Tropical Forest Research

Evaluation of the CO_2 sequestration potential of afforestation projects and secondary forests in two different climate zones of South America

Tropical Forest Research

Evaluation of the CO_2 sequestration potential of afforestation projects and secondary forests in two different climate zones of South America

Free de Koning, Roland Olschewski,
Edzo Veldkamp, Pablo Benítez,
Pablo Laclau, Magdalena López,
Mercedes de Urquiza, Tomás Schlichter

Eschborn, 2002

TOEB publication number: TWF-37e

Published by:
Deutsche Gesellschaft für
Technische Zusammenarbeit (GTZ) GmbH
Postfach 5180
D-65726 Eschborn, Alemania

Responsible:
Programa de Apoyo Ecológico (TÖB)
Dr. Claus Bätke, Elisabeth Mausolf

Authors:
Free de Koning[1,2], Roland Olschewski[3],
Edzo Veldkamp[2], Pablo Benítez[1],
Pablo Laclau[4], Magdalena López[1],
Mercedes de Urquiza[4], Tomás Schlichter[4]

Authors' contacts:

[1]: Proyecto CO2 - GTZ
Casilla 17-21-1925, Quito, Ecuador
e-mail: ppffdk@ecnet.ec

[2]: University of Göttingen
Institute of Soil Science and Forest Nutrition
Busgenweg 2, 37770 Göttingen, Germany

[3]: University of Göttingen
Institute of Forest Economy
Busgenweg 5, 37770 Göttingen, Germany

[4]: Instituto Nacional de Tecnología Agropecuaria
C.C. 277, 8400 S.C. de Bariloche, Argentina

Layout: Michaela Hammer

ISBN: 3-9801067-15-3

Nominal fee: 5,- €

Produced by: TZ Verlagsgesellschaft mbH, D-64380 Rossdorf

Preface

Adopted at the 1992 United Nations Conference on Environment and Development, at which 178 countries were represented, *Agenda 21* includes a section devoted to forests. Together with the UNCED Forests Statement, *Agenda 21* forms a basis for international cooperation on the management, conservation and sustainable development of all types of forests. The Rio resolutions also serve as the foundation for a process of national-policy modification designed to stimulate environmentally compatible sustainable development in both industrialized and emerging countries.

Ideally, *sustainable development* builds on three primary guiding principles for all policy-related activities: economic efficiency, social equity and ecological sustainability. With regard to the management of natural resources, this means that their global utilization must not impair future generations' developmental opportunities. With their myriad functions, forests in all climate zones not only provide one of humankind's most vital needs but also help preserve biological diversity around the world. Forest resources and wooded areas must therefore be sustainably managed, preserved and developed. Otherwise, it would neither be possible to ensure the long-term generation of timber, fodder, food, medicine, fuels and other forest-based products, nor sustainably and appropriately to preserve such other important functions of forests as the prevention of erosion, the conservation of biotopes, and the collection and storage of the greenhouse gas CO_2.

Implemented by the Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH on behalf of the German Federal Ministry for Economic Cooperation and Development (BMZ), the "Tropical Forest Research" project aimed to improve the scientific basis of sustainable forest development and, hence, to help implement the Rio resolutions within the context of development cooperation.

Application-oriented research served to improve our understanding of tropical forest ecosystems and their reciprocity with the economic and social dimensions of human development. The project also served to promote and encourage practice-oriented young German and local researchers as the basis for development and dissemination of ecologically, economically and socially appropriate forestry production systems.

Through a series of publications, the "Tropical Forest Research" project made the studies' results and recommendations for action available in a form that is generally comprehensible both to organizations and institutions active in the field of development cooperation and to a public interested in environmental and development-policy affairs.

