction costs per hectare resulting from project design and implementation, land-acquisition or land-rent contracts, and carbon monitoring and verification. Experience gained from carbon sequestration projects in India and Costa Rica suggests that the yearly costs of monitoring and verification are between \$3 and \$5 per hectare (Brown et al., 2000). In Table 5, we show the summary of the sensitivity analysis with respect to these main factors, showing three selected points of the curve for every test. A more detailed sensitivity analysis for this supply-curve is described in Benítez and Obersteiner (2003).

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

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

Table 5. Sensitivity analysis of supply-curve of afforestation in Latin America.

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

5. Conclusions

This paper described a methodology for deriving supply-curves of carbon sequestration through afforestation. The method is based on determining sequestration costs for cells of a homogenous geographical grid. For each cell, spatial information obtained from GIS databases was used for estimating carbon uptake, timber production and land prices. Major advantages of the method are: (i) there is no need to entirely depend on comprehensive data that are often scarce in developing countries, instead, major parameters are estimated indirectly from more general databases and GIS datasets available worldwide. (ii) Results are obtained for each cell, so that maps with the geographical distribution of carbon costs can be elaborated. This facilitates comparison across countries and identification of least-cost regions for carbon sequestration. (iii) Supply-curves are estimated for multiple years to support decision making at different stages of the Kyoto process. (iv) Estimation of sequestration costs takes the entire life-cycle of the sequestered carbon into account, including carbon uptake during growing phase, carbon emissions during harvest, and residual carbon storage in short and long lived-products. Explicit treatment of the full life-cycle helps to avoid problems with carbon accounting which have become a major concern for CDM-sink projects (Brown et al., 2000).

The model illustration for Latin America suggests that under reasonable assumptions concerning the land and timber price and given a real interest rate of 5% and carbon prices of \$20/tC, the potential carbon sequestration by 2012 and 2020 would amount to 125 MtC and 337 MtC, respectively. This would imply an afforestation of 8 million hectares of land by 2020, representing 3% of the suitable area for plantations of the region. Given this price scenario and under the assumption that all projects are compliant with additionality criteria, total net benefits of carbon sequestration for the period 2000-2020 would be approximately US\$ 2.3 billion. If additionality rules for CDM-sinks are strict and binding in the sense that projects profitable in the absence of carbon payments are rejected, net benefits would be reduced by 80%. From this we can conclude that main limitations for implementing CDM-sink projects could turn out to be additionality constrains in combination with low carbon prices. Afforestation might play a more important role in the future, if carbon prices rise and provisions for CDM become more flexible, e.g. elimination of the cap on CDM sinks.

Long-term estimates of the cumulative sequestration potential for 100 years suggest that afforestation could compensate between 7 and 23 years of current CO_2 emissions of the region's energy sector at costs between \$20/tC and 50/tC. Therefore, there are no doubts that Latin America could offset a substantial proportion of its emissions by tree-planting at low carbon prices. But, regarding global emissions abatement in a more general context outside the Kyoto agreements, the Latin American contribution through afforestation would still be limited, so there is need to extend our analysis towards a global scale.

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

The demonstrated applicability of the method for Latin American conditions, suggests that the model approach can be expanded to global scales. However, there is still a need to improve data quality to reduce uncertainty. In addition, further work should consider risk more explicitly, which in case of forestry is a major determinant for decision making due to the long-term nature of these investments.

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Appendix

We need to solve,

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

We know that,

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

Replacing W'(t) in P,

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

which equals,

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

We proceed to solve the following integral,

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

Replacing in P leads to

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

and finally,

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

This is approximately equal to

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

Chapter 4

Global Supply for Carbon Sequestration: Geographical Distribution, Country Risk and Policy Implications

This chapter is based on:

Benítez P.C., I. McCallum, M. Obersteiner and Y. Yamagata. Global Potential for Carbon Sequestration: Geographical Distribution, Country Risk and Policy Implications. Submitted for publication in *Ecological Economics*.

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Abstract

We have provided a framework for identifying least-cost sites for carbon sequestration and deriving carbon sequestration cost curves at a global level in a scenario of limited information. Special attention is given to country risk considerations and the sensitivity to spatial datasets. Our model results suggest that within 20 years and considering a carbon price of $50/tC, afforestation could offset one year of global carbon emissions in the energy sector. However, if we account for country risk considerations — associated with political, economic and financial risks — carbon sequestration is reduced by approximately 60%. With respect to the geography of supply, illustrated by grid-scale maps, we find that most least-cost projects are located in Africa, South America and Asia. Once risk is factored into the equation, these countries become more expensive to operate in. By comparing emissions reductions through afforestation with the emission abatement scenarios of integrated assessment models (RICE-99) for a 100-yr time span, we find that, (1) Afforestation is relevant in a global context where its potential carbon sequestration ranges from 5% to 25% of the emissions reduction targets of policy scenarios and, (2) Policy scenarios requiring larger emission abatement would need a larger share of emission reductions through afforestation than those with smaller abatements.

Keywords: climate change, carbon costs, country risk, afforestation, carbon sequestration, integrated assessment models

1 Introduction

Global warming as a consequence of human-induced emissions of greenhouse gases (GHG) is a growing concern. Latest predictions of the International Panel of Climate Change (IPCC) suggest that by 2100 the globally averaged surface air temperature will increase by 1.4–5.8°C and the average sea level will rise to between 8 and 88 cm, leading to major disturbances for human settlements and natural ecosystems (IPCC, 2001).

Global warming would vary between regions causing diverse impacts on agriculture, forestry, human health and biodiversity. For example, tropical regions would be more affected by a decrease in agricultural production, while temperate regions would face the expansion of vector-born diseases like malaria and dengue fever, and would confront higher temperatures and more frequent heat waves during summer (IPCC, 2001). Globally, increases in the occurrence of extreme weather events will lead to higher insurance premiums and might result in certain risks being reclassified as uninsurable. Natural systems such as coral reefs, mangroves, tropical forests, polar and alpine ecosystems, and prairie wetlands are at the risk of irreversible damages and the loss of vulnerable species.

Facing these threats and the costs of adaptation to be borne by future generations, mitigation measures have been proposed within international agreements like the Kyoto Protocol (UNFCCC, 1998). As a general classification, mitigation is divided into two groups: (1) the reduction of GHG emissions in the energy sector and industrial process, and (2) the enhancement of carbon sinks.

Integrated assessments in the energy sector have estimated carbon mitigation cost curves (Gritsevskyi and Schrattenholzer, 2003; Sijm et al., 2000). To a lesser extent, these have been done in the sink sector. As an imperative need for finding least-cost mitigation alternatives, we aim to estimate carbon sequestration cost curves at a global level and determine sites where these costs are at a minimum.

Global assessments of the potential of sinks for carbon mitigation started in the 1990s. Trexler and Haugen (1995) have estimated the potential for carbon sequestration in the tropics and Nilsson and Schopfhauser (1995) estimated the global afforestation potential. These early studies determined how much carbon could be sequestered in forests, but omitted cost estimations of such activities. Economic studies providing sequestration costs exist from case studies of particular countries incluiding the US (Stavins, 1999), China (Xu, 1995), Brazil (Fearnside, 1995), India (Ravindranath and Somashekhar, 1995), Mexico (de Jong et al., 2000) and Argentina (Sedjo, 1999). However, economic studies providing carbon supply curves at a global level are limited, where the research of Sohngen et al. (1999), and Sohngen and Mendelsohn (2003) seem to be pioneers. By using optimal control and timber supply models, they evaluated the interaction of timber markets and carbon fluxes. Given the complexity of the analysis, they used high aggregation levels for representing relevant world regions.

Contrasting to these studies and as a new research contribution, we estimate global supply curves by using information at a disaggregated level, and scrutinizing the potential afforestation area so that sequestration costs are estimated at geographically explicit cells of approximately 50 × 50 km. We select applicable land classes, and exclude highly productive land, areas of high population density, areas of high elevation and areas where there is no net carbon uptake (desserts, forests). By doing so, we evaluate how the heterogeneity in land attributes (e.g., net primary productivity and suitability for agriculture) and the heterogeneity of prices (e.g., land and timber prices), influence sequestration costs and determine carbon-supply patterns; and identify least-cost locations for carbon sequestration. Being aware of the effect of country considerations associated to political, financial and economic risks, we evaluate its influence on the global supply of carbon. In addition, we perform a sensitivity analysis of the land cover classes by utilizing multiple datasets for comparison.

This article is structured as follows. We first describe the model in section 2. In section 3 we discuss how country-risk considerations are taken into account. Global datasets and parameters used for our analysis are provided in section 4. Results are shown and discussed in section 5. The article ends with concluding paragraphs in section 6.

2 The Model

The analysis starts by selecting grid-cells (areas with known geographical coordinates) that are suitable for afforestation, i.e., non-forest areas where tree-planting is viable and will not compromise food security. We then estimate sequestration costs for each grid-cell[1] based on estimates for *inter alia* biological growth, plantation costs, expected timber and land prices, and carbon storage in products. Finally, we obtain the cumulative sequestration cost-curve by aggregating grid-level results, taking into account that afforestation activities occur only in cells where the carbon price exceeds sequestration costs. Besides obtaining the cost-curve, the method allows identifying the geographic distribution of carbon costs and growth potentials throughout a region. The methodology is fully described in Chapter 3 of this thesis with a short summary of major model equations provided here.

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

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

Net present value of forestry (f) in cell "i" during one rotation interval is,

$$f_i = -cp_i + pw_i \cdot V_i \cdot (1+r)^{-R_i} + B_i \tag{2}$$

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

We consider carbon uptake as a positive externality and its benefits are a function of the rate of change of biomass or timber volume over time (van Kooten et al., 1995; Creedy and Wurzbacher, 2001). In a similar fashion, carbon release during harvest is a negative externality and its costs are a function of the amount of biomass

[1] For ease on the reading we call "grid-cells" simply as "cells".

or timber volume removed from the forest. In practice, not all the carbon removed from the forest after harvest is immediately released to the atmosphere, however a fraction, θ, is stored for longer time periods in the atmosphere (van Kooten et al., 1995). Storage after harvest could take place in a wide range of products including long-lived products like furniture, structures, construction materials and thick branches and; short-lived products like paper, leaves and thin branches. This broad definition for "forest products" is used throughout this study.

Including forest biomass and products, the equation for the present value of carbon benefits is (see Chapter 3),

$$B_i = pc\sum_{t=1}^{R_i}\omega_i\left(1+r\right)^{-t} \;-\; pc\cdot\omega_i\cdot R_i(1+r)^{-R_i} + pc\cdot\theta\cdot\omega_i\cdot R_i(1+r)^{-R_i} \tag{3}$$

The term θ depends on the fraction of the forest biomass stored in long-lived products, ϕ , and the decay rates of short-lived products (k1) and long lived products (k2).[2]

The net 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). In our analysis, we consider that the carbon stored in the baseline represents a fraction b_i of the carbon stored in the forest. We call b_i, the baseline factor. By summing up carbon benefits in biomass and products and subtracting the carbon in the baseline, we get the final expression for total carbon benefits,

$$B_i = pc_i\cdot\omega_i(1-b_i)\left\{r^{-1}\left[1-(1+r)^{-R_i}\right]-R_i(1-\theta_i)(1+r)^{-R_i}\right\} \tag{4}$$

By means of equations (2) and (4) we estimate net present value of forestry for one rotation interval (f_i); and from this, we obtain net present value for an infinite number of rotations (F_i). Given constant prices and fixed rotation intervals we have,

$$F_i = f_i\left[1-(1+r)^{-R_i}\right]^{-1} \tag{5}$$

[2] In Chapter 3 we proved that $\theta = 1-\frac{k1\ \phi}{k1+r}-\frac{k2\ (1-\phi)}{k2\ +r}$

The land price function is estimated by assuming a two-factor Cobb-Douglas production function. The first factor is suitability for agriculture, S_i, and indicates the aptness of the land for agricultural production given its endowments of soil and ecosystem properties. The second is population density, D_i, and is a proxy for labor intensity and infrastructure. When output follows a Cobb-Douglas function, net present value of agriculture has the following functional form,

$$A_i = \upsilon_i \cdot S_i^{\alpha_i} \cdot D_i^{\gamma_i} \tag{6}$$

Where υ_i α_i and γ_i are the parameters for the production function.

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

$$pc_i = \frac{A_i\left[1-(1+r)^{-R_i}\right] + cp_i - pw_i \cdot V_i(1+r)^{-R_i}}{\omega_i(1-b_i)\left\{r^{-1}\left[1-(1+r)^{-R_i}\right]-R_i(1-\theta_i)(1+r)^{-R_i}\right\}} \tag{7}$$

By means of equation (7) the minimum carbon price that is required for switching from non-forest land to forestry is estimated for each cell.

Carbon supply curves represent the relationship between the carbon price and the amount of carbon sequestered. Equation (7) leads to cost estimation, but we also need to predict quantities, which need to be specified for a give time period, T. If there exist a market price of carbon, pc*, the cumulative carbon sequestration that occurs from time zero to time T is,

$$C_T = \sum_{i=1}^{I}\sum_{k=1}^{K} A_{i,k}\left(1-b_i\right)\left(C_{i,k,T}^{b} + C_{i,k,T}^{p}\right) \tag{8}$$

$$\forall i \,\middle|\, pc_i < pc^*$$

The index k denotes stands within a cell that have different ages. $C_{i,k,T}^{b}$ measures the cumulative carbon sequestration per hectare in the biomass of stand k of cell i at time T, and $C_{i,k,T}^{p}$ measures the cumulative carbon sequestration in forest products. The detailed equations for such estimation are described in Chapter 3 of this thesis.

3 Considering Country Risk

In the preceding section we assumed that investors do not care about country risk, meaning that they would be indifferent about planting trees in Canada or Sierra Leone under equal sequestration costs. However, for implementing afforestation projects for timber production and carbon sequestration purposes, it is clear that every investor will take into consideration country particularities like institutions, government credibility, corruption, economic stability, inflation, wars and terrorism. By a simple screening of some of these aspects, investors would prefer (by far) to allocate funds for plantation projects in Canada rather than Sierra Leone. In this study, we attempt to account how country considerations associated to political, financial and economic risks influence the global cost of sequestration.

There are ways for accounting risk in investment projects. A commonly applied method is the use of risk-adjusted discount rates or required returns. For employing this technique in our study, the discount rate used for estimating carbon costs (equation 7) needs to be adjusted to risk. Generally, the Capital Asset Pricing Model (CAPM) serves for estimating risk-adjusted discount rates. The CAPM considers market efficiency where the differences between the market return and the risk-free rate are a measure of the price paid for market risk. The fundamental equation of the CAPM is:

$$r = r_f + \beta\left(r_m - r_f\right) \tag{9}$$

Where r is the required return for an asset, r_f is the risk-free rate of return, r_m is the market rate of return and β (beta) measures the contribution to risk of the investment relative to the market. Extensions of the CAPM have been applied globally (see Bekaert and Harvey, 1995) where expected returns are influenced by both world and country factors. While these CAPM extensions lead the estimation of required returns for different countries, it has limited applicability for worldwide analyses given the absence of equity markets in most developing countries. Considering this factor, Erb et al. (1996a) used an alternative formulation for estimating expected returns in a large number of developing countries, under the assumption that expected returns are a function of risk ratings:

$$r_i = \gamma_0 + \gamma_1 \ln(RR_i) + \varepsilon_i \tag{10}$$

Where r_i is the expected return in country i, RR_i is the risk rating of country *i*, γ_0, γ_1 are parameters of the return function, and ε_i is the error term. The log-linear model has been proposed in order to capture potential non-linearities when country risk is high. Since risk rating agencies provide data for more than 70% of the world's countries, this method is applicable worldwide. In practice, the estimation of expected returns is done as follows, (1) select a country risk index that reflects major risk concerns, e.g. ICRG, CCR, Moody´s, S&P; (2) find a list of countries where expected returns of the investment in question are available; (3) by means of regression analysis, estimate the parameters γ_0, γ_1 with the available expected returns and the corresponding risk indexes; and (4) use equation -10- for predicting expected returns for other countries.

4 Data

4.1 Global datasets

For estimating how much area could be used for tree-planting, we rely on global land cover datasets. We choose four of the most relevant datasets for our comparison, namely, (1) International Geosphere Biosphere Project, IGBP (USGS, 2003); (2) University of Maryland, UMD (Hansen et al., 2000); (3) Global Land Cover 2000, GLC2000 (JRC, 2003); and (4) MODerate resolution Imaging Spectroradiometer, MODIS (MODIS, 2002). Table 1 provides a summary of the main characteristics of these datasets. Obvious and sometimes major differences exist between the datasets including sensor-type, temporal scales and classification methods etc. In order to allow for comparison, all datasets were converted to the IGBP land cover classification.

Table 1. Main characteristics of land cover datasets compared in this study.