I. Hoven	Dr. C. v. Tuyll
Head of Division: Environmental Policy, Protection of Natural Resources, Forestry; CSD, GDF	Head of Division: Rural Development
German Federal Ministry for Economic Cooperation and Development (BMZ)	Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH

Contents

List of tables

List of figures

Abbreviations

ABH	Age at Breast Height
Alo	Oxalate extracted aluminium
Alp	Pyrophosphate extracted aluminium
BD	Bulk Density
CDM	Clean Development Mechanism
CER	Certified Emission Reductions
COP	Conference of the Parties
CO_2	Carbon dioxide
Cp	Pyrophosphate extracted carbon
CV	Coefficient of Variation
DBH	Diameter at Breast Height
d	Discount rate
Feo	Oxalate extracted iron
Fep	Pyrophosphate extracted iron
FSU	Former Soviet Union
GTZ	Deutsche Gesellschaft für Technische Zusammenarbeit (German Technical Cooperation)
GWP	Global Warming Potential
ha	Hectare
i	Interest rate
INTA	Instituto Nacional de Tecnología Agropecuaria
IPCC	Intergovernmental Panel on Climate Change
JI	Joint Implementation
masl	metres above sea level

MC	Marginal costs
n	number of observations
n.a.	not available
NPV_F	Net Present Value of forestry land use
NPV_P	Net Present Value of pasture land use
OECD	Organization for Economic Co-Operation and Development
P_{CER}	Price of a Certified Emission Reduction unit
PL	Plantation forest
PPF-RN	Proyecto Asesoramiento Político en la Gestion Forestal y de Recursos Naturales
PRODESAR	Proyecto de Prevención y Control de la Desertificación para el Desarrollo Sustentable de la Patagonia
PV	Present value
SF	Secondary forest
SI	Site index
Sio	Oxalate extracted silica
SOC	Soil Organic Carbon
t CO_2	Metric tonne of carbon dioxide
t/ha	Metric tonne per hectare
UNFCCC	United Nations Framework Convention on Climate Change

Preface

The inclusion of carbon sinks in the Clean Developing Mechanism (CDM) defined in the 1997 Kyoto Protocol and the subsequent Conferences of the Parties (COPs) of the United Framework Convention on Climate Change (UNFCCC) has created a new potential source of income for forestry projects. Under the CDM, industrialised countries may invest in carbon sequestration in reforestation and afforestation projects in developing countries, and offset part of their domestic greenhouse gas emissions in order to comply with their commitments to the Kyoto Protocol. Additional income from carbon sequestration, one of the environmental services of forests, may stimulate landowners to switch part of their non-forest land to forest. Forests established within the framework of CDM should support sustainable development and can bring additional benefits such as the protection of biodiversity, water and soils. This new market has generated a need for methodologies to quantify and value carbon sequestration under different ecological and economic conditions.

For this reason the Tropical Ecology Support Program (TÖB) of the Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ, or German Technical Cooperation), together with the University of Göttingen in Germany, initiated the project "Evaluation of the CO_2 sequestration potential of afforestation projects and secondary forests in two different climate zones of South America". The two study areas were the north-western part of Ecuador and north-western Patagonia in Argentina.

In Ecuador the project was integrated within the GTZ project "Political Advice on the Management of Forests and Natural Resources" (PPF-RN), collaborating directly with the Ministry of Environment of Ecuador. In Argentina the related GTZ technical cooperation project was the "Project for the Prevention and

Control of Desertification for the Sustainable Development of Patagonia" (PRODESAR), with its operational counterpart INTA (National Institute for Agricultural Technology).

The overall objective was to determine the ecological and economic feasibility of carbon sequestration in the biomass and soils of secondary forests and plantation forests in Ecuador and Argentina, and to define the role carbon sequestration can have for forest management, forest policies, sustainable development, local economies, soil conservation and the combating of desertification.

This report is the final overall report. The project has also resulted in a series of technical reports that are referred to in the text.

We acknowledge the following persons and organisations for their support:

In Ecuador:

Wolfgang Lutz of the GTZ project PPF-RN, the Ministry of Environment of Ecuador, especially the National Forest Direction and the Climate Change Office, Virginia García, the landowners of forests and pastures who permitted us to collect all the information necessary, Fernando Montenegro and Lino Veloz of "Fundacion Forestal J.M.D.", Eduardo Beltran of "Unidad Coordinadora para el Desarrollo Forestal Sostenible de la Provincia de Esmeraldas", the team of the GTZ project "Manejo Forestal Comunitario Esmeraldas", Angel Suco of "Foundation Rainforest Rescue", Luis Fernando Jara of "Profafor", and Todd Smidt and Hugo Paredes of "Fundación Altropico".

In Argentina:

Werner Moosbrugger of the GTZ project PRODESAR, all the owners of the estancias who allowed us to collect information about pastures and forests, Raúl Hevia, and Esteban Bello for field assistance, Ernesto Andenmatten, Arrigo

Marcolín and María Luisa Lanciotti of INTA, Uriel Mele of the "Asentamiento Universitario de San Martín de los Andes", Raúl Fernandez of the "Subsecretaría de la Producción de Neuquén (Delegación San Martín de los Andes)", and Marcelo Rey and Carlos Bialaus of the "Servicio Forestal Andino de Río Negro".

In Germany:

Elisabeth Mausolf, Michaela Hammer, Rüdiger Wehr, Dorothea Otto, Claus Bätke and Michael Tampe of the Tropical Ecology Support Program (TÖB) of GTZ, Michael Bruenjes and Klaus Werner of the Soil Laboratory of Göttingen University, Christoph Kleinn of the Institute for Forest Inventory and Forest Growth of Göttingen University and Simon Scott-Kemball and Oliver Pye of the Language Services of GTZ.

Summary

Within the context of the Kyoto Protocol, a study was executed to evaluate the potential of forestry projects for carbon sequestration in north-western Ecuador and Argentinean Patagonia. Two forest systems were considered in each country: secondary forests and laurel (*Cordia alliodora*) plantations in Ecuador, and native cypress (*Austrocedrus chilensis*) forests and pine (*Pinus ponderosa*) plantations in Argentina. In selected sites, the quantity of carbon was determined that can be accumulated by forests growing on sites that were previously pasture. Carbon in biomass was considered, as well as carbon in soil organic matter. In Ecuador, secondary forest can accumulate approximately 100 tonnes of carbon per hectare during the first 30 years after pasture abandonment. Laurel plantation can accumulate around 120 tonnes of carbon in the first 20 years at suitable sites. In Argentina, pine plantations can accumulate 120 tonnes of carbon per hectare in rotations varying between 23 and 48 years, depending on site suitability. In Ecuador, if reforestation takes place in pastures older than 20 years, which are generally degraded, the amount of soil organic carbon in the top 50 cm soil layer also increases during forest growth, and can reach up to 15 tonnes of carbon per hectare. In Argentina, compared to pastures no increase of soil organic carbon under existing pine plantations was observed on average, while cypress forests had on average 29 tonnes more soil organic carbon than pastures.

On the basis of this information, an economic analysis was performed to determine the compensation that would have to be paid to a landowner in order to make him or her switch from cattle ranching to a forestry alternative, assuming a joint-production of timber and carbon sequestration. These compensations reflect the opportunity costs of land use change, and were expressed as the minimum price per ton of CO_2. In order to calculate these costs, the net present value of

three land use alternatives in Ecuador was compared: cattle ranging, managed secondary forests and laurel plantations, and two land use alternatives in Argentina: cattle ranging and pine plantations. Cypress forests were not included in the economic analysis because of the lack of cypress forest management models that can simulate a complete rotation. Two project durations were compared: 30 years and 100 years.

In Ecuador, the opportunity costs of carbon sequestration depend predominantly on the productivity of the land use alternatives, which in turn depend on geographical location within the study area. For a 30-year project the estimated costs vary between \$1.5 and \$16 per tonne of CO_2, depending on the zone. Minimum compensations do not differ much between secondary forests and plantations. This permits landowners with small-size to medium-size properties, who normally do not have the resources to make high investments, to participate in carbon sequestration projects, provided problems of scale are resolved. Secondary forests have the additional benefit of higher biodiversity compared to plantations. In Patagonian Argentina, the cost of carbon sequestration in pine plantations for a 30-year project varies between \$1 and \$15 per tonne of $CO_{2,}$ depending mainly on the suitability of a site for growing pine. In projects with a duration of 100 years, costs are reduced in both Ecuador and Argentina by about 50% compared to a 30-year project. The results allow for the optimization of site selection in order to reduce opportunity costs.