Characteristics	IGBP	UMD	GLC2000	MODIS
Sensor[a]	AVHRR	AVHRR	SPOT4 Veg	MODIS
Time of Data Collection	April 92–March 93	April 92–March 93	1 Nov. 1999–31 Dec. 2000	10/15/00–10/15/01
Input Data	12 Monthly NDVI[b] composites	41 Metrics derived from NDVI and bands 1–5	Daily mosaics of 4 spectral channels and NDVI	12, 32-day composites of 8 input parameters
Classification Technique	Unsupervised clustering	Supervised classification tree	Generally unsupervised classification	Supervised decision-tree classifier, neural networks
Classification Scheme	IGBP (17 classes)	Simplified IGBP (14 classes)	FAO LCCS[c] (IGBP correspondence)	IGBP
Validation	High resolution satellite images	Used other digital datasets	Statistical Sampling (in progress)	Confusion matrices, confidence values

a. Details for sensors. AVHRR: Advanced Very High Resolution Radiometer from NOAA satellites. SPOT4 Veg: Vegetation monitor from SPOT4 satellite. MODIS: Moderate Resolution Imaging Spectroradiometer from the Terra and Aqua satellites (also called Earth Observation System AM/PM satellites).
b. NDVI: Normalized Difference Vegetation Index.
c. FAO LCCS: Land Cover Classification System of the FAO.
Source: USGS (2003)

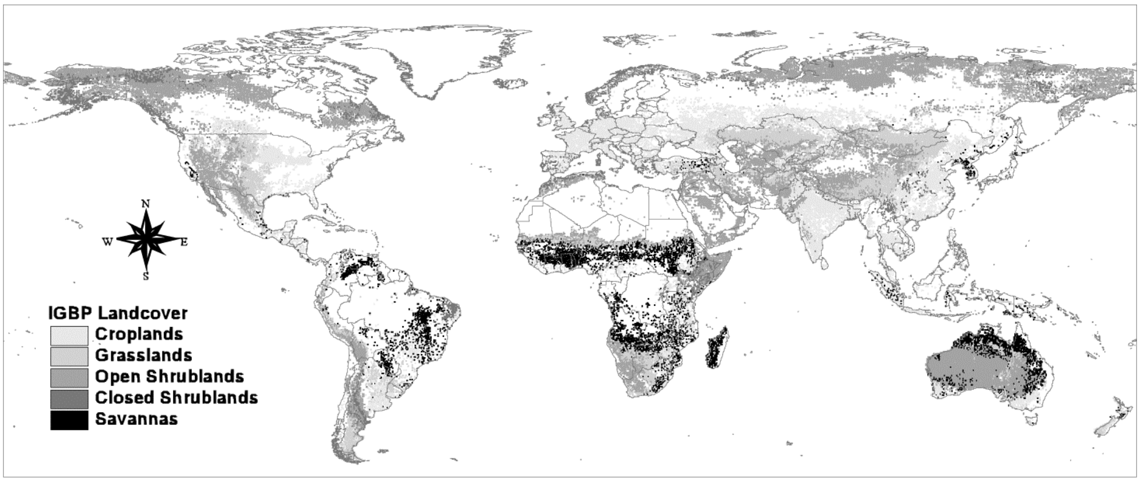
In addition to land cover datasets, we use spatial information to identify world countries, agricultural suitability, population density, elevation, net primary productivity (NPP) and carbon stock. Table 2 provides major details of these datasets. For reasons of uniformity in the analysis, all datasets were converted to a resolution of 0.5 degree.

Table 2. Spatial datasets used for our analysis.

Dataset	Original Resolution	Units	Source
World Countries	0.5 degree	Countries/Continents	ESRI (1998)
Population 1995	2.5 minutes	Persons/km^2	CIESIN (2000)
Agricultural Suitability	0.5 degree	(%)	Ramankutty et al. (2001)
Elevation	30ArcSeconds	Meters	GTOPO30 (1996)
IGBP Land Cover	30ArcSeconds	(17) IGBP classes	USGS (2003)
UMD Land Cover	30ArcSeconds	IGBP classes	Hansen et al. (2000)
GLC2000 Land Cover	30ArcSeconds	IGBP classes	JRC (2003)
MODIS Land Cover	30ArcSeconds	IGBP classes	MODIS (2002)
NPP	0.5 degree	gC/m^2/year	Alexandrov et al. (1999); Alexandrov et al. (2002)
Carbon Stock (non-forest)	0.5 degree	tC/ha	Alexandrov et al. (1999); Alexandrov et al. (2002)
Carbon Stock (30 year old)	0.5 degree	tC/ha	Alexandrov et al. (1999); Alexandrov et al. (2002)

4.2 Land Available for Afforestation

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. Given these prescriptions, we selected the following five land cover classes: *grasslands, open shrublands, closed shrublands, savannas* and *croplands* (see Map 1). These land cover classes are defined as follows (Hansen et al., 2000): *Grasslands* are lands with a herbaceous type of cover with tree and shrub cover between 0 and 10%. *Open Shrublands* are lands with woody vegetation less than two meters tall and shrub cover from 10 to 60%. *Savannas* are lands with herbaceous and other understory systems, with forest cover between 10 and 30%. *Closed Shrublands*: are lands with woody vegetation less than two meters tall and shrub cover greater than 60%. *Croplands*: are lands covered with temporary crops.



Map 1: IGBP land cover dataset showing the five classes used in this study

For estimating the area available for plantations, we exclude the following cells from the selected land classes, (1) highly productive land where the indicator of suitability for agriculture is above 50% (this indicator ranges from 0 to 100%); (2) cells where the population density is over 200 hab/km^2; (3) cells with elevation more than 3500 m; and (4) cells where there is no net carbon uptake, i.e. the difference between carbon stocks in forest and non-forest is zero. The estimated area available for plantations for the four land cover datasets is shown in Table 3. Note that the differences among datasets could be as much as 35%, when compared using the IGBP classification.

Table 3. Land available for plantations.

Land-cover dataset	Area available for plantations (million km^2)
IGBP	26
GLC	28
MODIS	30
UMD	35

4.3 Tree Growth Parameters

Grid data on carbon uptake is obtained directly from the spatial databases of Alexandrov et al. (1999, 2002). In order to estimate net carbon uptake, we subtract the carbon in the non-forest scenario (baseline) by considering two components: (1) a site-specific baseline corresponding to the non-forest carbon stock (Alexandrov et al., 1999; Alexandrov et al., 2002); and (2) a regional baseline which subtracts possible afforestation and revegetation trends in a business-as-usual scenario. For this we deduct 10% of the carbon sequestration for each cell[3]. Timber volume is proportional to forest biomass. We use a timber/carbon ratio of 2 m^3/tC (refer to Chapter 3 for explanation). Rotation intervals – the time between planting and harvesting one stand – are considered uniform worldwide. We use an average value of 30 years corresponding to temperate regions (Nilsson and Schopfhauser, 1995). Note that in the tropics rotations could be shorter and in boreal regions larger.

Estimating carbon sequestration in products requires knowledge of rates of decay or half-life times.[4] We consider that 50% of the forest biomass is stored in long-lived products with a half-life time of 20 years and the remaining biomass consisting of short-lived products has a half-life time of one year. Finally, we assume that tree-planting in each cell requires 50 years for completion and that planting occurs at a constant rate as in Trexler and Haugen (1995).Considering a 50-yr period for completing planting in each cell, reflects the enormous efforts that are required to start large-scale afforestation projects in areas where trees have never existed before.

4.4 Prices

Regarding prices, we take Brazil as a reference, which is the country with one of the largest potentials for forestry and carbon sequestration. We use $800/ha for plantation costs in Brazil, which is within the range provided by Ecosecurities (2002) and Fearnside (1995). For other countries, we correct prices using the price index which is the ratio between the purchasing power parity (PPP) conversion factor and the official exchange rate in 2001 (World Bank, 2003). These price indexes are relative to the US. For countries not appearing in the reference we assigned the following indexes: low

[3] Afforestation and reforestation worldwide accounts 4.5 million hectares each year in the absence of carbon payments - baseline scenario (FAO, 2001). If such rate would continue for a 50-year period, it would represent about 10% of the area suitable for plantations worldwide.
[4] The rate of decay (k) is related to the half life time ($t_{1/2}$) by the following: $k = \ln(2)/ t_{1/2}$.

income countries, 0.2; lower-middle income countries, 0.5; and upper-middle income countries, 0.7.

Land prices depend on suitability of agriculture and population density following a Cobb-Douglas relationship. For fitting the parameters of the land price function (A_i), we set minimum and maximum bounds, so that the upper bound corresponds to cells where suitability for agriculture and population density are the highest, and the lower bound corresponds to cells where these indicators are the lowest. We assign equal weights for both indicators, so that $\alpha_i = \gamma_i$ in equation (6). For Brazil, the higher bound for land prices is set at \$2000/ha which resembles sites of good quality in Latin America (de Jong et al., 2000; Benítez et al., 2001). The lower bound is set to \$200/ha. Timber stumpage prices across cells are estimated with a similar procedure as the land price. In the absence of a detailed infrastructure map that allows a precise estimation of transportation costs, we consider that timber stumpage prices are dependent on population density. Taking into account that transportation costs are major determinants of timber stumpage prices, we expect that in areas of high population density, transportation costs will be low since distances to markets are small and infrastructure availability is high. The higher bound for timber price in Brazil is \$35/m^3, based on an export price of \$50/m^3 (FAO, 2002) and harvesting and transportation costs of \$15/m^3. The lower bound for timber price is \$5/m^3 and the values in-between are adjusted linearly with population density. Timber and land prices for countries other than Brazil are estimated using the same price index that was used for plantation costs. Given the rough approximation for land and timber prices, we conducted an in-depth sensitivity analysis.

4.5 Country Risk Data

In order to estimate expected returns for each of the countries included in the analysis, we follow the procedure indicated in section 3. First, we select the country risk index; then, we find the necessary data on expected returns for fitting the parameters of equation (10), and finally; we forecast the required returns for all countries included in the analysis.

Selection of country risk index

A number of risk indicators have emerged, which are available for a large number of countries including (Erb et al., 1996b), (1) Institutional Investors: provides country credit ratings (CCR) based on surveys from bankers located worldwide; (2) Moody's: provides ratings describing the creditworthiness of corporate bonds; (3) Standard and Poor's (S&P): use a similar rating system as Moody's, but creates a finer rating; and (4) International Country Risk Guide (ICRG): provides ratings for political, financial and economic risk factors and also calculates a composite index. Some of the factors included in the political risk rating of ICRG are political leadership, economic planning failures, external conflict, corruption, military and religion in politics, civil war, terrorism and quality of the bureaucracy. Financial risk includes loan default, repudiation of contracts by government, losses from exchange controls and expropriation of private investments. Finally, some of the economic risk factors are inflation, debt service and international liquidity. ICRG uses a scale from 0 (worse) to 100 (best).

Given the available risk rating systems, we used the ICRG as it is not limited only to credit risk but compiles political, economic and financial aspects that determine the overall concern for investing in a specific country. We used the ICRG 5-year composite index forecast for our analysis[5].

Return and Risk

The parameters of the return function (equation 10) are estimated using Ordinary Least Squares regression with the following model,

$$r_i = \gamma_0 + \gamma_1 \ln(ICRG_i) + \varepsilon_i \tag{11}$$

where, r_i is the risk-adjusted discount rate for carbon sequestration projects in country i, ICRG is the country risk index according to the international country risk guide, and γ_0, γ_1 are the regression coeficients. For the regression we use available data on discount rates that have been used for these types of projects in 8 different countries.

[5] The forecast includes a worst and best risk forecast. We use the average.

Table 4 summarizes the data and regression results. In the upper section of the table, we show the country, the dependent variable (r_i), the regressor, and the data source for r_i. In the lower section of the table, we show the regression output.

Table 4. Regression analysis for forestry expected returns.

A. Data:

Country	*Expected return, r_i*	*ICRG[a]*	*Reference for expected return*
US	5%	78.5	Stavins (1999)
Canada	4%	79.8	van Kooten et al. (2002)
Argentina	10%	66.3	Sedjo (1999)
Brazil	12%	67.8	Fearnside (1995)
Costa Rica	7%	74.5	Nieuwenhuyse et al. (2000)
India	17%	65.3	Ravindranath and Somashekhar (1995)
Indonesia	20%	57.5	Cacho et al. (2002)
Mexico	10%	66.8	Masera et al. (1995)

B. Regression output:

	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept, γ_0	2.15584	0.3069	7.0230	0.000416
ICRG Variable, γ_1	-0.4837	0.0724	-6.678	0.000546
Adjusted R Squared:	0.862			

a. 5-year forecast, average between worse and best forecast (PRS, 2004).

Forecast for expected returns

By means of equation (11) and using the fitted regression parameters, we predict the required return for world countries as a function of the ICRG index for each country (refer to Appendix for data and results). When the forecasted return for the less risky countries is below 3%, we assign a value of 3% in order to avoid having a rate below a risk-free rate[6]. Although the primal data for the regression used a sample of only eight countries (Table 4), the estimated returns for the others seems reasonable. For example, for the stable economy of Australia we estimated a rate of 3.6%. For China, we have a moderate rate of 7.5%. Chile, as a newly industrialized country, has a rate of 7.4%. Countries under conflict, like Somalia and Liberia, have rates of 33%, reflecting their unattractiveness for private investment.

6 US treasury bills are often used as a reference for risk-free rates. For early 2004, 3-month treasury bills yield about 1%. The average for the last five years is 3.6% (FFC, 2004).

4.6 Data summary

In Table 5, we summarize model parameters used for estimating the global supply for carbon sequestration.

Table 5. Summary of model parameters.

Parameter	Value / Source
Discount rate, r	a) Benchmark scenario: 5% b) Risk-adjusted scenario: expected returns shown in Appendix
Plantation Costs, cp	\$800/ha for reference country, Brazil. Adjusted to other countries using 2001 price index.
Timber price, pw	Range reference country: US\$5–35/m^3 depending on population density.
Land price, A	Range reference country: US\$200–2000/ha depending on population density and suitability for agriculture.
Suitability for agriculture , S	Source: Ramankutty et al. (2001)
Population density, D	Source: CIESIN (2000)
Carbon uptake, ω	Alexandrov et al. (1999); Alexandrov et al. (2002)
Rotation interval, R	30 years
Timber/Carbon ratio	$2m^3$/tC
Planting scenario	50 years required for planting 80% of a cell. Rest of the cell is kept in its original land use.
Carbon in long-lived products, ϕ	50%
Rate of decay long-lived products, k1	0.0347
Rate of decay short-lived products, k2	0.693
Baseline factor, b	Baseline has two components. (a) Site specific, Alexandrov et al. (1999); Alexandrov et al. (2002). (b) Regional : 10%.

5. Results

5.1 Carbon supply: the benchmark case

Our benchmark case excludes country risk considerations and uses a uniform discount rate of 5% as in Gritsevskyi and Schrattenholzer (2003). We derive global carbon-supply curves for the four different land cover datasets described in Table 1. In our first scenario analysis, we consider a sequestration interval of 20 years. This interval is chosen in order to provide information relevant for the post-Kyoto era, i.e. after

2012.[7] Later we estimate supply curves for a 100-year period in order to compare our results with those of integrated assessment models focusing on 100-year scenarios.

From Figure 1, we find zero-cost options for carbon sequestration at the left-side of the curve (the carbon price appears to be negative), where timber benefits would provide sufficient incentive to convert non-forest use of land into plantations for timber production. For comparison between databases, we take a referential price of \$50/tC.[8] As shown in Figure 1, IGBP provides the most conservative estimate of the supply-curve, while UMD gives a much higher estimation. GLC and MODIS provide similar estimates. Differences resulting from database selection could be up to 45% for the cumulative sequestration. This difference is caused by differences in main characteristics of the datasets such as classification techniques, input data, sensor and time of data collection (see Table 2) which result in different estimates of the land suitable for afforestation, e.g. the area classified according to UMD is 35% larger than that for IGBP[9].

For the remaining part of this analysis, we use the IGBP dataset that provides the lower bound of carbon sequestration estimates.

[7] For the first commitment period of Kyoto, there is a cap of 165 MtC for CDM sinks. As shown in Chapter 3, only one word region, Latin America, could fulfil this cap at a low price. Thus, further information for this period is not strictly necessary. Here we focus on the post-Kyoto era, where policy developments are still in a very early process.

[8] This is just a tentative price for illustrating our results. The carbon price for a 20-year time period depends on the climate policy option which stil needs to be set. If the policy choice is to limit GHG emissions at 1990 levels, the average shadow price of carbon for the next 20 years would be about \$90/tC (Nordhaus and Boyer, 2001). If the policy is optimal, meaning that mitigation costs equal global warming damages, the average carbon price for the next 20 years would be just \$13/tC.

[9] This finding emphasizes the need to utilize multiple datasets in this work in an attempt to show the upper and lower bounds of carbon sequestration estimates.

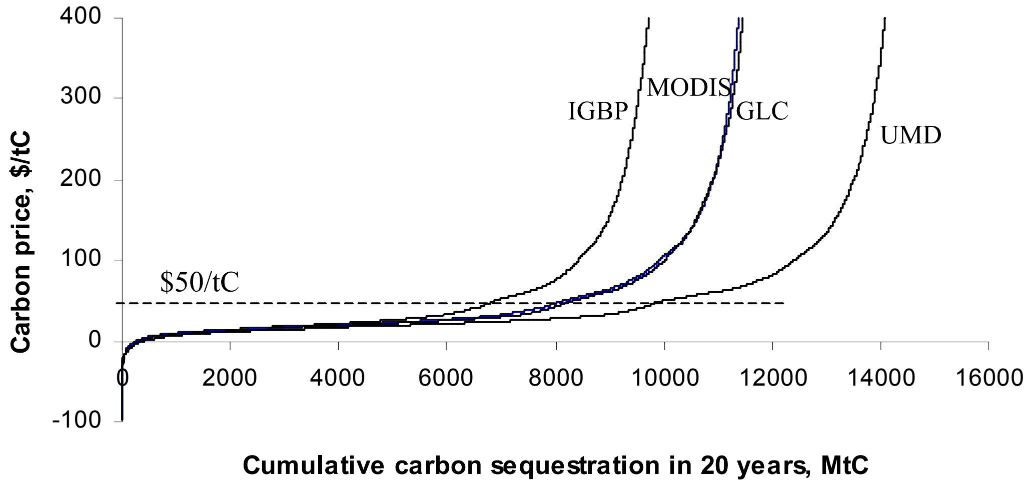


Figure 1. Carbon supply for different global land cover datasets (benchmark scenario).

5.2 Carbon supply under country risk

Having evaluated the impact of database selection, we now test how the carbon supply is influenced by taking into consideration country risk. Figure 2 shows the difference between the benchmark and non risk-adjusted scenarios, and shows significant differences, particularly at low carbon prices. For example, with a price of $50/tC the cumulative sequestration level is 59% less when country risk is considered. These results stress the importance of including country risk in global assessments in order to prevent an over-estimation of the carbon mitigation potential.