On the basis of these results we calculated the income per hectare that landowners would get from carbon sequestration, if the compensation were actually paid to them. With this payment the forest alternative (including timber production) would generate the same net present value as cattle ranging. However, a welfare increase - one of the objectives of the Clean Development Mechanism – is not generated and would only be achieved by payments higher than the opportunity costs.

Whether the supply of sequestered CO_2 units at the calculated minimum prices is internationally competitive depends on the situation on the carbon market, which has recently been developing. Initial estimates after the withdrawal of the US from the Kyoto Protocol indicate that a relatively high number of players on the supply side will in the future be competing for a relatively small demand. At the same time, a voluntary market exists where companies and organisations that want to compensate for the negative impacts of their operations on the global climate can operate. Trading on this voluntary market is more flexible, and can also consider the conservation of native forests in order to avoid carbon emissions caused by deforestation.

Without payment for carbon sequestration, forest projects are not competitive compared to cattle ranging in the majority of cases. A sensitivity analysis also indicated that when interest rates or prices of wood, milk or meat change within reasonable limits, in most cases landowners would not switch to a forestry alternative, confirming the probable additional nature of forest projects, a requisite of the protocol.

Large-scale monoculture plantations present possible economical and ecological risks (e.g. diseases, low biodiversity). For this reason, mixed plantations with native species should be considered. In Ecuador, managed secondary forests offer an interesting alternative. These also reduce the social risks of displacement.

In order to offer market access to a variety of landowners - also those with small or medium land holdings - it is important to overcome problems of scale. Trust funds in which the supply of certified emission reduction units of various landowners is summed to sufficiently large volumes can be a solution.

Resumen

En el contexto del protocolo de Kyoto se realizó un estudio para evaluar el potencial de proyectos forestales para fijación de carbono en el Noroccidente de Ecuador y en la Patagonia Argentina. Se consideraron dos tipos de bosques en cada país: en Ecuador bosques secundarios y plantaciones de laurel (*Cordia alliodora*), y en Argentina bosques nativos de ciprés (*Austrocedrus Chilensis*), y plantaciones de pino (*Pinus ponderosa*). En sitios seleccionados, se determinó la cantidad de carbono estos bosques pueden acumular en tierras que antes eran pastos naturales o sembrados. Se consideró carbono en la biomasa aérea y en la materia orgánica del suelo. En Ecuador, los bosques secundarios pueden acumular alrededor de 100 toneladas de carbono por hectárea 30 años después del abandono de pasto. Una plantación de laurel puede acumular 120 toneladas de carbono en 20 años en sitios aptos. En Argentina, las plantaciones de pino pueden acumular 120 toneladas de carbono por hectárea en rotaciones con una duración entre 23 y 48 años, dependiendo de la aptitud del sitio. Si en Ecuador la reforestación es en pastos de mas de 20 años, los cuales por lo general se encuentran degradados, también se aumenta el nivel de carbono en el suelo durante el crecimiento del bosque, hasta un aumento de 15 toneladas de carbono por hectárea. En Argentina, comparado con los pastizales, no se verificó un aumento en carbono en suelo bajo plantaciones de pino mientras que los bosques de ciprés en promedio tuvieron 29 toneladas más carbono en el suelo que los pastizales adyacentes.

En base a esta información se hizo un análisis económico para determinar cuanto dinero exigiría un propietario de tierras con pastizales, para que el uso forestal (incluyendo la producción de madera) sea competitivo con el uso alternativo: la ganadería. Esta compensación refleja los costos de oportunidad del cambio del uso de suelo y está expresada como precio mínimo por tonelada de CO_2 fijado.

Para calcular este costo se comparó el valor actual neto de tres usos alternativos en Ecuador - ganadería, bosques secundarios manejados y plantaciones de laurel - y dos usos alternativos en Argentina - ganadería y plantaciones de pino. No se incluyó ciprés en el análisis económico por falta de modelos de manejo forestal que puedan simular una rotación completa. Se compararon proyectos forestales de diferente duración: de 30 años y de 100 años.

Los costos de oportunidad de la fijación de carbono dependen en Ecuador sobre todo de la productividad de las alternativas, la cual a su vez depende de la ubicación geográfica dentro de la zona. Para un proyecto de 30 años los costos estimados fueron entre 1.5$ y 16$ por tonelada de CO_2, dependiendo de la zona. No hay mucha diferencia entre las compensaciones para bosques secundarios y plantaciones. Eso permitiría que pequeños y medianos propietarios, que no tienen los recursos para altos inversiones, puedan participar en proyectos de fijación de carbono si se superan problemas de escala. Bosques secundarios tienen además la ventaja de una mayor biodiversidad comparada con plantaciones. En Patagonia argentina los costos para fijación de carbono en plantaciones de pino variaron para un proyecto de 30 años entre 1$ y 15$ por tonelada de CO_2 dependiendo sobre todo de la aptitud del sitio para el crecimiento de pinos. En caso de proyectos de 100 años los costos se reducen en Ecuador y Argentina alrededor de un 50% comparado con proyectos de 30 años. Los resultados del análisis permiten seleccionar sitios donde se genera los menores costos de oportunidad.

En base a estos resultados se calcularon los ingresos adicionales por hectárea para propietarios en caso que se pagaran los precios mínimos calculados por tonelada de CO_2. Con estos pagos, el bosque generaría los mismos beneficios netos que la ganadería. Sin embargo, no se aumentaría el nivel del bienestar, lo cual es uno de los objetivos de proyectos dentro del Mecanismo de Desarrollo Limpio. Para llegar a este objetivo, el pago debería ser más alto que el costo de oportunidad.

La competitividad al nivel internacional de la oferta de la fijación de carbono a los precios mínimos calculados depende del mercado del carbono, que recién se esta definiendo. Sin embargo, en el contexto de Kyoto después de la retirada de los EE.UU. el mercado se caracteriza por un gran numero de actores en el lado de la oferta competiendo ante una demanda relativamente baja. Al mismo tiempo existe un mercado voluntario donde operan empresas y organizaciones en búsqueda de mecanismos para compensar impactos negativos de sus operaciones en el clima global. El mercado voluntario es más flexible, y puede considerar proyectos de conservación de bosques nativos para evitar emisiones de carbono por su deforestación.

Sin pago por carbono en la mayoría de los casos los proyectos forestales no son competitivos con la ganadería. Un análisis de sensibilidad indicó que también cuando cambia la tasa de descuento o precios de madera, leche o carne dentro de rangos factibles, proyectos forestales en la mayoría de los casos no son competitivos sin pago por fijación de carbono. Esto significa, que la adicionalidad de proyectos forestales (un requisito dentro del protocolo) es probable.

Plantaciones a grande escala en monocultivo presentan posibles riesgos económicos y ecológicos (enfermedades, baja biodiversidad). Por eso se debe considerar plantaciones mixtas con especies nativas. En Ecuador, los bosques secundarios manejados ofrecen una alternativa. Estos también reducen el riesgo social de desplazamiento. Para ofrecer acceso al mercado a una variedad de propietarios, también pequeños y medianos, hay que superar problemas de escala. Sin embargo a través de fideicomisos se podría acumular unidades de producción que agrupen certificados de reducciones de emisiones, para llegar a un volumen suficientemente grande.