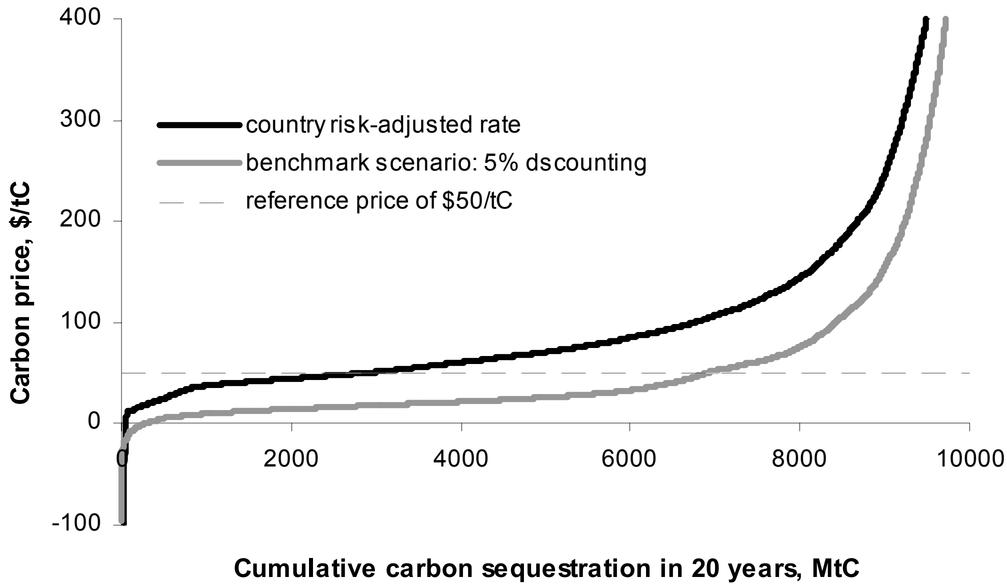


Figure 2. Effect of country-risk considerations on carbon-supply (IGBP dataset).

Furthermore, owing to the use of disaggregated datasets in this analysis, we are able to analyze the results from a spatial viewpoint. Figure 3 represents the cumulative carbon sequestration in 20 years under a carbon price of $50/tC. Based on this graph, Africa provides the higher potential for carbon sequestration, followed by Asia and South America. This is also visible in the maps provided in Appendix 2. When we include risk into the analysis, the relationships are maintained but the cumulative sequestration of most regions is diminished significantly. However, we should be aware that these results need to be taken with caution, since the supply-curve seems to be highly sensitive to risk.

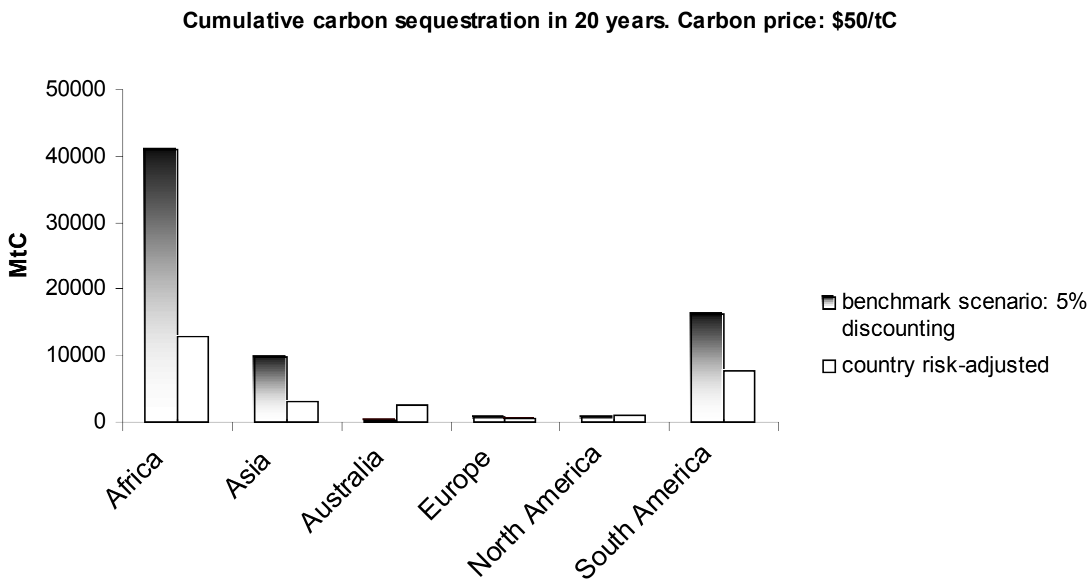


Figure 3. Comparison of carbon supply per continent for a 20-year period and a carbon price of $50/tC.

5.3 Long-term carbon supply and policy implications

In order to find the (long-term) policy implications of afforestation and its role in global warming mitigation, we compare our results with the costs of carbon mitigation resulting from Integrated Assessment Models (IAM) of climate change[10]. IAM predict the amount of emission reductions that are needed for reaching a policy target and the costs per ton of carbon (shadow price of carbon, carbon tax) associated with such emissions reductions. The emission abatement costs curves included in IAM usually concern the energy sector, where afforestation is not considered. Therefore, our interest is to estimate how much carbon could be sequestered through afforestation given carbon prices obtained from IAM. These models usually deal with time periods of about a century, so we estimate the carbon supply for a 100-year period based on the scenario of risk-adjusted discount rates (Figure 4). Note that this supply-curve has a similar shape as the 20-year curve (Figure 3), but the cumulative sequestration is about 7 times larger.

[10] Chapter 2 of this thesis provides further details on these models.

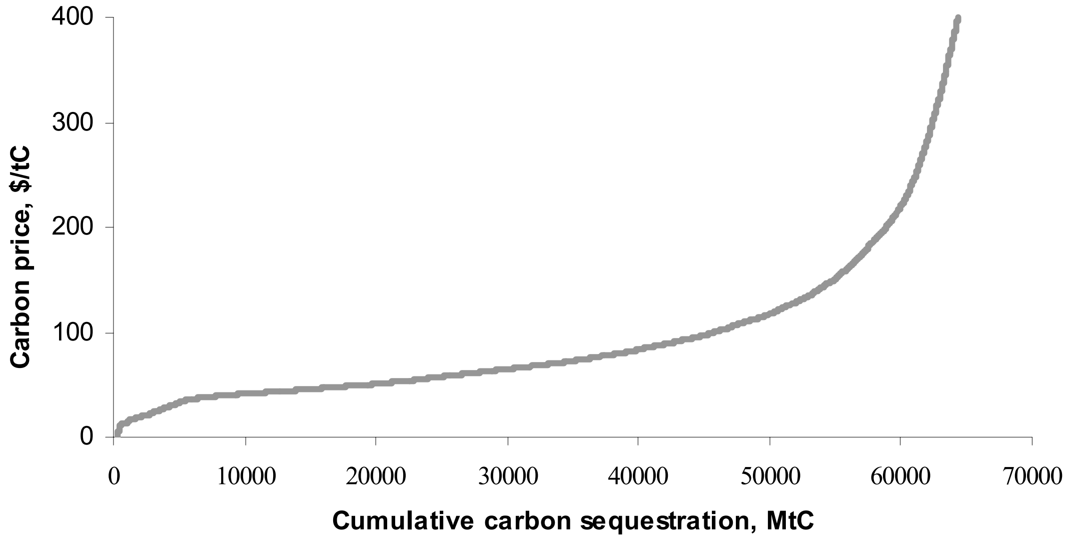


Figure 4. 100-year estimate of the carbon supply. Risk-adjusted scenario, IGBP dataset.

In this research, we use the RICE-99 model (Nordhaus and Boyer, 2000). The results of our analysis are summarized in Table 6 where we show the policy target (first column), the required emission reductions (second column) and the associated average carbon price[11] (third column) according to the different policy alternatives dealt within the RICE-99 model. Then, based on this carbon price, we estimate how much carbon could be sequestered, on average, for a 100-year period (fourth column). The last column shows the relative importance of emissions reduction through afforestation.

[11] We provide average carbon prices in order to be compatible with our model.

Table 6. Comparison of carbon sequestration through afforestation with emission reductions of RICE-99.

Climate Policy Scenario	Average emission reductions of policy scenario (GtC/yr)	Average carbon price associated to policy scenario ($/tC)	Average carbon sequestration corresponding to carbon price of the policy scenario (GtC/yr)	Carbon sequestration as a fraction of emission reductions in policy scenario (%)
Optimal	0.8	34	0.051	6%
Limit to 1990 emissions	4.4	312	0.627	14%
Limit to 2 time CO_2 Concentrations	1.4	73	0.349	25%
Limit temperature rise to 2.5 degrees	3.1	207	0.593	19%

Note: The analysis holds for a 100-year period

Based on the results shown in Table 6, we can draw two important conclusions: (1) afforestation is an important option for global warming mitigation, where its potential carbon sequestration ranges from 6% to 25% of the emissions reduction targets of different policy scenarios and therefore, it needs to be included as a policy option; and (2) the relevance of afforestation strategies increases with increasingly strict policy alternatives. Policy scenarios requiring larger emission abatements would need a larger share of emission reductions through afforestation than those with smaller abatements.

5.3 Sensitivity Analysis

There are innumerable uncertainties in the assessment of carbon sequestration with respect to parameter choice and input data. We test the sensitivity for three relevant factors: land price, timber price and the rate of carbon uptake. In Table 7, we provide a summary of the sensitivity analysis with respect to these factors where we tested the impact of 50% changes in land and timber prices and 25% changes in carbon uptake. The sensitivity analysis used the 20-year cost curve, the IGBP dataset and the benchmark scenario of 5% discounting. For ease of reading we show results of the sensitivity analysis for only 3 points on the carbon supply curve (at prices of $50/tC, $100/tC and $200/tC), but the analysis was performed for the whole curve.

Table 7. Sensitivity analysis of global supply-curve (IGBP dataset, 5% discounting).

	Cumulative carbon sequestration, 20-year period		
	Carbon price: US$50/tC	**Carbon price: US$100/tC**	**Carbon price: US$200/tC**
1. Land price			
50% lower for each cell	7759	8746	9372
Main scenario	6889	8420	9242
50% higher for each cell	6358	8119	9067
2. Timber price			
50% lower for each cell	6528	8214	9159
Main scenario	6889	8420	9242
50% higher for each cell	7425	8605	9292
3. Carbon uptake			
25% lower for each cell	4466	5879	6686
Main scenario	6889	8420	9242
25% higher for each cell	9723	11027	11779

The sensitivity analysis leads to similar conclusions as in the Latin American study shown in Chapter 3: (1) carbon uptake is the most sensitive parameter because it influences both the carbon sequestration potential and the timber productivity but, increasing research efforts on this aspect are reducing current uncertainty levels; (2) land prices have a lower impact on the supply curve, but it is difficult to have accurate estimates from those; and (3) carbon prices have a strong influence on the sensitivity where the higher the carbon price is, the lower the sensitivity.

6 Conclusions

We have extended the framework presented in Chapter 3 for estimating carbon supply curves in order to apply the method globally. Major improvements are: (1) we accounted for country risk considerations based on the CAPM theory; (2) we developed carbon supply curves using different land cover datasets in order to get lower and upper bounds for carbon sequestration; and (3) we used spatial datasets providing rate of carbon uptake for both the baseline and sequestration scenario.

We started the global analysis using a benchmark scenario that considers 5% discounting for all countries. Our model results suggested that under reasonable assumptions of the land and timber price and excluding country risk considerations, the global supply of carbon at a price of $50/tC during a 20 year period would be 6.9 GtC, roughly equivalent to one year of carbon emissions in the energy sector. This is valid when the IGBP database is used. Using other land cover databases could lead to a sequestration potential of up to 45% higher.

Due to the fact that country risk is a major investor's concern, we have estimated required returns for forestry investments based on CAPM theory. In the absence of equity markets in most developing countries, required returns for forestry investments were determined as a function of the composite ICRG index that aggregates political, financial and economic risk for each country. By taking into account country risk considerations, the supply for carbon sequestration is reduced significantly: 59% given a carbon price of $50/tC. Regardless of this constraint, afforestation could still play a relevant role in global warming mitigation.

When we compare emissions reductions through afforestation with the required emission reductions of various climate policy scenarios of the RICE-99 model, we found that: (1) afforestation is an important option for global warming mitigation, where its potential carbon sequestration ranges from 5% to 25% of the emissions reduction targets of different policy scenarios and therefore, it needs to be included as a policy option; and (2) the relevance of afforestation strategies increases with increasingly strict policy alternatives. Policy scenarios requiring larger emission abatements would need a larger share of emission reductions through afforestation than those with smaller abatements.

With respect to the geography of supply, as illustrated by our grid-scale maps, we find that the majority of least-cost projects are located in Africa, South America and Asia. However these findings appear to be very sensitive to risk, and one needs to look at risk further. Chapter 5 of this thesis provides a more comprehensive approach for risk assessment in carbon sequestration projects.

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Appendix 1: Risk-adjusted Discount Rates

Country	ICRG rating[a]	Risk-adjusted discount rate	Country	ICRG rating[a]	Risk-adjusted discount rate
Afghanistan[b]	57.70	19.4%	Lithuania	72.50	8.4%
Algeria	62.50	15.6%	Macedonia[c]	52.50	24.0%
Angola	54.75	22.0%	Madagascar	65.50	13.3%
Argentina	66.25	12.7%	Malawi	59.25	18.1%
Armenia	63.50	14.8%	Malaysia	64.50	14.0%
Australia	80.00	3.6%	Mali	62.50	15.6%
Austria	85.50	3.0%	Mauritania[b]	57.70	19.4%
Azerbaijan	60.50	17.1%	Mexico	66.75	12.4%
Belarus	56.25	20.7%	Mongolia	61.75	16.1%
Benin[b]	57.70	19.4%	Montenegro	52.50	24.0%
Bhutan[b]	57.70	19.4%	Morocco	67.50	11.8%
Bolivia	68.75	10.9%	Mozambique	55.00	21.7%
Bosnia/Herzegovina[c]	52.50	24.0%	Myanmar	52.75	23.8%
Botswana	80.75	3.2%	Namibia	73.50	7.7%
Brazil	67.75	11.7%	Nepal[b]	57.70	19.4%
Brunei	78.75	4.4%	Netherlands	84.50	3.0%
Bulgaria	73.25	7.9%	New Zealand	78.75	4.4%
Burkina Faso	62.75	15.4%	Nicaragua	51.75	24.7%
Burundi[b]	57.70	19.4%	Niger	60.25	17.3%
Cambodia[b]	57.70	19.4%	Nigeria	57.25	19.8%
Cameroon	61.50	16.3%	Norway	86.50	3.0%
Canada	79.75	3.8%	Pakistan	55.25	21.5%
Central African Rep.[b]	57.70	19.4%	Panama	70.25	9.9%
Chad[b]	57.70	19.4%	Papua N. Guinea	62.25	15.7%
Chile	74.00	7.4%	Paraguay	55.75	21.1%
China, P.R.	73.75	7.5%	Peru	63.75	14.6%
Colombia	59.75	17.7%	Poland	75.25	6.6%
Congo D.R. (Zaire)	51.50	24.9%	Portugal	79.00	4.2%
Congo, Republic	54.50	22.2%	Romania	59.50	17.9%
Cote d'Ivoire	63.00	15.2%	Russian Fed.	55.00	21.7%
Czech Republic	76.50	5.8%	Saudi Arabia	69.00	10.8%
Denmark	84.00	3.0%	Senegal	59.25	18.1%
Ecuador	59.50	17.9%	Serbia	52.50	24.0%
Eritrea[b]	57.70	19.4%	Sierra Leone	44.75	31.7%
Ethiopia	59.75	17.7%	Slovenia	77.25	5.3%
Finland	82.75	3.0%	Somalia	43.75	32.8%
France	82.00	3.0%	South Africa	64.00	14.4%
Gabon	65.75	13.1%	Spain	82.25	3.0%
Georgia[d]	55.00	21.7%	Sudan	52.50	24.0%

Country	ICRG rating 5-year forecast[a]	Risk-adjusted discount rate	Country	ICRG rating 5- year forecast[a]	Risk-adjusted discount rate
Germany	82.50	3.0%	Suriname	65.75	13.1%
Ghana	61.75	16.1%	Swaziland[e]	64.00	14.4%
Guinea	58.00	19.2%	Sweden	80.75	3.2%
Guyana	64.25	14.2%	Switzerland	86.50	3.0%
Iceland	79.50	3.9%	Syria	64.25	14.2%
India	65.25	13.5%	Tajikistan[d]	55.00	21.7%
Indonesia	57.50	19.6%	Tanzania	59.50	17.9%
Iran	68.25	11.3%	Thailand	66.75	12.4%
Iraq	57.00	20.0%	Togo	61.00	16.7%
Ireland	82.25	3.0%	Tunisia	66.75	12.4%
Israel	66.75	12.4%	Turkey	66.75	12.4%
Italy	77.25	5.3%	Turkmenistan[d]	55.00	21.7%
Japan	84.75	3.0%	Uganda	60.75	16.9%
Jordan	72.00	8.7%	Ukraine	58.50	18.8%
Kazakstan	64.00	14.4%	United Kingdom	79.00	4.2%
Kenya	61.25	16.5%	United States	78.50	4.5%
Korea, D.P.R.	44.00	32.5%	Uzbekistan[d]	55.00	21.7%
Kyrgyzstan[d]	55.00	21.7%	Venezuela	63.75	14.6%
Laos[b]	57.70	19.4%	Vietnam	60.25	17.3%
Latvia	70.25	9.9%	Yemen, Republic	64.50	14.0%
Lesotho[b]	57.70	19.4%	Zambia	58.00	19.2%
Liberia	44.00	32.5%	Zimbabwe	56.00	20.9%
Libya	62.25	15.7%			

Note: Countries having no areas available for plantations are not shown.

[a] ICRG 5-year forecast. The average index between worse and best scenario is shown (PRS, 2004).

[b] Average ICRG index for low income countries.

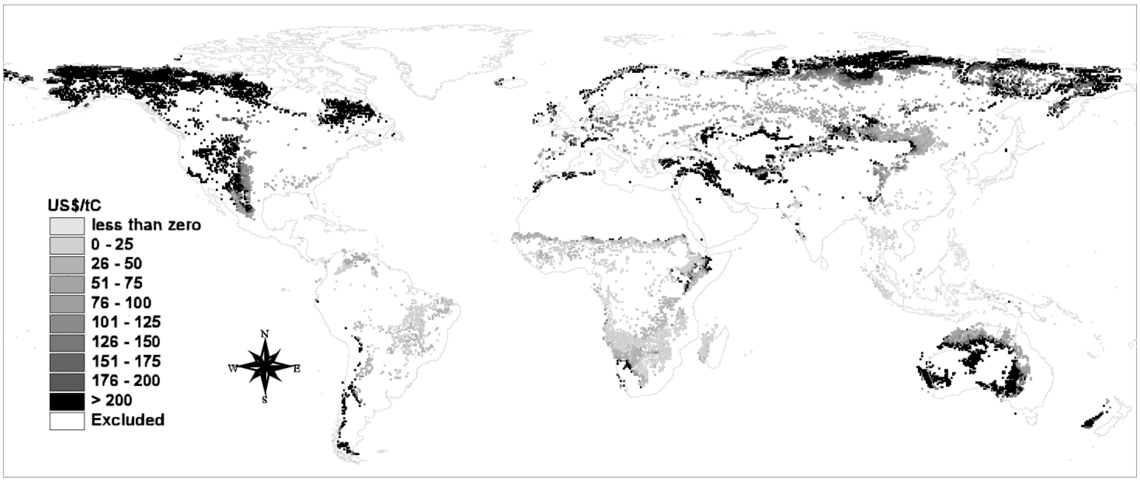
[c] Data for Serbia.

[d] Data for the Russian Federation.

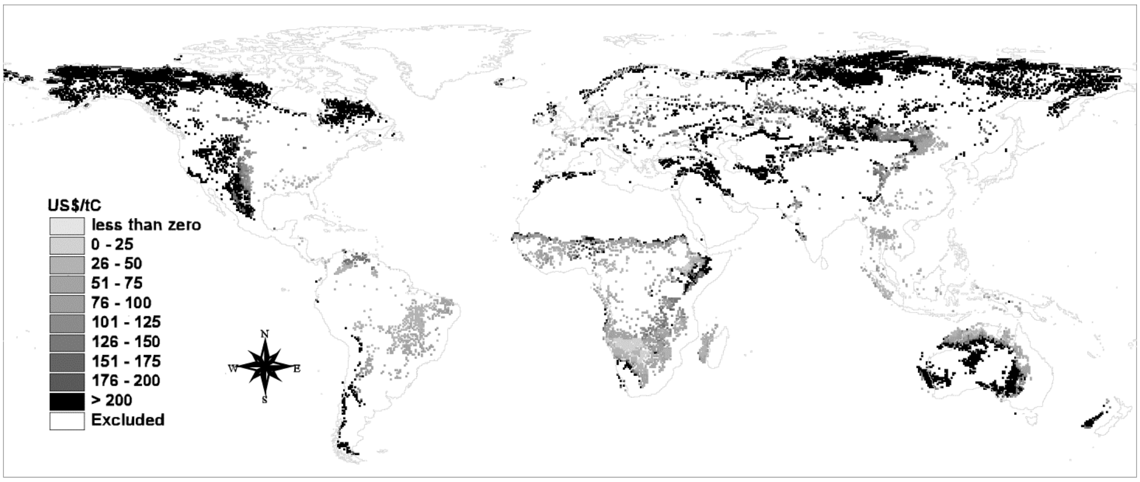
[e] Data for South Africa.

Appendix 2: Geographical distribution of carbon costs

A. IGBP dataset. Benchmark scenario



B. IGBP dataset. Risk-adjusted discount rates



Chapter 5

Conservation Payments under Risk: A Stochastic Dominance Approach

This chapter is based on:

Benítez, P.C., T. Kuosmanen, R. Olschewski and G.C. van Kooten. Conservation Payments under Risk: A Stochastic Dominance Approach. Submited and revised for publication in *American Journal of Agricultural Economics*.

Benítez, P.C., R. Olschewski, T. Kuosmanen, and G.C. van Kooten, 2004. Conservation Payments under Risk: A Stochastic Dominance Approach. Conference Proceedings XIII Annual EAERE Conference, 25-28 June 2004, Budapest.

Abstract

Conservation payments can be used to preserve forest and agroforest systems in developing countries. To explain landowners' land-use decisions and determine the appropriate conservation payments, it is necessarily to focus on risk associated with agricultural price and yield volatility. In this paper a theoretical framework is provided for assessing land-use allocation problems under risk and setting risk-efficient conservation payments when returns are not necessarily normally distributed. Stochastic dominance rules are used to derive conditions for determining the conservation payments required to guarantee that the environmentally-preferred land use dominates, even when land uses are not considered to be mutually exclusive. An empirical application to shaded-coffee protection in the biologically important El Chocó region of West Ecuador shows that conservation payments required for preserving shaded-coffee areas are much higher than those calculated under the assumption of risk-neutrality. Further, the extant distribution of land has a strong impact on the required conservation payments.

Keywords: risk, conservation payments, land allocation, stochastic dominance, agroforest systems, portfolio diversification.

1. Introduction

Forests and agroforest systems produce a variety of global benefits, including carbon uptake and biodiversity services. Without payments for these services, forestry might not be an attractive land use for private owners. This is certainly true for shaded-coffee in West Ecuador, where cultivated area has been reduced at the expense of temporary crops (e.g. maize and rice) and pasture. Conversion of shaded-coffee lands[1] to annual crops and/or pasture releases stored carbon to the atmosphere and reduces biodiversity. International payments for carbon storage or biodiversity conservation may help prevent land conversion.

A variety of economic models have been used to evaluate the effect of land-use policies that enhance the environmental services from forests. Econometric approaches have provided insights into the aggregated impact of carbon uptake and conservation policies (Stavins; Deininger and Minten; Plantinga, Mauldin and Miller; Plantinga, Alig and Cheng); general equilibrium models have been used for predicting changes due to environmental payments (Callaway and McCarl); and optimal control models have strengthened knowledge concerning mitigation of climate change through forestry (Sohngen and Mendelsohn 1998, 2003; van Kooten). The evaluation of conservation policies rarely takes into account risk, a factor that is often decisive in allocating land uses (Collender and Zilberman; Just and Pope). Here we focus on the landowner's allocation problem under risk and evaluate how risk-efficient conservation policies could be implemented for maintaining existing shaded-coffee areas in West Ecuador.

Mean-variance (M-V) analysis is a classical approach to risk management (Markowitz). Widely used in the financial world, its application is limited to situations where returns are normally distributed or the decision-maker's utility function is quadratic, conditions not always met when considering forests and other natural resource assets (Heikkinen and Kuosmanen). For example, fire risk is one cause for non-normality in forest returns. M-V also fails to show dominance in cases where almost every farmer would prefer one land use over another (Leshno and

[1] Shaded-coffee is a permanent crop cultivated below trees.

Levy). Suppose that a landowner is to choose between land uses *A* and *B*, where $\sigma_A > \sigma_B$. No matter how much greater E(*A*) is than E(*B*), the M-V approach is unable to tell us that *A* is unambiguously better than *B*. It is unable to recommend a (risk-free) conservation payment that would make the landowner choose land use *A* over *B*.

An alternative to M-V analysis is the more general choice rule based on stochastic dominance (SD). This technique sets minimum restrictions on landowners' utility functions and is valid for all types of return distributions. While stochastic dominance had been limited in its applicability for solving portfolio problems with diverse options, recent advances have extended possible applications (Shalit and Yitzhaki; Kuosmanen; Post; Mkenda and Folmer).[2] In this study, we use SD for situations with and without diversification possibilities, in contrast to traditional SD studies where diversification has not been considered (Harris and Mapp; Johnson and Cramb; Williams et al.). We also extend the SD literature on first- and second-order marginal conditional SD and apply the framework to land use in a developing country.

We begin our investigation with a brief review of stochastic dominance rules (section 2). We then provide a theoretical framework for the determination of risk-efficient conservation payments under different stochastic dominance criteria (section 3). The theoretical model is applied to a case-study in West Ecuador. The case-study and its corresponding data is described in section 4. Major findings on stochastic dominance and required payments for conservation are discussed in section 5. Some conclusions follow.

[2] Levy and Kroll extended the SD rules for investment choice between two risky assets by combining them with a risk-free asset. Shalit and Yitzhaki developed the so-called marginal conditional stochastic dominance rule, which tests if a marginal increase in the portfolio weight of one asset at the expense of another results in a dominating portfolio. The Shalit-Yitzhaki rule offers a necessary but not sufficient condition for portfolio efficiency. Kuosmanen presented the first necessary and sufficient test for portfolio efficiency. This approach has subsequently been further developed by Post.

2. General Stochastic Dominance Rules

A comprehensive review of stochastic dominance rules is provided by Levy (1992, 1998). Here we provide a brief summary focusing on land-use applications. Assume that a landowner must decide whether to invest in forestry/agroforestry, *f*, or an alternative crop, *g*, with cumulative net revenue distribution functions given by $F(x)$ and $G(x)$, respectively. Forestry dominates the crop alternative by first-order stochastic dominance (FSD) *iff*,

$$G(x) - F(x) \geq 0, \ \forall x \in \mathrm{R}, \text{ with at least one strict inequality.} \qquad (1)$$

The FSD criterion has an intuitive interpretation in terms of the von Neumann-Morgenstern expected utility theory: if one investment alternative dominates another, every non-satiated investor (with non-decreasing utility function, $U' \geq 0$) will prefer the dominant alternative. While this criterion seems reasonable, it is not very discerning. In practice, the cumulative distributions of net returns of the two investment alternatives often intersect, in which case FSD cannot discriminate between the alternatives.

If investors are risk averse in addition to insatiable (i.e., $U'' \leq 0$ and $U' \geq 0$), second-order stochastic dominance (SSD) could be used to choose between them. Formally, forestry dominates cropping in the SSD sense *iff,*

$$\int_{-\infty}^{x} \big(G(z) - F(z)\big)dz \geq 0 \ \forall x \in \mathrm{R}, \ \text{ with at least one strict inequality} \qquad (2)$$

In words, SSD requires that the area under the cumulative density function for forestry is always smaller than the area under the cumulative density function for the crop. Every risk-averse, non-satiable investor prefers the investment alternative that dominates by SSD.

In empirical analysis, the probability distributions *G* and *F* are unknown and must be estimated from available data. Hence, we consider a finite, discrete sample of observations on returns in forestry and a crop alternative over *T* periods, which we interpret as states of nature. We assume the states are drawn randomly with replacement from a common pool of possible states. States are assumed to be identically and independently distributed such that each observed state is equally likely to occur in any period, and the occurrence of a state in one period does not influence the probability distribution in any other period.

Standard algorithms for identifying stochastic dominance utilize pair-wise comparisons of sorted series of net revenue distributions (Levy 1992, 1998). Denote original series of observations on net revenues from forestry (f) and cropping (g) by $\mathbf{y}_f$ and $\mathbf{y}_g$, respectively, and the vectors of the re-arranged series sorted in ascending order by $\mathbf{x}_f$ and $\mathbf{x}_g$. Index t is used to indicate elements of the original series vector, while i indicates elements of the sorted series vector. From the sorted revenue series, we construct the cumulative sum vector $\mathbf{x}_f'$ with elements i as,

$$x'_{f,i} = \sum_{k=1}^{i} x_{f,k} \tag{3}$$

Following the same procedure, we get x_g'. We now express the empirical SD rules as follows (Levy 1992):

FSD*:* Forestry dominates cropping *iff* $x_{f,i} \geq x_{g,i}\ \forall i = 1,....,T$ (4)

SSD*:* Forestry dominates cropping *iff* $x'_{f,i} \geq x'_{g,i}\ \forall i = 1,....,T$ (5)

with at least one strict inequality holding in both cases.

The pair-wise comparisons of empirical revenue distributions apply to situations where land-use alternatives are mutually exclusive. If the land can be freely proportioned to smaller parcels such that each parcel has a different crop, the rules based on pair-wise comparisons fail to account for the infinite number of different land-use portfolios. The case of non-exclusive land uses can be seen as an example of portfolio diversification. Like any investor, the land owner can hedge the overall risk of the land portfolio by diversifying into parcels with different uses so that return fluctuations in different crops can at least partially cancel out.

Using portfolio weights $\mathbf{w} = (w_f, w_g)$ for forestry and cropping, the revenue portfolios are represented by vector $\mathbf{y}_p = w_f \mathbf{y}_f + w_g \mathbf{y}_g$. The key to empirical application of SD rules for portfolio analysis under portfolio diversification is to preserve the cross-sectional structure of revenues, because it is impossible to recover portfolio returns from the sorted revenue series; for example, $w_f\mathbf{y}_f + w_g\mathbf{y}_g \neq w_f\mathbf{x}_f + w_g\mathbf{x}_g$ (see Kuosmanen). That is, when we first sort series according to each series' revenues and then estimate portfolio revenues given **w**, we might get portfolios consisting of crop revenues of different years (say a portfolio consisting of 50% of year 1990 coffee with 50% of year 2000 maize) which is unreasonable. Therefore, an alternative criterion for sorting series is required.

Shalit and Yitzhaki and Post propose to sort all revenue series according to the portfolio revenues $\mathbf{y}_p$, such that portfolio revenues are in ascending order. Denote the resulting sorted portfolio revenue series by $\mathbf{x}_p^{\mathbf{w}}$, and the revenue series for forestry and cropping, sorted according to the portfolio revenues, by $\mathbf{x}_f^{\mathbf{w}}$ and $\mathbf{x}_g^{\mathbf{w}}$, respectively. While elements of $\mathbf{x}_p^{\mathbf{w}}$ are in ascending order, the elements of $\mathbf{x}_f^{\mathbf{w}}$ and $\mathbf{x}_g^{\mathbf{w}}$ are usually not. The rationale of sorting all series according to the portfolio returns is to guarantee that $\mathbf{x}_p = w_f\mathbf{x}_f + w_g\mathbf{x}_g$.

Following Shalit and Yitzhaki, we apply SD rules (4) and (5) to revenue series sorted according to the portfolio revenues rather than separately for each crop, to get the so-called marginal conditional stochastic dominance (MCSD) rules. Again, we form the cumulative sum vectors $\mathbf{x}_f^{\mathbf{w}\prime}$ and $\mathbf{x}_g^{\mathbf{w}\prime}$, as in (3). The first- and second-order marginal conditional stochastic dominance (FMCSD and SMCSD) rules are defined as follows (see Shalit and Yitzhaki):[3]

FMCSD: Forestry dominates cropping *iff* $x_{f,i}^{\mathbf{w}} \geq x_{g,i}^{\mathbf{w}}$ $\forall i = 1, \ldots, T$ (6)

SMCSD: Forestry dominates cropping *iff* $x_{f,i}^{\mathbf{w}\prime} \geq x_{g,i}^{\mathbf{w}\prime}$ $\forall i = 1, \ldots, T$ (7)

with at least one strict inequality holding in both cases.

Shalit and Yitzhaki show that if an asset (here forestry) dominates another asset (crop) by SMCSD, then every non-satiated risk averse investor (landowner) will be better off if the portfolio weight of the dominating asset is increased at the expense

3 Shalit and Yitzhaki only consider the second-order MCSD rule. The first-order MCSD rule is an innovation made here.

of the dominated one. One can verify that FMCSD implies that every non-satiated landowner (irrespective of risk preferences) will benefit from an increase in the portfolio weight of the dominating asset at the expense of the dominated one.

3. Stochastic Dominance for Determining Conservation Payments

Stochastic dominance provides a framework for estimating the conditions under which forestry is a risk-efficient land-use choice. Assume that forests are privately owned with well-established property rights and that landowners have a basic set of common preferences: they maximize expected utility, their utility function is non-satiated and they are risk averse. Under these assumptions, second-order stochastic dominance is the appropriate decision tool for land-use choice. In addition, we need to identify farms' diversification possibilities. SD comparisons of unmixed alternatives might lead to wrong results when they are not mutually exclusive and the correlation coefficients of returns are below a certain threshold value (McCarl et al.).

Empirical evidence of deforestation patterns indicates whether or not diversification exists on farms. For the case study in West Ecuador both situations have been observed. Therefore, we evaluate both possibilities.

3.1 Mutually exclusive land uses

Consider the case where a forestland owner faces the possibility of investing in new crops where she can only plant one crop at a time (land uses are mutually exclusive). Using SD analysis and pair-wise comparisons of forestry with the alternative land uses, three mutually exclusive situations that result in high to low deforestation can be distinguished:

(A) Forestry is not a risk-efficient land use, so at least one land use dominates forestry, and retaining forests is not an option. There is then a high chance that deforestation occurs.

(B) Forestry is a risk-efficient land use, but not the only one. Depending on preferences of individual landowners some farm-forests will be converted and others not.

(C) Forestry is the only risk-efficient land use – forestry dominates all other land uses. This guarantees that no deforestation takes place.

Dominance among A, B and C can be influenced by a conservation payment, s. We determine minimal payments, s_{min}, that guarantee that at least *some* landowners consider forestry as the optimal land use (limiting situations A and B), but payments below s_{min} have no impact. Also, there will be a payment s_{max} where *all* landowners find forestry the optimal land use (limiting situations B and C). Any payments above s_{max} represent an inefficient use of financial resources. In order to find s_{min} and s_{max} under FSD, we recognize that the non-stochastic conservation payment shifts the cumulative distribution function of forestry returns to the right. Thus, each $x_{f,i}$ from forestry is now $x_{f,i} + s$. Using FSD conditions (4), we get (with formal proof in Appendix A):

FSD: $s_{min}=\min_i(x_{g,i} - x_{f,i})$ and $s_{max}=\max_i(x_{g,i} - x_{f,i})$. (8)

Similarly, using (5) we get for SSD (see Appendix A):

SSD: $$s_{\min} = \min_i \left(\frac{x_{g,i}' - x_{f,i}'}{i} \right) \text{ and } s_{\max} = \max_i \left(\frac{x_{g,i}' - x_{f,i}'}{i} \right). \quad (9)$$

The level of payment for a risk-neutral landowner, for whom $s_{max}=s_{min}=E(x_{g,i}-x_{f,i})$, lies between the FSD limits. The upper and lower bounds in SD analysis emerge due to heterogeneity of landowners' preferences. If all of them had the same utility function, we would have $s_{max}=s_{min}$ based on direct expected utility analysis. If we know little about their utility function, as in FSD, we expect a broad range between s_{max} and s_{min}. Further knowledge of the utility function (e.g., $U''\leq 0$, making SSD valid) narrows this payment range.[4]

The conditions for s_{min} and s_{max} could be extended to cases where more than one alternative land use exists. By comparing forestry with each of the alternative land uses, we obtain a single s_{max} and s_{min} for each comparison. The overall s_{max} is the maximum of all the individual s_{max} and the overall s_{min} is the maximum of all the individual s_{min}, where s_{min} and s_{max} are measures of the efficiency of land use f. Large values of s_{min} represent land uses that are least risk efficient, while small values of s_{max} represent risk-efficient land uses that nearly dominate all other land uses.