Zusammenfassung

Vor dem Hintergrund des Kyoto-Protokolls wurde eine Studie durchgeführt, um das Potenzial forstlicher Projekte zur Kohlendioxid-Festlegung im Nordwesten Ecuadors und im argentinischen Patagonien zu prüfen. In jedem Land wurden zwei forstliche Systeme untersucht: Sekundärwald und Laurel-Plantagen (*Cordia alliodora*) in Ecuador und die natürlich vorkommende Zypresse (*Austrocedrus chilensis*) sowie Kieferplantagen (*Pinus ponderosa*) in Argentinien. Auf ausgewählten, vorher als Weide genutzten Standorten wurde die Kohlenstoffmenge bestimmt, die durch eine forstliche Nutzung gespeichert werden kann. Dabei wurden sowohl die C-Speicherung in der Biomasse als auch im Boden berücksichtigt. In Ecuador können Sekundärwälder in den ersten 30 Jahren nach einer Aufgabe der Weidenutzung ca. 100 Tonnen Kohlenstoff pro Hektar speichern. Laurel-Plantagen erreichen auf geeigneten Standorten in den ersten 20 Jahren ca. 120 Tonnen Kohlenstoff pro Hektar. In Argentinien können Pinus-Plantagen ebenfalls ca. 120 Tonnen C pro Hektar festlegen. In Abhängigkeit vom Standort werden dafür zwischen 23 und 48 Jahre benötigt. Eine Wiederbewaldung auf Flächen in Ecuador, die vorher über 20 Jahre lang als Weide genutzt wurden - und dann in der Regel degradiert sind -, führt auch zu einem Anstieg des Kohlenstoffmenge in der oberen 50cm-Bodenschicht um bis zu 15 Tonnen C pro Hektar. In Argentinien konnte beim Vergleich zwischen existierenden Pinus-Plantagen und Weideland keine Zunahme des organischen Bodenkohlenstoffs festgestellt werden. Zypressenwälder hingegen wiesen im Durchschnitt 29 Tonnen mehr organischen Bodenkohlenstoff auf Weideland.

Auf Basis dieser Informationen wurde eine ökonomische Analyse durchgeführt, um zu prüfen, welche Kompensation einem Landnutzer mindestens zu zahlen ist, um ihn zu veranlassen, von seiner bisherigen Weidenutzung zu einer forstlichen

Alternative zu wechseln. Dabei wurde eine Kuppelproduktion von Holz und Kohlenstoffspeicherung unterstellt. Die Kompensationszahlung spiegelt die Opportunitätskosten einer Landnutzungsänderung wider und wurde als Minimumpreis pro Tonne CO_2 formuliert. Um diese Opportunitätskosten zu bestimmen, wurde eine Nutzen-Kosten-Analyse für die verschiedenen Landnutzungsalternativen durchgeführt. In Ecuador waren dies: Rinderweide, bewirtschafteter Sekundärwald und Laurel-Plantage; in Argentinien wurden Rinderweide und Pinus-Plantage gegenüber gestellt, während Zypressenwälder aufgrund eines Mangels an Bewirtschaftungsmodellen nicht in die ökonomische Analyse einbezogen wurden. In beiden Länder wurden Projektlaufzeiten von 30 und 100 Jahren untersucht.

In Ecuador werden die Opportunitätskosten der CO_2-Speicherung entscheidend von der Produktivität der Landnutzungsalternativen beeinflusst, welche wiederum von der geographischen Lage innerhalb der Untersuchungsregion abhängt. Für 30-jährige Projekte liegen die Kosten je nach Zone zwischen 1,5$ und 16$ pro Tonne CO_2. Dabei haben die minimalen Kompensationsforderungen für Sekundärwald und Plantage in etwa die gleiche Höhe. Das bedeutet, dass es sich auch für Eigentümer kleiner bzw. mittelgroßer Nutzungsflächen – die in der Regel nicht über finanzielle Mittel für größere Aufforstungs-Investitionen verfügen – bei einer entsprechenden Zahlung für die CO_2-Speicherung lohnen würde, Sekundärwälder zu begründen und diese zu bewirtschaften. In Argentinien variieren die Kosten hauptsächlich in Abhängigkeit von der Eignung des Standortes für eine forstliche Nutzung zwischen 1$ und 15$ pro Tonne CO_2. In beiden Ländern wird bei Projekten mit einer Laufzeit von 100 Jahren im Durchschnitt mehr CO_2 pro Hektar festgelegt. Entsprechend vermindern sich die Opportunitätskosten pro Tonne CO_2 im Vergleich zu Projekten mit 30 Jahren Laufzeit um die Hälfte.