3.2 Land uses with diversification possibilities

The previous minimum and maximum bounds pertain to the case where all land is assigned to a single use. Applying the previous insights to the FMCSD criteria, we get the following minimum and maximum payments (see Appendix A):

FMCSD: $$s_{\min} = \min_i \left(x^{w}_{g,i} - x^{w}_{f,i}\right) \text{ and } s_{\max} = \max_i \left(x^{w}_{g,i} - x^{w}_{f,i}\right) \quad (10)$$

Similarly, the minimum and maximum payments under SMCSD are (see Appendix A):

SMCSD: $$s_{\min} = \min_i \left(\frac{x^{w\,\prime}_{g,i} - x^{w\,\prime}_{f,i}}{i}\right) \text{ and } s_{\max} = \max_i \left(\frac{x^{w\,\prime}_{g,i} - x^{w\,\prime}_{f,i}}{i}\right) \quad (11)$$

[4] With data on risk aversion parameters, more discerning extensions of SD could be used to determine narrower bounds for s. For example, knowledge of the risk aversion range permits using stochastic dominance with respect to a function (see Williams et al.), while excluding extreme utility functions permits using the so-called *almost stochastic dominance* (Leshno and Levy).

Note the similarity of these conditions with the ones for FSD and SSD, with the only difference that here the series are sorted according to portfolio revenues. The FMCSD (SMCSD) conditions give the minimum and maximum bounds for the conservation payment to guarantee that all non-satiated (and risk averse) landowners have no incentive (marginally) to increase the weight of cropping in the land portfolio. If there is only one alternative crop (*g*), these bounds fully exhaust the diversification options. However, if there are multiple alternative crops (say *g* and *h*), then the bounds should be constructed such that there is no portfolio of alternative crops that dominates forestry in the sense of MCSD.

Since the current portfolio weights are denoted by **w**, we use v_g and v_h as the portfolio weights of crops *g* and *h* in the sub-portfolio that threatens to replace forestry as the land use. To take the diversification options fully into account, we need to solve the following max-min and max-max problems:

FMCSD:

$$s_{\min} = \max_{v_g, v_h}\left[\min_i\left((v_g x^{\mathrm{w}}_{g,i} + v_h x^{\mathrm{w}}_{h,i}) - x^{\mathrm{w}}_{f,i}\right)\right] \quad \text{and}$$

$$s_{\max} = \max_{v_g, v_h}\left[\max_i\left((v_g x^{\mathrm{w}}_{g,i} + v_h x^{\mathrm{w}}_{h,i}) - x^{\mathrm{w}}_{f,i}\right)\right] \tag{12}$$

SMCSD:

$$s_{\min} = \max_{v_g, v_h}\left[\min_i \frac{1}{i}\left((v_g x^{\mathrm{w}\,\prime}_{g,i} + v_h x^{\mathrm{w}\,\prime}_{h,i}) - x^{\mathrm{w}\,\prime}_{f,i}\right)\right] \text{ and}$$

$$s_{\max} = \max_{v_g, v_h}\left[\max_i \frac{1}{i}\left((v_g x^{\mathrm{w}\,\prime}_{g,i} + v_h x^{\mathrm{w}\,\prime}_{h,i}) - x^{\mathrm{w}\,\prime}_{f,i}\right)\right] \tag{13}$$

subject to $v_g + v_h = 1$ and $v_g, v_h \geq 0$. In practice, these bounds can be solved by using linear programming (LP), with the LPs provided in Appendix B.

4. Shaded-coffee in West Ecuador: Preliminaries and Data

The study area is in the province of Manabí, located in the tropical lowlands of west Ecuador. The natural vegetation is a continuation of the *Chocó*, a bio-geographical region known as one of the world's hotspots of biodiversity because of its species richness, high levels of endemism and stress from human activities (Myers et al.). Primary forests are found mostly in protected areas such as the Mache Chindul Reserve and the Machalilla National Park. Important areas of coffee plantations are found throughout Manabí, which constitutes one of the main areas for coffee production and where all coffee is produced under shade. While state and private actions increasingly protect primary forests, shaded-coffee systems that provide a buffer zone for biodiversity protection are being cleared. Government estimates suggest that coffee plantations have been reduced nationally by about 40% during the last decade (SICA).

We consider four land uses: shaded-coffee, upland rice, maize, and pasture for double purpose cattle (producing meat and milk). Time series for estimating yearly revenues are available for 1967-2002 from several government offices in charge of agricultural statistics. For coffee, rice and maize yield, we have data for 1991-2002 (SICA) and 1967-1990 (MAG).[5] Since these series correspond to country-level yield data, we convert them to provincial yields based on factors obtained from the 2000 census (INEC, MAG and SICA). For cattle, we use the assumption of constant yield.[6] This approximation is valid due to the extensive nature of cattle grazing, where weather variability has a small impact on annual cattle growth. Cattle yield is estimated using the method described in Benítez et al. where cattle stock is assumed to be in equilibrium, i.e. the number of cows, bulls and calves is constant on time. For the stocking density of 1.1 head per hectare found in Manabí province, the estimated

[5] Data sources are from different publications, but most of the primary data on crop yield and prices were collected by the *Dirección de Información Agropecuaria* of the Agricultural Ministry. This work has been complemented in the last few years by the World Bank's SICA project, which attempts to improve information management and dissemination.

[6] This assumption is justified on the grounds that farmers mitigate risks associated to weather events affecting cattle growth. For example, during extreme dry seasons farmers reduce temporary their cattle stock in order to reduce the demand for grass.

growth in cattle live weight yield is 93 kg per ha per year and this equals the yearly sales of cattle. A dairy cow in this region yields 2.6 liters of milk per day (INEC, MAG and SICA). Since 41% of the livestock herd consists of cows and 40% of them produce milk, annual production is calculated to be 172 liters/ha/year.

Producer prices for crops are available for the periods 1991-2002 (SICA) and 1978-1990 (Whitaker, Colyer and Alzamora). For the period 1967-1977, we estimate producer prices as a function of retail prices (INEC).[7]

Cost estimates are based on survey data taken in 2003. For coffee, costs include land preparation, planting, cleaning, pruning and shade control. Land preparation and planting costs are annualized using a discount rate of 5% and a period of 15 years.[8] For annual crops (maize and rice) costs include land preparation, seeds, planting, fertilizer, weeding and pest control. These costs are the same for all years except for seed costs, which depend on annual crop prices. Variable costs include harvest and transport costs. For cattle, costs include brush control, the opportunity costs of cattle stock, cattle losses, vaccines and pest control. The opportunity costs of cattle stock and costs associated with cattle losses also depend on annual (cattle) prices. General farm costs such as administration and fence maintenance are not included, since they have no influence on land-use choice. Based on this information, we estimate net revenues for each year as the product of price and yield minus costs.

4.1 Revenue trends

SD analysis is based on the assumption that each observed state of nature is equally likely to occur and that the probabilities do not change over time. This assumption is not valid if revenue follows a time trend, as is the case when crop yield (y) is a function of t:

[7] In order to account for inflation and estimate net revenues in real terms, we convert prices into constant US$ for year 2000 based on Ecuador's consumer price index. In 2000, the local currency (*sucre*) was officially eliminated and replaced by the US dollar. Prices before 2000 are first converted into constant (year 2000) *sucre*, and then transformed into US dollars using the 2000 exchange rate; dollar prices after 2000 are converted into constant US dollars using the CPI.

[8] Coffee has existed on some parcels for up to 80 years, although they have been renewed periodically.

$$y_t = a + bt + e_t. \quad (14)$$

Then $E(y_T) = a+bT$, for example, in contrast to the assumption that returns are equally likely to occur. However, returns can be de-trended before determining the SD of a series. A series can be de-trended in various ways, including curve fitting, first differencing, digital filtering and piece-wise polynomials, but we employ the most common procedure of curve fitting (Hamilton). We first test for the existence of significant trends in the yields and prices of each of the four land uses by testing if the coefficient b of equation (14) is significant.[9] Results shown in Appendix C indicate that maize yields have a statistically significant (at the 0.05 level of significance) increasing trend and rice prices a decreasing trend. Price and yield for other series have no significant trends.

It is reasonable to expect that the increase in land productivity due to technological improvements (e.g., development of new seeds) has its limits and that yield growth should decrease over time. Nor can prices fall continuously. Therefore, a concave trend function (in our case logarithmic) is considered in addition to a linear trend, and both trend functions are tested (see Table 1). Diagnostic tests of the residuals include White's heteroskedasticity test, a Breusch-Godfrey Serial Correlation Test, and the Jarque Bera test for normality. Based on R^2 and diagnostic tests of the residuals, we select a linear model for both rice and maize.[10] We de-trend the series by adding the residuals of the linear regression to the expected value of equation (14) at time T in order to guarantee that $E(y_T) = a+bT$.[11] In this way, the trends of the series are (partially) eliminated and our expectations at time T coincide with the expected value of the series.

[9] Testing yield and price separately is adequate given the small correlation between both series in the case of rice, maize and pasture. For coffee, there is some correlation between price and yield (correlation coefficient is 0.16), so we also tested the net revenue trends.

[10] When the hypothesis of autocorrelation is accepted it reflects the existence of trends in the residuals. Therefore, the linear model is a better model than the logarithmic model.

[11] For our SD analysis we did not use first-differencing because we need to preserve the cross sectional structure of the data. When taking first differences, residuals of the de-trended series are modified and years of high revenues would not necessarily correspond to points located at the right side of the cumulative distribution.

Table 1. Tests for Trends in Series for Rice Price and Maize Yield, Manabí, 1967-2002.

Model	R^2	White hetero., no cross terms, p-value	Breusch-Godfrey Serial Correlation Test, 2 lags. p-value	J. Bera test, p-value
Rice_price				
Linear trend	0.407	0.376	0.08	0.069
Logarithm trend	0.278	0.611	0.01*	0.173
Maize yield				
Linear trend	0.658	0.00004*	0.2	0.394
Logarithm trend	0.492	0.034*	0.0048*	0.01*

*Significant with 5% confidence level

Once the price and yield series are corrected for trends, we re-estimate net revenues. The descriptive statistics for the net revenue series, including the Jarque-Bera and Shapiro-Wilk tests for normality, are provided in Table 2. Non-normality is particularly evident for coffee and it is caused by both positive skewness and high kurtosis[12]. In Table 2 we also show the cultivated area of the different land uses in the southern districts of Manabí (Jipijapa, 24 de Mayo and Paján) where shaded-coffee is produced.

Table 2. Summary Statistics for Net Revenues Series of Land-use Systems in Manabí, 1967-2002.

	Coffee	Maize*	Rice*	Pasture
Cultivated area (ha)**	44700	12500	3000	74000
Mean (2000 US$/ha)	78	108	57	53
Standard Deviation (2000 US$/ha)	86	56	61	18
Skewness	1.6	0.5	0.7	0.7
Kurtosis	6.5	3.5	2.8	2.3
Jarque-Bera p-value	0.000	0.4	0.2	0.2
Shapiro-Wilk. p-value	0.01	0.5	.07	0.01

* De-trended series.
** Source: Census of year 2000 (INEC, MAG and SICA). Includes the districts of Jipijapa, 24 de Mayo and Paján only.

[12] This motivates the use of the SD approach, which is valid for any type of distribution.

4.2 Bootstrapping

Bootstrapping has been used to increase the power of empirical applications of stochastic dominance tests. One of the advantages is that bootstrapping smoothes the cumulative density function (CDF) so that it mitigates problems associated with obtaining reliable estimates of order statistics and its impact on SD tests (Nelson and Pope). For example, sample error might lead to estimating order statistics above (or below) the real CDF. By repetitive re-sampling with replacement, bootstrapping smoothes such “highs” and “lows” and allows SD tests to be more discerning since it avoids inadvertent intersection of cumulative distributions.

A simple bootstrapping algorithm based on Nelson and Pope is employed. We first re-sample with replacement from the original empirical distribution function (EDF) and then find the average of each order statistic for computing a new EDF. The number of samples needs to be sufficiently large so that the resulting distribution will not be affected by additional re-sampling. In Figure 1, we provide an indication of the effect that bootstrapping of the coffee series (with 1000 samples) has on the original EDF. Irregularities are eliminated and the bootstrapped distribution is assumed to be the appropriate one for estimating the risk efficient conservation payments under FSD and SSD.

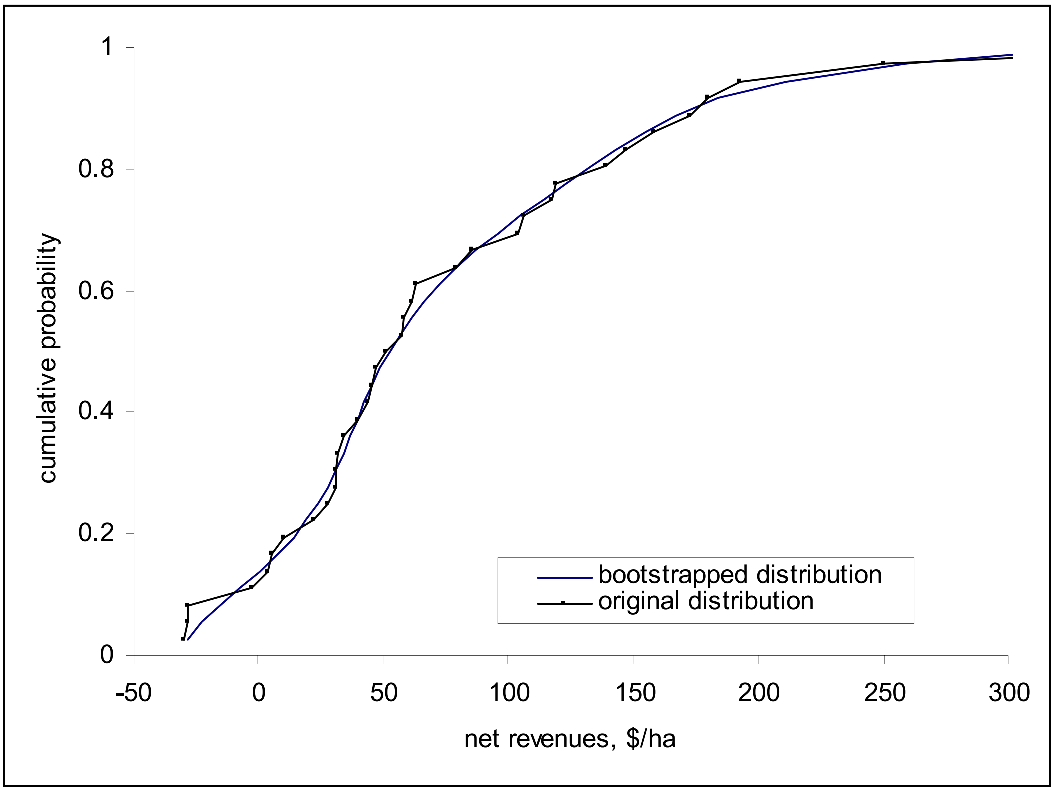


Figure 1. Original and Bootstrapped EDFs for Coffee

5. Shaded-Coffee in West Ecuador: Stochastic Dominance Results and Payments for Conservation

We now estimate the risk-efficient conservation payments under conditions of mutually exclusive land uses alternatives and when full portfolio diversification is allowed.

5.1 Mutually exclusive land uses

The FSD efficient land-use alternatives can be determined by direct observation of the intersections of the (bootstrapped) EDFs of the different land uses (Figure 2). The EDF for maize is always to the right of that of rice, indicating that maize dominates rice by FSD. Since the EDFs for coffee, pasture and maize all intersect, the FSD efficient set contains these three land uses. To rank the other land uses requires further differentiation, which we do using SSD.

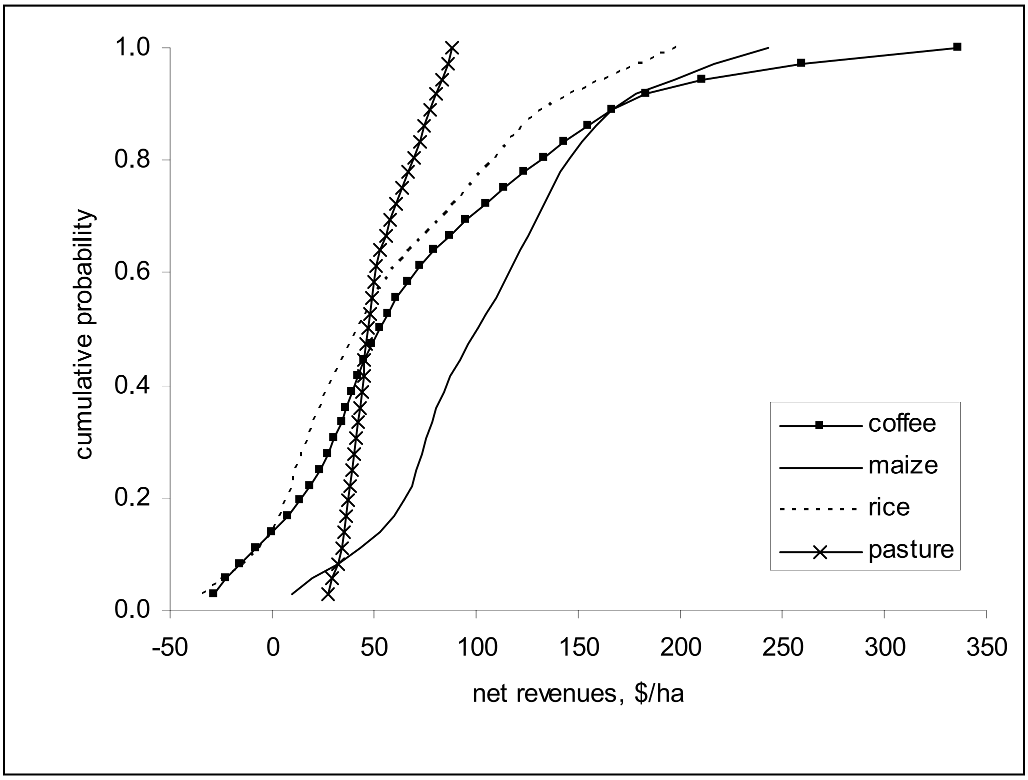


Figure 2. Bootstrapped EDFs for Major Land Uses in West Ecuador

Since maize dominates rice by FSD, it also dominates rice by SSD. Maize dominates coffee and coffee dominates rice by SSD, but there is no dominance relation between maize and pasture. Thus, the SSD efficient set consists of maize and pasture. The FSD and SSD results are summarized in Table 3.