Auf Basis dieser Ergebnisse wurde das Einkommen pro Hektar berechnet, das Landnutzer für die Festlegung von Kohlendioxid bezögen, wenn sie tatsächlich die von ihnen geforderten Zahlungen erhalten würden. Der dabei erzielte Netto-Nutzen pro Hektar (incl. Holzproduktion) entspricht dann genau dem Netto-Wohlfahrtsbeitrag der Weidenutzung. Eine Wohlfahrtssteigerung – eines der Zieles des Clean Development Mechanisms (CDM) – wäre damit nicht verbunden, sondern erst durch Zahlungen zu erreichen, die die Opportunitätskosten übersteigen.

Ob das Angebot der CO_2-Sequestration zu den kalkulierten Minimumpreisen international konkurrenzfähig ist, hängt von den Gegebenheiten auf dem sich im Aufbau befindlichen CO_2-Markt ab. Erste Untersuchungen der Marktstruktur nach dem Rückzug der USA aus dem Kyoto-Prozess deuten auf eine Vielzahl von Anbietern hin, die um eine im Vergleich zum Angebot geringe Nachfrage konkurrieren. Gleichzeitig existiert ein Markt für freiwillige Emissionsreduktionen auf dem Unternehmen und Organisationen auftreten, die die negativen Effekte ihrer wirtschaftlichen Tätigkeit auf das globale Klima kompensieren möchten. Der Handel auf diesem freiwilligen Markt ist flexibler, da auch CO_2-Einheiten aus vermiedener Deforestation, etwa durch den Schutz von Naturwäldern, berücksichtigt werden können.

Ohne Zahlungen für die CO_2-Sequestration sind forstliche Projekte im Vergleich zur Weidewirtschaft nicht konkurrenzfähig. Eine Sensitivitätsanalyse zeigte, dass selbst bei einer Veränderung des Zinssatzes sowie der Preise für Holz, Fleisch und Milch innerhalb bestimmter Grenzen, kein Landbesitzer aus ökonomischen Gründen zu einer forstlichen Alternative wechseln würde. Das bedeutet, dass die Additionalität - eine Forderung des Kyoto-Protokolls für CDM Projekte - als erfüllt gelten kann.

Großangelegte Monokulturplantagen bergen ökonomische und ökologische Unsicherheiten (Krankheitsanfälligkeit, Biodiversitätsverlust). Aus diesem Grund sollten Misch-Plantagen unter Einbeziehung natürlich vorkommender Baumarten in Betracht gezogen werden. In Ecuador bietet sich mit der Bewirtschaftung von Sekundärwäldern eine interessante Alternative, die gleichzeitig soziale Risiken, wie zum Beispiel die Abwanderung aus ländlichen Gebieten, mindern könnte.

Um einer Vielzahl von kleinen und mittleren Landeigentümern, den Zugang zum Markt für CO_2-Reduktionen zu eröffnen, ist es notwendig, das Problem der mangelnden Größe zu überwinden. Hier bietet sich die Schaffung eines Treuhandfonds an, der die zertifizierten Emissionsreduktionen einzelner kleiner Anbieter bündelt und dann in einem Gesamtpaket auf dem Markt anbietet.

1 Introduction

The inclusion of carbon sinks in the Clean Developing Mechanism (CDM) defined in the 1997 Kyoto Protocol and the subsequent Conferences of the Parties (COPs) of the United Framework Convention of Climate Change (UNFCCC) has created a new potential source of income for forestry projects. Under the CDM, industrialised countries may invest in carbon sequestration by reforestation and afforestation projects in developing countries, and offset part of their domestic greenhouse gas emissions in order to comply with their commitments as agreed in the Kyoto Protocol. Additional income for carbon sequestration, one of the environmental services of forests, may stimulate landowners to switch part of their non-forest land to forest, especially when payments become available during the initial years of the forestry system, as the long time period before income is obtained after establishing a forest is a main obstacle to landowners. Forests established within the framework of CDM should support sustainable development and can bring additional benefits such as the protection of biodiversity, water and soils. For this reason, carbon sequestration projects have received increasing attention in developing countries.