Table 3. FSD and SSD for mutually exclusive land uses

Dominance criteria	Dominance Relationships*	Efficient Set
FSD	maize $\succ$ rice	maize, coffee, pasture
SSD	maize $\succ$ rice maize $\succ$ coffee coffee $\succ$ rice	maize, pasture

*A $\succ$ B means A stochastically dominates B

These results explain some of the land-use choices in the study region. First, the conversion of existing shaded-coffee areas can be explained by the result that this land use is inefficient (under SSD). Second, pasture is the most extensive land use in the region (see Table 2) even though its expected revenues are lower than those of other land uses (for example, expected revenues of pasture are 30% lower than those of coffee). But, this is justified on the grounds that it is a risk-efficient land use, where the low expected revenues are compensated by smaller variation in revenues.

Finding the risk-efficient payment for conservation requires estimates of s_{min} and s_{max} that, in turn, depend on the alternative land-use opportunities. We calculate the minimum and maximum bounds required to make coffee a risk-efficient land-use alternative, comparing coffee returns separately with each alternative land use. The results are reported in Table 4. Since coffee is efficient under the FSD criterion, the lower bound s_{min} is equal to zero in the FSD case. The upper bound s_{max} varies annually between \$2/ha and \$55/ha. In the SSD case, the minimum conservation payment is \$30/ha (to break SSD dominance by maize). The maximum payment is \$55/ha, which would suffice to guarantee that coffee dominates all other alternatives.

Table 4. Minimum and Maximum Conservation Payments Required to make Coffee a Risk-efficient Land Use (Year 2000 US$ per ha)

Decision criteria	Land use alternative to coffee					
	Maize		Rice		Pasture	
	s_{min}	s_{max}	s_{min}	s_{max}	s_{min}	s_{max}
FSD	0	53	0	2	0	55
SSD	30	48	0	0	0	55
Difference in means (Risk neutrality assumption)	30	30	0	0	0	0

Note: A value of zero is assigned when the estimated payment is negative.

These payments can be compared with those required under risk-neutrality, where only expected values matter. When the alternative to coffee is pasture, there is no need for a payment under risk-neutral conditions since the mean net return to coffee is higher than that for pasture. However, for all risk-averse landowners to prefer coffee over pasture requires a payment of \$55/ha (based on SSD). Such a risk premium represents 70% of the (average) net revenues for coffee. These results stress the need for considering risk when implementing policy instruments aimed at conservation. Given the high variability of coffee revenues, it is risk and not expected values that discourages landowners. While provision of risk-free payments for protecting coffee areas is one strategy, a better one might be to incorporate risk-hedging strategies and insurance possibilities for small farmers, instruments that are slowly being developed in Ecuador's financial markets.

5.2 Non-exclusive land uses

In this section we first illustrate the MCSD concept using an arbitrary equally-weighted (50-50) portfolio of coffee and maize and then we determine risk-efficient payment under MCSD based on existing land-use shares in West Ecuador.

To illustrate the concept of FMCSD, a plot of the portfolio consisting of coffee $\mathbf{x}_f^w$ and maize $\mathbf{x}_g^\mathbf{w}$, and component net revenues series is provided in Figure 3 (panel A). (The axes in the figure have been switched to provide a better illustration.) One land use dominates another under FMCSD if there is no intersection of the individual land-use curves. As shown in the figure, both curves intersect, so we conclude that there is no FMCSD between coffee and maize for such portfolio. In panel B, the cumulative series for determining SMCSD are provided. Since the series for maize are always above the ones of coffee, maize dominates coffee by SMCSD. We conclude that second-order dominance does exist.

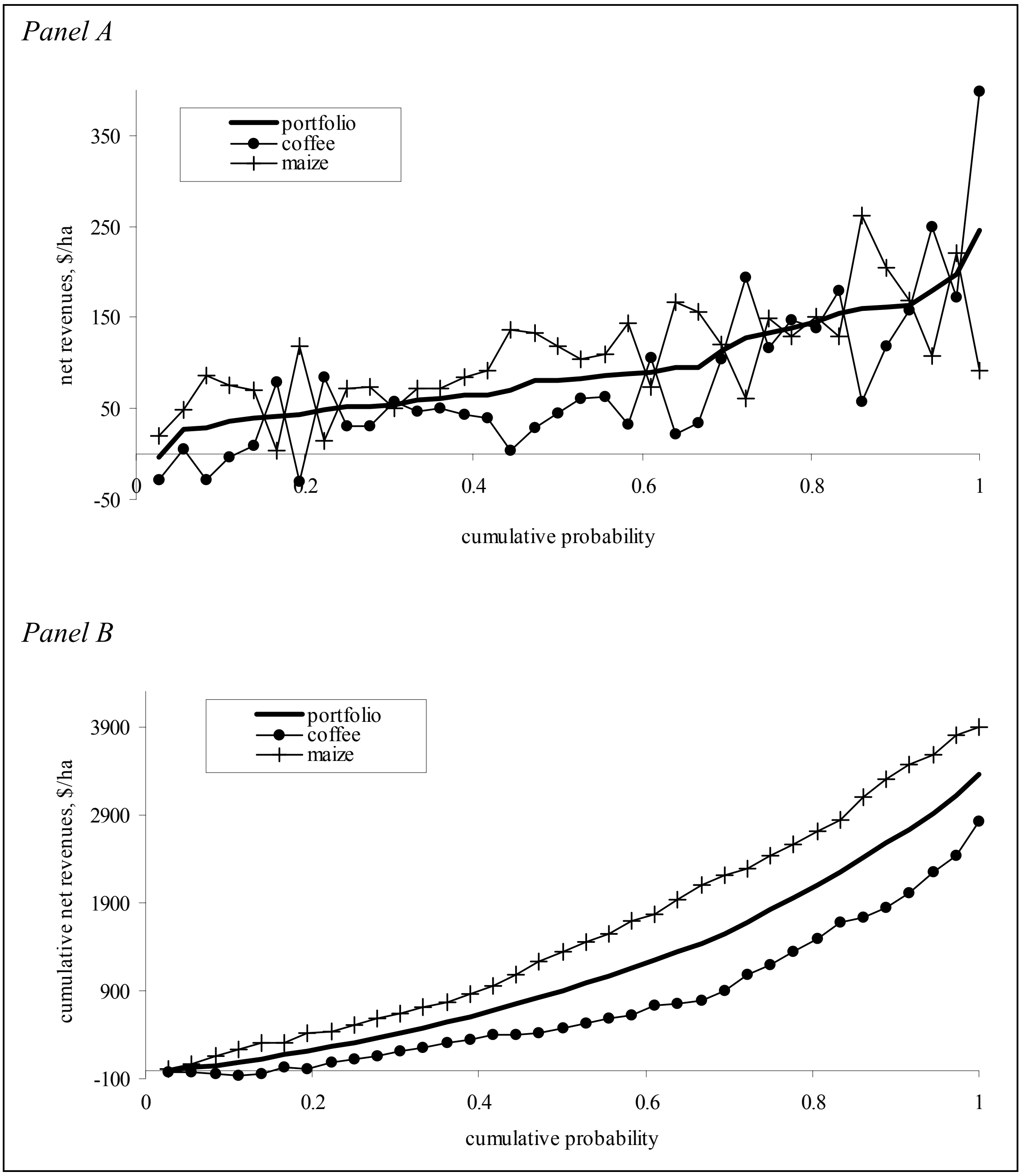


Figure 3. Graphical illustration of FMCSD (panel A) and SMCSD (panel B)

To estimate the efficient conservation payments under the MCSD criteria, we interviewed 92 coffee producers in the southern districts of Manabí in 2003 and asked each farmer about his land use shares, i.e. the number of hectares for each land use. We found that 35% of them do not diversify their land use. The remainder employ different combinations of land uses that, on average, have the portfolio shares shown in Table 5. As in the case of no diversification, we estimate risk-efficient conservation payments that prevent marginal conversions of shaded-coffee to other uses. These results are also summarized in Table 5, where s_{min} and s_{max} payments under FMCSD and SMCSD are provided.

Table 5. Required Payments for Shaded-coffee Conservation based on Responses from 60 Interviewed Coffee Producers with Diversified Farms (Year 2000 US$ per ha)

Land-use shares of representative farms	Decision rule			
	FMCSD		SMCSD	
	s_{min}	s_{max}	s_{min}	s_{max}
Farms with two land-uses				
Coffee: 56%; Pasture: 44%	0	77	0	73
Coffee:55%; Rice:45%	0	107	0	46
Coffee: 79%; Maize: 21%	0	204	30	104
Farms with three land-uses				
Coffee: 36%; Rice: 11%; Pasture: 53%	0	107	0	74
Coffee: 47%; Maize: 15%; Pasture: 38%	0	204	30	104
Coffee: 68%; Maize: 20%; Rice: 12%	0	204	30	104
Farms with four land-uses				
Coffee: 34%; Maize: 6%; Rice:9%; Pasture: 51%	0	204	30	111

Note: A value of zero is assigned when the estimated payment is negative.

In most of the portfolios analyzed, the payment s_{max} under SMCSD is higher than under SSD. Importantly, under SSD and SMCSD, the minimum payment s_{min} is often the difference in expected net returns between coffee and maize. To understand this peculiarity, note that a payment s_{min} requires breaking the dominance of maize over coffee. Since the distribution of coffee has a greater spread than that of maize, this dominance can only be broken by adding a payment that results in both land uses having the same mean. Then maize can never dominate coffee by SSD.

For examining the impact of portfolio shares in the minimum payments, we take as an example a farm with maize and coffee and estimate the payments for different shares of these land uses. The results shown in Table 6, where minimum and maximum payments are estimated under the SMCSD criterion, confirm the theoretical expectations. The level of a risk efficient payment depends on the given portfolio shares. The higher the share of coffee, the higher is the required conservation payment.

Table 6. Conservation payments for a coffee/maize portfolio under the SMCSD criterion.

share of coffee	share of maize	SMCSD*	s_{min}	s_{max}
10%	90%	none	0	31
20%	80%	none	0	48
30%	70%	none	0	48
40%	60%	maize $\succ$ coffee	5	55
50%	50%	maize $\succ$ coffee	30	72
60%	40%	maize $\succ$ coffee	30	87
70%	30%	maize $\succ$ coffee	30	104
80%	20%	maize $\succ$ coffee	30	104
90%	10%	maize $\succ$ coffee	30	104

* A $\succ$ B means A dominates B under SMCSD

6. Conclusions

In this article, we extend theoretical contributions for analyzing stochastic dominance tests with fully diversifiable portfolios (Post; Kuosmanen; Shalit and Yitzhaki) by including a first-order MCSD rule. We then apply the theory to the problem of identifying the magnitude of conservation payments needed to prevent land-use change that reduces biodiversity in developing countries. In particular, we introduce the concept of two efficiency measures for evaluating forestland use: (1) payments s_{min} that guarantee that at least *some* landowners consider forestry as the optimal land use; and (2) payments s_{max} where *all* landowners find forestry the optimal land use. Large values of s_{min} (relative to the mean) represent land uses that are least risk-efficient, while small values of s_{max} represent risk-efficient land uses that nearly dominate all other land uses. Knowledge of s_{min} and s_{max} helps to identify intervention strategies – payments for conservation – that can be implemented for attaining environmental goals at the lowest cost.

The methodology is applied to a West Ecuador case study, where shaded-coffee is compared with the most important alternative land uses in the region. Results indicate that (1) shaded-coffee is not a risk-efficient land use, no matter whether diversification is possible or not, which goes a long way towards explaining current land uses. (2) The payments required to preserve shaded-coffee areas are much higher than the compensation payments calculated under the assumption of risk-neutrality.

(3) The extant distribution of land uses has a strong impact on the required conservation payment. (4) Land-use policy interventions need to incorporate risk-hedging strategies and insurance possibilities for small farmers, instruments that are slowly developing in Ecuador's financial markets. As shown in this paper, pasture is a risk-hedging land use rather than a profit-maximizing land use. If revenue insurance is available for shaded-coffee producers, this could replace the use of pasture for risk-hedging and deforestation could be prevented.

Finally, the method for estimating risk-efficient conservation payments presented in this article could also be used to derive cost curves for a wide variety of environmental services and for diverse climate change applications. This may be particularly apt in the case of carbon sequestration as the Kyoto Protocol allows trading carbon offsets from forestry and agricultural activities. To derive a carbon uptake cost curve, it is necessary to first define a wide range of possible portfolios and then estimate the carbon level for each portfolio. For each portfolio, there is a corresponding level of compensation (or carbon uptake costs), and that information can be used to estimate a supply curve for carbon uptake services. This is an area of future research.

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APPENDIX

A. Minimum and maximum payments for conservation

Let f and g be two land uses with sorted net revenues series $x_{f,i}$ and $x_{g,i}$, respectively. We have the following propositions:

Proposition 1a. The payment level that guarantees first-order stochastic dominance of f over g is $s = Max_i(x_{g,i} - x_{f,i})$.

Proof. Denote by f^* the net revenue series of f that includes the conservation payment. FSD requires that $x_{f^*,i} \geq x_{g,i}$, $\forall i$. Since we know that net revenues of f^* equal f plus a non-stochastic payment (s), we have $x_{f^*,i} = x_{f,i} + s$. Replacing this in the previous expression yields $x_{f,i} + s \geq x_{g,i}$, $\forall i$. Thus, $s \geq x_{g,i} - x_{f,i}$, $\forall i$. Since this should hold for every pair-wise comparison on i, the payment needs to be at least as large as the maximum of the differences between $x_{g,i}$ and $x_{f,i}$, or $s = Max_i(x_{g,i} - x_{f,i})$.

Proposition 1b. The payment level that guarantees that f will not be dominated by g by FSD is $s = Min_i(x_{g,i} - x_{f,i})$.

Proof. If f is not to be dominated by g, we require, for at least one pair-wise comparison, that $\exists i \mid x_{f^*,i} \geq x_{g,i}$. This requires that, $\exists i \mid s \geq x_{g,i} - x_{f,i}$. If this holds for one pair-wise comparison, f will not be dominated by g by FSD. Thus, $s = Min_i(x_{g,i} - x_{f,i})$.

Proposition 2a. The payment level that guarantees SSD of f over g is $s = Max_i\left(\frac{x'_{g,i} - x'_{f,i}}{i}\right)$.

Proof. SSD requires that $x'_{f^*,i} \geq x'_{g,i}$, $\forall i$. If we add a non-stochastic payment (s) for land use f, we get the cumulative sorted series for f^*:

$x'_{f^*,i} = \sum_{t=1}^{i}\left(x_{f,t} + s\right) = \sum_{t=1}^{i} x_{f,t} + i \cdot s = x'_{f,i} + i \cdot s$. Replacing the latter expression in the former gives $x'_{f,i} + i \cdot s \geq x'_{g,i}$, and $s \geq (x'_{g,i} - x'_{f,i})/i$, $\forall i$. Thus, $s = Max_i\left(\frac{x'_{g,i} - x'_{f,i}}{i}\right)$.

Proposition 2b. The payment level that guarantees that *f* would not be dominated by *g* in second degree is $s = Min_i \left(\frac{x'_{g,i} - x'_{f,i}}{i} \right)$.

Proof. The proof follows the same reasoning as for 1b and 2a. Since we just need one i where

$s \geq (x'_{g,i} - x'_{f,i})/i$ holds, the minimum of the differences is enough.

The proofs for the $s_{\min}$ and $s_{\max}$ conditions in the cases of FMCSD and SMCSD follow the same line of reasoning as in the preceding propositions, but use the series sorted according to revenue portfolios ($\mathbf{x}_f^{\mathrm{w}}$, $\mathbf{x}_g^{\mathrm{w}}$) instead of ones sorted by individual land-use revenue portfolios ($\mathbf{x}_{\mathrm{f}}$, $\mathbf{x}_{\mathrm{g}}$).

B. Linear Programming Solution for Conservation Payments under SMCSD

We find $s_{\min}$ under FMCSD and SMCSD by solving the following LPs:

FMCSD

$$
\begin{aligned}
& s_{\min} = \max_{\Omega, v_g, v_h} \Omega \\
& s.t. \\
& \Omega \leq \left((v_g x^{\mathrm{w}}_{g,i} + v_h x^{\mathrm{w}}_{h,i}) - x^{\mathrm{w}}_{f,i} \right) \quad i = 1,...,T \\
& v_g + v_h = 1 \quad \text{and} \quad v_g, v_h \geq 0
\end{aligned}
$$

SMCSD

$$
\begin{aligned}
& s_{\min} = \max_{\Omega, v_g, v_h} \Omega \\
& s.t. \\
& \Omega \leq \frac{1}{i} \left(\left(v_g x^{\mathrm{w}\,\prime}_{g,i} + v_h x^{\mathrm{w}\,\prime}_{h,i} \right) - x^{\mathrm{w}\,\prime}_{f,i} \right) \quad i = 1,...,T \\
& v_g + v_h = 1 \quad \text{and} \quad v_g, v_h \geq 0
\end{aligned}
$$

We introduce the variable Ω in order to solve the max-min problem. We maximize Ω in order to compare our forest returns with the most efficient combination of alternative crops (that is, the choice of v_g and v_h should be the one that leads to the largest difference between the returns of forestry and cropping). But, because we want to estimate the minimum of the differences between cropping and forest returns among all states of the world, we add the constraint that Ω should be less than or equal to this difference for all states $i = 1,\ldots,T$. In this way Ω will give the solution to the max-min problem where the "max" part of the problem is in the objective function and the "min" part is in the inequality.

The objective function for the max-max problem is linear, so the LP solution gives the extreme values v_g =1 and v_h =0, or vice versa. Thus, the maximum bound (s_{max}) is calculated in two steps. First, make a pair-wise comparison between forest and all other crops and find s_{max} for each comparison, following equations (10) and (11). Then, choose the larger s_{max}.

C. Test for trends

We tested for trends in price and yield using an OLS regression based on the model,

$$y_t = a + bt + e_t,$$

Where y_t is the dependent variable (either yield of price) and; a and b are regression coefficients. Note that testing yield and price separately is adequate given the small correlation between both series in the case of rice, maize and pasture. But, for coffee there is some correlation between price and yield (correlation coefficient is 0.16), so we also tested the net revenue trends. The output of the analysis is,

1. Coffee price

Variable	Coefficient	Std. Error	t-Statistic	Prob.
a	0.228812	0.027709	8.257677	0.0000
b	-0.001783	0.001362	-1.309241	**0.1992**
R-squared	0.047995			

2. Coffee yield

Variable	Coefficient	Std. Error	t-Statistic	Prob.
a	852.7098	64.26242	13.26918	0.0000
b	-0.003361	3.157690	-0.001064	**0.9992**
R-squared	0.000000			

3. Coffee net revenues

Variable	Coefficient	Std. Error	t-Statistic	Prob.
a	100.5280	28.28191	3.554499	0.0011
b	-1.264187	1.389700	-0.909683	**0.3694**
R-squared	0.023761			

4. Maize price

Variable	Coefficient	Std. Error	t-Statistic	Prob.
a	0.145698	0.012022	12.11932	0.0000
b	0.000149	0.000591	0.252075	**0.8025**
R-squared	0.001865			

5. Maize yield

Variable	Coefficient	Std. Error	t-Statistic	Prob.
a	580.6986	68.36178	8.494492	0.0000
b	27.15182	3.359122	8.083010	**0.0000**
R-squared	0.657724			

6. Rice price

Variable	Coefficient	Std. Error	t-Statistic	Prob.
a	0.218635	0.010695	20.44188	0.0000
b	-0.002540	0.000526	-4.833288	**0.0000**
R-squared	0.407259			

7. Rice yield

Variable	Coefficient	Std. Error	t-Statistic	Prob.
a	1295.655	111.3049	11.64059	0.0000
b	4.326592	5.469237	0.791078	**0.4344**
R-squared	0.018073			

8. Meat price

Variable	Coefficient	Std. Error	t-Statistic	Prob.
a	0.866861	0.081230	10.67167	0.0000
b	0.001955	0.003991	0.489915	**0.6273**
Adjusted R-squared	-0.022196			

9. Milk price

Variable	Coefficient	Std. Error	t-Statistic	Prob.
a	0.179844	0.004343	41.40959	0.0000
b	0.000202	0.000213	0.944475	**0.3516**
Adjusted R-squared	-0.003094			

For maize yield and rice price, the null hypothesis of no-trends is rejected under a 5% significant level. For the other series, the null hypothesis is accepted.

Chapter 6
Summary and Conclusions

Climate change is a complex problem. It requires making decisions for preventing damages affecting 3 or 4 generations beyond with limited knowledge of how costly these damages would be, where such damages would occur, what are the greenhouse gas (GHG) emissions in a business-as-usual scenario for the next century, and how expensive are a large number of GHG mitigation strategies. This research focuses on this last aspect, the costs of some measures of GHG mitigation. Particularly, it deals with the economics of carbon mitigation in forests. This thesis contributes to policy decision-making within the climate change debate and provides theoretical contributions in the fields of forestry and agricultural economics.

The separate articles of this thesis include summaries of the main results and concluding paragraphs. Therefore, this chapter only provides a synthesis of major findings and recommendations for future research. Conclusions are divided into 3 major themes of this thesis: (1) comparison of land-use alternatives and carbon accounting methods, (2) cost curves for carbon sequestration at a regional and global level and (3) farm-level risk and its impact on the supply of ecosystem services.

Comparison of Land-Use Alternatives and Carbon Accounting Methods

There are diverse ways in which to enhance carbon uptake in forests. Forests could be artificially planted (tree-plantations) or forests could be the consequence of natural regeneration (secondary forests). Both systems lead to carbon uptake, but differ in their management practices, costs, and timber and carbon benefits. Tree-plantations have the advantage of providing more timber than secondary forests. But, in order to achieve an increase in timber production, plantations require higher investments in tree-planting and management.

Natural regeneration of secondary forests is a cost-efficient carbon mitigation activity in the humid tropics and should be considered as a policy option within the Kyoto Protocol. This was found in Chapter 2 through the comparison of costs and benefits of relevant land-use alternatives in distinct zones of Northwest Ecuador. This comparison showed that pasture is always a better option than forestry and that in order for afforestation to be viable it would always require payments associated with the environmental services of forests, e.g. payments for carbon uptake. It was found that secondary forests are economically more attractive than tree-plantations (laurel) and compensation costs per ton of CO_2 are lower for secondary forests than for plantations. These costs are also lower than predicted prices for CO_2 allowances within the Kyoto Protocol for the first commitment period (2008-2012). Natural regrowth of secondary forests - once accepted within the Clean Development Mechanism (CDM) - could play an important role as an effective and efficient project activity. This finding is even strengthened when further ancillary benefits of secondary forests are taken into account, such as soil and water protection or biodiversity conservation. We could expect that carbon uptake in secondary forests is not only attractive for Ecuador, but also for the humid tropics in general, where similar ecologic and economic conditions hold.

Different ways for carbon accounting exist and this has been debated within the United Nations Framework Convention on Climate Change (UNFCCC). In a recent decision, the Conference of the Parties of the UNFCCC, during its Ninth Session (COP9) in 2003, agreed on two possible ways for accounting certificates of emission reduction (CER) within the CDM: temporary (tCER) and long-term (lCER) crediting. Under both systems CER have an expiration date and thereafter the country that owns the certificate must acquire a new one or find a permanent solution to fulfill the emission reduction commitments. The main difference between tCER and lCER is the expiration date: the first ones expire at the end of commitment periods and the latter expire at the end of the project's crediting period or project's lifetime. This implies that revenues for carbon uptake are obtained earlier for lCER accounting than for tCER accounting (as shown in Chapter 2).

The cost-benefit analysis performed in Northwest Ecuador (Chapter 2) shows that long-term crediting is economically more attractive than temporary crediting. This advantage is particularly evident in the case of secondary forests where there are no clear-cuts within the project cycle. In this case, benefits of carbon uptake under the lCER method are 20% higher than those of the tCER method. The gains of lCER accounting over tCER are likely to hold in the general case for CDM projects excepting those situations with clear-cuts within the project cycle.

The methodology presented in Chapter 2, where carbon sequestration costs are estimated on the basis of the difference of net revenues of forest and non-forest land uses, is meant to support the decision making process regarding the supply side of a future CER market. Focusing on the development aspect of CDM means that forestry projects within this mechanism should generate higher income than the status quo. The case-study in Northwest Ecuador showed that there are zones (coastal area) where net revenues of current land uses are low and landowners would be better off by converting their land into forests by means of the CDM, but there are also other zones (closest to the capital) where land is highly suitable for agriculture and landowners would gain nothing by planting trees in their productive lands. Thus, developing countries should carefully evaluate the opportunity costs of land-use changes before taking decisions in favor of afforestation. The methodology used in Northwest Ecuador is easy-to-apply and it could be used by developing countries as a standard procedure for assessing the net benefits of potential CDM afforestation projects.

Aggregated Supply for Carbon Sequestration

Developing countries harbor large potential for carbon sequestration. However, economic studies on carbon sequestration in these countries have provided only average costs of carbon sequestration, excluding cost curves that assess how these costs increase when large-scale afforestation programs are implemented. Chapter 3 describes a framework for deriving forestry-based carbon uptake cost curves. The method is based on determining sequestration costs for geographical units whose coordinates are known (grid-cells). For each unit, spatial information obtained from Geographical Information Systems (GIS) datasets was used for estimating carbon uptake, timber production and land and timber prices. Advantages of this approach are: (i) There is no need to entirely depend on comprehensive data that are often scarce in developing countries, while major parameters are estimated indirectly from available, more general databases and GIS datasets. (ii) Results are obtained for each grid-cell, so that maps with the geographical distribution of carbon costs are elaborated. This facilitates comparison across countries and identification of least-cost regions for carbon sequestration. (iii) Supply-curves are estimated for multiple years to support decision making at different stages of the UNFCCC process. (iv) Estimation of sequestration costs accounts for the entire life-cycle of the sequestered carbon, including carbon uptake during the growing phase, carbon emissions during harvest, and residual carbon storage in short- and long-lived products. This method was used for assessing the carbon supply in Latin America (Chapter 3) and globally (Chapter 4).

Latin America could offset a substantial proportion of its emissions by tree-planting at relatively low carbon prices. As shown in Chapter 3, long-term estimates of the cumulative sequestration potential for 100 years imply that afforestation could offset 7 years of Latin American emissions in the energy sector at a carbon price of \$20/tC. When the carbon price rises to \$50/tC, 23 years of the Latin American emissions are compensated through afforestation. Focusing on the emissions reduction target for the Kyoto Protocol in 2012, Latin America could share an important part of the market for CDM sinks. Given a price of \$20/tC, 125 MtC would be fixed by 2012 which equals 75% of the cap on CDM-sinks that has been set for the first commitment period of the Kyoto Protocol. This scenario would require planting trees in 4.8 million hectares, with afforestation taking place mostly in tropical countries like Brazil and Colombia. Economic gains are expected in these countries and rural areas would benefit from foreign investment associated with the CDM of the Kyoto Protocol.

Country-risk has a strong influence in the global supply for carbon. Forestry investors are aware of the enormous differences in country attractiveness for investing throughout the globe. For example, investors in Canada would pay little attention to risk associated to corruption, wars, terrorism and riots; while investors in Sierra Leone and Somalia might fear these risks and demand a risk premium. Chapter 4 compared the carbon supply in two scenarios: a benchmark scenario without risk considerations and a scenario with risk-adjusted discount rates for every country. Risk-adjusted discount rates for forestry investments in each country were estimated based on the capital asset pricing model (CAPM). In the absence of equity markets in most developing countries, required returns for forestry investments are determined as a function of the composite International Country Risk Guide index that aggregates political, financial and economic risk for each country. Results showed that in a without-risk scenario, the global supply of carbon at a price of $50/tC during a 20 year period would be 6.9 GtC. But, in the second scenario that includes country-risk, the supply for carbon sequestration is 59% less. The strong impact that country-risk has on GHG mitigation in sinks could be generalized to other sectors. For example, country-risk influences investment in renewable energy sources like hydropower, wind and solar. The rate of investment in these activities depends on factors like economic stability, government credibility, exchange rate volatility and market regulations.

Afforestation is an important policy option that reduces global costs of carbon mitigation. In Chapter 4, global emissions reductions through afforestation (in the scenario of risk-adjusted discount rates) were compared with the required emission reductions of various climate policy scenarios given by Integrated Assessment Models (RICE-99). It was found that, (1) Afforestation is an important option for global warming mitigation, where its potential carbon uptake ranges from 5% to 25% of the emissions reduction targets of different policy scenarios. (2) Policy scenarios requiring larger emission abatement would need a larger share of emission reductions through afforestation than those with smaller abatement. The relevance of afforestation as a policy option suggests evaluating other land use activities. For example, we could expect more efficiency gains when the CDM includes deforestation prevention, forest regeneration, agroforestry and cropland and grazing land management.

The majority of least-cost sites for afforestation are located in Africa, South America and Asia. This was illustrated by grid-scale maps included in Chapter 4. Carbon sequestration through afforestation would most likely represent significant investment from industrialized countries in developing countries. Therefore, policy makers should pay special attention to capacity building and to strengthen institutions in developing countries in order to facilitate the engagement of investors in the prompt start of large-scale afforestation projects.

Risk at the Farm Level and its Impact on the Supply of Ecosystem Services

Conservation payments can be used to preserve forest and agroforest systems in developing countries and prevent the release of carbon emissions. To explain landowners' decisions and determine the appropriate payment for conservation, it is necessary to account for risk associated with agricultural price and yield volatility. Two methods are often used for risk assessment in agriculture: (i) the Mean Variance Approach (M-V) and (ii) Stochastic Dominance (SD).

In evaluating the risk-efficiency of conservation payments SD could be more appropriate than M-V for the following reasons. M-V requires that returns are normally distributed or the decision-maker's utility function is quadratic, conditions not always met when considering forests and other natural resource assets. In contrast, SD sets minimum restrictions on landowners' utility functions and is valid for all types of return distributions. Also, M-V fails to show dominance in cases where almost every farmer would prefer one land use over another. Suppose that a landowner is to choose between land uses *A* and *B*, where $\sigma_A > \sigma_B$. No matter how much greater E(*A*) is than E(*B*), the M-V approach is unable to tell us that *A* is unambiguously better than *B*. It is unable to recommend a (risk-free) conservation payment that would make the landowner choose land use *A* over *B*. However, under the SD rule, there would always be a level of payment that would make one land use a better choice than the other.

Chapter 5 contributes to the application of SD theory in agricultural economics by extending the SD tests for fully-diversifiable portfolios (or farms) and the use of first and second order marginal conditional stochastic dominance. Based on these rules, two efficiency measures for evaluating forestland are introduced: (1) payments s_{min} that guarantee that at least *some* landowners consider forestry as the optimal land use; and (2) payments s_{max} where *all* landowners find forestry the optimal land use. Large values of s_{min} (relative to the mean) represent land uses that are least risk-efficient, while small values of s_{max} represent risk-efficient land uses that nearly dominate all other land uses. Knowledge of s_{min} and s_{max} helps to identify intervention strategies – e.g. payments for conservation – that can be implemented for attaining environmental goals at the lowest cost.

The SD methodology was applied to a West Ecuador case study, where shaded-coffee is compared with relevant land-use alternatives of the region. Results indicate that (1) shaded-coffee is not a risk-efficient land use, no matter whether diversification is possible or not. This goes a long way towards explaining current land uses. (2) The payments required to preserve shaded-coffee when risk is taken into account are much higher than the compensation payments calculated under the assumption of risk-neutrality. (3) The extant distribution of land uses has a strong impact on the required conservation payment. (4) Land-use policy interventions need to incorporate risk-hedging strategies and insurance possibilities for small farmers, instruments that are slowly developing in Ecuador's financial markets. As shown in Chapter 5, pasture is a risk-hedging land use rather than a profit-maximizing land use. If revenue insurance is available for shaded-coffee producers, this could replace the use of pasture for risk-hedging and deforestation could be prevented.

Results of the case-study of West Ecuador in Chapter 5 could be generalized in the context of conservation policies and payments for carbon sequestration worldwide. The landowners' choice for afforestation or deforestation depends on net returns and risk, and efficient conservation policies should look at both. When the forestry alternative is subject to risk, payments for conservation would most likely require a risk-premium. This risk-premium is not only dependent on the risks of forestry, but also on the extant land-use allocation of farms and risks associated with non-forest land uses. Combining payments for conservation with risk-hedging strategies is a policy option to be considered by conservation agencies worldwide.

Suggestions for Further Research

This research dealt with the supply of carbon sequestration through afforestation and showed that this mitigation alternative could represent an important share of global emission reductions (from 5% to 25% depending on the policy scenario). The next step is to evaluate the potential and costs for other carbon sequestration alternatives like: forest regeneration, deforestation prevention, agroforestry, and cropland and grazing land management. For such analysis, the methodology used throughout this thesis is applicable. For example, when dealing with case-studies and evaluating farm-level decisions regarding land use change, the approach used in Chapters 2 and 5 could be a starting point. When estimating cost curves at a regional or global level for the alternative carbon sequestration activities, the methodology used in Chapters 3 and 4 is valid.

Natural forests and plantations would be affected by climate change. In one hand, forest growth would increase due to higher CO_2 atmospheric concentrations and the so-called CO_2 fertilization effect. In the other hand, climate change would increase the risk of fire and pest attacks. Further research is needed in order to evaluate how climate change would influence the costs and potential of long-term afforestation projects.

Chapter 5 discussed how risk-free payments influence land-use choices. Given our findings that risk is a decisive factor, the implementation of risk-hedging strategies is expected to have a strong influence on land use. Therefore, further research is needed in order to investigate how sustainable land uses could be encouraged when risk reduction policies like weather insurance, forward contracts, and options are implemented.

Chapter 5 dealt with the problem of land-allocation under uncertainty in a static manner. But, crops' yields and prices often follow time-trends. This would cause decisions been time-varying. It would be of interest to have extensions of the application of stochastic dominance in a more dynamic framework. In addition, land allocation decisions involve the possibility of irreversibilities (e.g. destroying forest canopy from a shaded-coffee parcel) that would create option value to land clearing. Further research is needed for accounting these aspects in the estimation of efficient policy instruments that aim forest conservation.

Throughout this thesis, risk is considered at the micro and macro levels. At the micro level, Chapter 5 evaluated risk perceived by landowners and its impact on land allocation between crops and forests. At a macro level, Chapter 4 considered country risk associated with political, economic and financial aspects and its impact on the investor's choice for allocating funds in carbon sequestration programs. Both levels of risk are related and have a cause-effect relationship. Further research is needed in order to link them and evaluate how policies could be implemented for reducing risk at both levels.

Resumen

Ensayos Económicos sobre la Fijación de Carbono en Bosques

Introducción

El cambio climático es un problema controversial y complejo. Para tomar decisiones acertadas sobre cómo actuar frente al calentamiento global del planeta cuyos impactos en la humanidad se esperan en un lapso de 100 años, debemos tener pleno conocimiento de (entre otros): la magnitud de estos impactos, dónde ocurrirán estos impactos, cuáles serán las emisiones de gases de efecto invernadero (GEI) a nivel mundial en los próximas décadas y cuánto nos costará mitigar estas emisiones. Desafortunadamente, nuestro conocimiento sobre estos temas es todavía limitado y las decisiones en el contexto de políticas de cambio climático se las hace parcialmente a ciegas.

Un punto central para la toma de decisiones con respecto al calentamiento global es determinar cuán costoso es mitigar las emisiones de GEI. Hay diversas formas de mitigar estas emisiones y se clasifican en dos grupos: la reducción de emisiones en el sector energético, y la reducción de emisiones por cambios en el uso del suelo y actividades forestales. Esta tesis trata sobre la segunda opción y tiene un enfoque en el sector forestal.

El Mecanismo de Desarrollo Limpio (MDL) del Protocolo de Kyoto (PK) de Cambio Climático permite que países industrializados inviertan en proyectos de reducción de emisiones en países en vías de desarrollo con el fin de cumplir con sus obligaciones dentro del Protocolo. Para el primer período de compromiso del PK (2008-2012), el MDL en el sector forestal es limitado: solo se permite proyectos de aforestación y reforestación[1] y las emisiones reducidas mediante estas actividades no pueden ser mayor al 1% de las emisiones de los países industrializados. Sin embargo,

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[1] De acuerdo a la Convención Marco de Cambio Climático las actividades de aforestación y reforestación difieren únicamente en el tiempo durante el cual el suelo permaneció sin cobertura boscosa. Por simplicidad, se utiliza el término aforestación para las dos actividades.

para los siguientes períodos de compromiso las decisiones dentro del PK están abiertas a discusión. Por ello es importante determinar cual es el potencial de reducción de emisiones mediante actividades forestales a un mediano y largo plazo de tal forma que esta información se la tome en cuenta para el futuro del PK.

El objetivo principal de este estudio es analizar aspectos económicos fundamentales que determinan la fijación de carbono en bosques. Existen tres temas principales de discusión en esta tesis: (1) la comparación de costos de fijación de carbono en distintos sistemas forestales bajo diferentes sistemas de contabilidad del carbono, (2) la evaluación de curvas de oferta de fijación de carbono mediante proyectos de aforestación a nivel regional (América Latina) y global, y (3) el análisis de riesgos a nivel de finca y su impacto en la oferta de fijación de carbono y otros servicios ambientales. Esta investigación incluye estudios de caso en las provincias de Esmeraldas y Manabí en Ecuador.

Costos de Sistemas Forestales y Contabilidad del Carbono

Existen diversos sistemas para la captura de carbono en bosques. Los bosques pueden ser plantados de forma artificial (plantaciones forestales), o los bosques pueden ser la consecuencia de la regeneración natural (bosques secundarios). Estos sistemas forestales difieren en su manejo, costo, producción de madera y rendimiento en la fijación de carbono. En general, las plantaciones tienen una mayor productividad de madera, pero para ello, requieren mayores inversiones en plantación y manejo.

La regeneración natural de bosques secundarios es una actividad costo-eficiente para la mitigación de GEI y es recomendable que se la tome en cuenta dentro del MDL. Esto se determinó en el Capítulo 2 de esta tesis donde se compararon costos y beneficios de usos del suelo en tres zonas de la provincia de Esmeraldas, Ecuador (zonas Norte, Costanera y Sur). Se encontró que es más económico fijar carbono mediante regeneración natural de bosques secundarios que mediante plantaciones. En las tres zonas de estudio que tienen características ecológicas y económicas distintas, los costos por tonelada de fijación de carbono en bosques secundarios son menores que los costos en plantaciones. También se encontró que en dos zonas (Norte y Costanera de Esmeraldas) los costos de fijación de carbono son menores a los precios esperados de permisos de emisión de GEI en el período 2008-2002. Esto implica que la regeneración natural de bosques secundarios, una vez aceptada dentro del MDL, podría jugar un papel importante en la mitigación de emisiones en bosques y convertirse en una fuente de ingreso adicional para los agricultores. Las ventajas de los bosques secundarios se ven incrementadas cuando se toma en cuenta otros servicios ambientales que ellos proveen, tal como es la protección de cuencas hidrográficas y la conservación de los suelos. Es de esperar que la opción de utilizar bosques secundarios para fijación de carbono no sea atractiva únicamente para el Ecuador, sino también para otras regiones húmedas tropicales donde existen similares condiciones ecológicas y económicas.

El sistema de contabilidad para la captura de carbono en bosques ha sido un tema de intenso debate en la Convención Marco de las Naciones Unidas de Cambio Climático. Recientemente, la Convención en su Novena Sesión en 2003 decidió que dos sistemas de contabilidad son permitidos en el marco del MDL forestal: créditos temporales (tCER) y créditos de larga duración (lCER). Bajo los dos sistemas, los créditos de reducción de emisiones tienen validez limitada, y a su fecha de expiración el país dueño de estos créditos deberá reemplazarlos o buscar una solución permanente para reducir sus emisiones. Estos sistemas de contabilidad difieren en su período de validez: los lCER expiran al final de períodos de compromiso del PK y los tCER expiran al final del tiempo de validez del proyecto. Esto implica (como se demuestra en el Capítulo 2) que los ingresos por fijación de carbono bajo el sistema lCER son recibidos antes que los ingresos en el caso de tCER.

El análisis costo-beneficio realizado en la provincia de Esmeraldas muestra que lCER es más atractivo que tCER. Esta ventaja es evidente en el caso de bosques secundarios donde no existen talas rasas del bosque durante el ciclo del proyecto. En este caso, los pagos por fijación de carbono con el método lCER son 20% mayores que aquellos pagos con el método tCER. Esta ventaja del sistema lCER puede generalizarse para proyectos MDL en otros países donde el diseño del proyecto excluya talas rasas del bosque hasta el final del proyecto.

El método presentado en el Capítulo 2, donde los costos de fijación de carbono se estiman en base a la diferencia de ingresos netos de bosques y usos del suelo alternativos, permite tomar decisiones en cuanto a la participación o no en el MDL. Proyectos MDL forestales fomentan el desarrollo de un país o región siempre y cuando ellos brinden un mayor ingreso que los usos del suelo actuales. El estudio de caso en Ecuador muestra que en algunas zonas (Norte y Costanera de Esmeraldas) esto sucede, mientras que en otras zonas (Sur de Esmeraldas), los agricultores estarían a pérdida cuando son partícipes de proyectos de aforestación. Por lo tanto, países en vías de desarrollo deberán analizar cuáles son las zonas más favorables para estos proyectos en base a la evaluación de sus costos de oportunidad y beneficios forestales. La metodología utilizada en los trópicos de Ecuador puede ser utilizada como un modelo estándar para la evaluación de los beneficios netos del MDL forestal en otros países.

Curva de Oferta de Fijación de Carbono

El Protocolo de Kyoto permite la compra y venta de certificados de reducción de emisiones. Esto implica que existirá una oferta y demanda para la fijación de carbono. La demanda depende de los países industrializados que tienen compromisos en la reducción de emisiones y la oferta depende de los países con áreas aptas para la aforestación. Estudios anteriores han determinado que los países en vías de desarrollo disponen de grandes extensiones de terreno aptas para la aforestación. Sin embargo, las investigaciones que se han realizado en estos países se han limitado únicamente a proveer información sobre costos promedios de fijación de carbono asociados a proyectos específicos, excluyendo curvas de oferta que indican como varían los costos cuando programas más grandes de aforestación son implementados.

En el Capítulo 3 se describe un marco metodológico para evaluar curvas de oferta de fijación de carbono. El método consiste en dividir la región de estudio en pequeñas *celdas* con coordenadas geográficas conocidas y determinar los costos de fijación de carbono en cada celda. Estos costos se estiman de manera indirecta a partir información ecológica y económica proveniente de bases de datos espaciales asociadas a Sistemas de Información Geográfica (SIG). Las ventajas de esta metodología son: (1) No es necesario depender de estadísticas de uso del suelo a nivel de país, pero muchos parámetros son estimados en base a información disponible en bases de datos globales asociadas a SIG de fácil acceso. (2) Los resultados de costos de fijación de carbono se obtienen para cada celda. Esto permite identificar las zonas de menor costo y elaborar mapas que indican la distribución geográfica del potencial y costo en la fijación de carbono. (3) El modelo proporciona curvas de oferta de fijación de carbono en distintos años, convirtiéndose en una herramienta versátil para la toma de decisiones en los distintos períodos de negociación asociados al Protocolo de Kyoto. (4) Al estimar los costos de fijación de carbono, se toma en cuenta la captura de carbono durante el crecimiento del bosque, las emisiones de carbono en los períodos de extracción de madera y la fijación de carbono en los productos del bosque. Este método fue utilizado con el fin de evaluar la oferta de carbono en América Latina (Capítulo 3) y a nivel global (Capítulo 4).

América Latina puede compensar una cantidad importante de sus emisiones de GEI del sector energético mediante la fijación de carbono en bosques a un costo relativamente bajo. Como se determinó en el Capítulo 3, la implementación de proyectos de aforestación por un lapso de 100 años permite que la fijación de carbono en estos nuevos bosques compense 7 años de emisiones en el sector energético a un costo de $20/tC. Si el precio de fijación de carbono sube a $50/tC, proyectos de aforestación pueden compensar hasta 23 años de emisiones. Con respecto al mercado de reducción de emisiones asignadas bajo el Protocolo de Kyoto para el año 2012, América Latina puede satisfacer una buena parte del mercado del MDL forestal. Tomando en cuenta un precio de $20/tC, un total de 125 MtC pueden ser fijadas, lo cual equivale al 75% del mercado del MDL forestal. En este escenario, la mayoría de las plantaciones serán establecidas en zonas tropicales en Brazil y Colombia. Se espera que áreas rurales en estos países se beneficien de la inversión extrajera asociada al MDL.

El riesgo-país tiene gran influencia en la oferta de fijación de carbono a nivel global. Es muy probable que los inversionistas forestales tomen en cuenta las diferencias entre países con respecto a las garantías que ellos proveen para la inversión en proyectos de largo plazo. Por ejemplo, inversionistas en Canadá prestarán poca atención a riesgos relacionados con corrupción, guerras, terrorismo, levantamientos populares y volatilidad en la tasa de cambio; mientras que inversionistas en Sierra Leona o Somalia tomarán muy en cuenta estos riesgos antes de tomar la decisión de iniciar proyectos de aforestación en ellos. En el Capítulo 4 se evalúa la curva de oferta de carbono bajo 2 escenarios: un escenario de referencia donde no se incluye riesgos y un escenario con tasas de descuento ajustadas acorde al riesgo país. Por medio de extensiones del Modelo de Valoración de Activos del Capital (*CAPM*), se estimaron tasas de descuento ajustadas al riesgo para proyectos forestales. Tomando en cuenta que no existen bolsas de valores en muchos países en vías de desarrollo, tasas de retorno para proyectos forestales se determinaron como una función del índice *ICRG* (Guía Internacional de Riesgo País) que agrega riesgos asociados a factores políticos, financieros y económicos para cada país. Los resultados muestran que en el escenario de referencia, la oferta de carbono a un precio de $50/tC durante 20 años es de 6.9 GtC. Pero, cuando se incluye riesgo-país en el análisis, la oferta de carbono disminuye en un 59%. El impacto significativo que tiene el riesgo-país en la oferta de mitigación de emisiones puede ser generalizado para otros sectores. Por ejemplo, la inversión en proyectos de energías renovables como son la energía hidroeléctrica, eólica y solar dependerá mucho de factores asociados a estabilidad económica, credibilidad de gobiernos, volatilidad en la tasa de cambio y corrupción; factores que están representados en los indicadores de riesgo-país.

Aforestación es una actividad que permite reducir los costos globales de mitigación de carbono. En el Capítulo 4 se comparó la reducción de emisiones mediante aforestación (en el escenario de tasas de descuento ajustadas al riesgo) con la reducción de emisiones de varios escenarios de mitigación incluidos en Modelos de Evaluación Integral de Cambio Climático (específicamente el modelo *RICE-99*). Se encontró que el potencial de fijación de carbono asociado a actividades de aforestación equivale a un 5% - 25% de la reducción de emisiones requeridas en los distintos escenarios de mitigación. También se determinó que en los escenarios de mitigación más estrictos (los que requieren una mayor reducción en las emisiones) la proporción de reducción de emisiones por medio de aforestación es mayor.

La mayoría de los sitios de menor costo para la fijación de carbono están en África, América Latina y Asia. Esto se determinó en el Capítulo 4, donde la ventaja comparativa de estas regiones está ilustrada en mapas SIG. Se espera que en un corto y mediano plazo, proyectos de aforestación representen inversiones de países industrializados en países en vías de desarrollo. Para que esto ocurra, sin embargo, es necesario mejorar la capacidad en el diseño e implementación de proyectos forestales en estos países y también fortalecer las instituciones involucradas (e.g. organismos de investigación y producción forestal, comercializadoras de madera, bancos, aseguradoras).

Riesgos a Nivel de Finca y su Impacto en la Oferta de Servicios Ambientales

Los bosques y sistemas agroforestales producen una variedad de beneficios globales como fijación de carbono y conservación de la biodiversidad. Pero, sin pagos por estos servicios, estos usos del suelo son frecuentemente inatractivos. Entre los motivos principales para la conversión de bosques a otros usos están los bajos ingresos y altos riesgos. Para evaluar riesgos en los usos del suelo agrícola y forestal es común utilizar dos métodos: el modelo de Media-Varianza (M-V), y la Dominancia Estocástica (DE).

Como se explica en el Capítulo 5, DE es una herramienta más adecuada para la evaluación de pagos por sistemas ambientales que M-V. Las principales razones son: M-V requiere que los ingresos netos tengan una distribución normal o que la función de utilidad del agente de decisión sea cuadrática. Estas condiciones no siempre se cumplen para proyectos forestales. Al contrario, DE requiere muy pocas restricciones en la función de utilidad del agente de decisión y es válida para cualquier tipo de distribución de ingresos. También, M-V es una herramienta que no puede determinar cual es el pago por servicios ambientales en ciertas situaciones. Por ejemplo, supongamos que un agricultor tiene que elegir entre el uso agrícola del suelo (A) y el uso forestal (F), donde la media de A es mayor a la media de F, $E(A) > E(F)$, y la desviación media de F es mayor que la desviación media de A, $\sigma_F > \sigma_A$. En base del modelo M-V no es posible determinar cual es el pago por servicios ambientales que garantiza que todos los agricultores prefieran el uso forestal sobre el uso agrícola. Por más grande que sea el pago por servicios ambientales (y por lo tanto el incremento de $E(F)$), el modelo M-V no puede decir que el uso del suelo forestal será siempre el preferido. Al contrario, bajo la regla de DE, siempre existirá un pago que motivará que todos los agricultores prefieran el uso del suelo forestal sobre el agrícola.

El Capítulo 5 de esta tesis contribuye a la aplicación de la teoría de DE en la economía agrícola y forestal al extender pruebas de DE a situaciones en las cuales los portafolios (o fincas) se pueden diversificar, es decir, situaciones en las que se pude dividir una finca en dos o más usos. Para ello se utiliza las reglas de Dominancia Estocástica Condicional Marginal de primer y segundo orden. En base a estas reglas, se introducen dos medidas de eficiencia para evaluar proyectos forestales: pagos s_{min} que garantizan que por lo menos algún agricultor considere al bosque como uso óptimo del suelo, y pagos s_{max} que garantizan que todos los agricultores consideren al bosque como uso óptimo del suelo. Conocimiento de pagos s_{min} y s_{max} permite identificar políticas de intervención como son los pagos por servicios ambientales.

El café con sombra en la provincia de Manabí, Ecuador provee importantes servicios ambientales relacionados a la fijación de carbono y la protección de la biodiversidad. Por ello, se utilizó el método DE para evaluar posibles pagos por servicios ambientales asociados a cultivos de café con sombra. Los resultados del estudio de caso ilustrado en el Capítulo 5 indican que: (1) el café con sombra no es un uso del suelo eficiente y esto explica las tendencias actuales de conversión de uso del suelo, (2) los pagos requeridos para conservar cultivos de café con sombra cuando se toma en cuenta riesgos son significativamente superiores a aquellos pagos estimados cuando se asume neutralidad ante los riesgos, (3) la distribución existente del suelo tiene un impacto significativo en los pagos requeridos para la conservación del café con sombra, y (4) políticas de conservación deben incorporar estrategias de reducción de riesgos y programas de seguros para agricultores. Como se indica en el Capítulo 5, los agricultores utilizan parte de sus fincas para el cultivo de pastos con el fin de reducir riesgos en sus ingresos. Si se implementan sistemas de seguros que disminuyen la variabilidad en los ingresos netos del café con sombra, esto podría reemplazar el uso de pasto como estrategia de reducción de riesgos y prevenir la deforestación.

Los resultados del estudio de caso en Manabí, Ecuador pueden ser generalizados en el contexto de políticas de conservación y pagos por fijación de carbono en otras zonas tropicales. La decisión de los agricultores para aforestación o deforestación depende de los ingresos netos y riesgos. Es muy probable que para que los pagos por servicios ambientales sean efectivos, los propietarios del suelo requieran una prima sobre el riesgo. Esta prima no solo depende de los riesgos del proyecto forestal, pero también de la distribución del suelo existente y los riesgos asociados a usos del suelo no-forestales. Combinar pagos por conservación con estrategias de reducción de riesgo es una política que debe ser considerada por las agencias de conservación que trabajan en los trópicos.

Curriculum Vitae

Pablo César Benítez Ponce was born on June 9, 1974 in Quito, Ecuador. He completed his high school education at the American School of Quito. In 1998, he graduated in Chemical Engineering from the *Escuela Politécnica Nacional,* Quito. After his graduation, he completed a Master of Science in Environmental Sciences at Wageningen University. His Master thesis entitled *Economic and Environmental Aspects of Solid Waste Management in Quito-Ecuador* was awarded a *H.C. van der Plas* Prize. Since year 2000, he has been enrolled as a "sandwich" PhD at Wageningen University focusing on the economics of climate change mitigation in forests. He took the opportunity to combine his PhD studies with research projects in Ecuador, The Netherlands and Austria.

During 2000-2001 he worked for the CO_2 Project of the German Agency of Technical Cooperation (GTZ). During the year 2002 he worked for the Energy Research Centre of the Netherlands (ECN) and he was a participant in IIASA's Young Scientist Summer Program. In 2003, he returned to his home country, Ecuador for been part of the research staff of Bio-Sys Project of the University of Göttingen.

As part of his PhD studies, he successfully completed the Training and Supervision Plan of the Socio-Economic and Natural Sciences of the Environment (SENSE). In addition, he participated in PhD economic courses in Tilburg University (The Netherlands) and Lund University (Sweden).

Currently he is a consultant on environmental and resource economic issues.