1.1 Description of technical cooperation projects

Ecuador

The related GTZ technical cooperation project in Ecuador is called "Asesoramiento Político en la Gestion Forestal y de Recursos Naturales", PPF-RN (translation: Political Advice on the Management of Forests and Natural Resources). PPF-RN operates within the GTZ Programme "Gestion Sostenible de Recursos Naturales", GESOREN (translation: "Sustainable Management of Natural Resources") (www.gtzecuador.org). PPF-RN was initiated in 1992 and its counterpart is the Ministry of Environment of Ecuador. Especially relevant for the current project were the National Forestry Direction and the Climate Change Office, both operating within the Ministry of Environment.

The objective of PPF-RN is to strengthen the Ministry of Environment and other relevant institutions in Ecuador in their capacity to introduce practical policy changes for the sustainable management and protection of forest resources.

The fields of action of PPF-RN are:

- To give advice at the national level with respect to forest policies and the protection of natural resources, and to support the operationalization of sustainable forest management within legislation.
- To support the integration of Ecuadorian environmental policies within international initiatives and vice versa.
- To support representatives of civil society to find regional and national political platforms to express their interests and participate in the definition of policies for the management of forests and natural resources.
- To empower owners and users of forests to defend their interests with respect to conflicts in land use and the political decision-making process, recognising the ecological and economical value of forests.

Some of the (expected) results of PPF-RN are:

- National and regional political decision-making processes increasingly take into account the rights and wishes of the owners and users of forests. Platforms exist at the regional and national levels where the civil society can express its interests with respect to natural resources. These platforms facilitate information, coordination and conflict management.

- Provincial collaborators will recognise the Ministry of Environment as a trustworthy institution. The latter’s personnel will understand and promote new laws and rules. Through decentralisation, decision-making will be facilitated.
- At the local level, forest users and owners will be able to apply principles of sustainability to forest management and process products in order to obtain better access to markets and higher prices. Organisational issues and the exchange of experiences will improve. Natural resources will be better protected.

A main focus of the GESOREN programme is to apply the principles of an environmental economy, defined within the programme as activities that are economically profitable and oriented at a sustainable use of natural resources that allow equitable access to the resources and benefits they generate. Within this context, the payment for ecosystem services is seen as an important instrument that recognises the benefit to society of services such as the protection of water, biodiversity and air as a result of sustainable land use. Monetary compensation for landowners generating these services is a way to stimulate more sustainable ways of land use. In Ecuador’s new forest and biodiversity law, a system of payments for ecosystem services is proposed. For this reason, PPF-RN requested information on the ecological and economic aspects of carbon sequestration in forest systems in Ecuador.

Argentina

The related GTZ technical cooperation project in Argentina is called PRODESAR: "Proyecto de Prevención y Control de la Desertificación para el Desarrollo Sustentable de la Patagonia" (Translation: "Project for the Prevention and Control of Desertification for the Sustainable Development of Patagonia"). In 1990, GTZ along with the Secretary of Agriculture and Fishery of Argentina signed an agreement for four years of cooperation in setting up an ecological monitoring system in Patagonia. With its operational counterpart INTA (Instituto Nacional de Tecnología Agropecuaria), this cooperation continued under the name PRODESAR. The concept of sustainable development is the central theme of PRODESAR's intervention strategy, taking into account a clear dependence between socio-economic development and control of desertification. The project not only develops and validates models for the sustainable management of natural resources, but also takes accompanying measures for the implementation of sustainable techniques at the regional level, such as legislation, financial support, tax measures etc. Through legislation based on technical assessments, developed together with authorities for application and control, and with commitments at the political level, sustainability criteria are applied in order to control overgrazing and desertification. Some of the main results of PRODESAR are as follows: 1. Increased awareness of the problem of desertification in Patagonian society; 2. Mapping of the actual situation of desertification, scale 1:1,500,000; 3. Development of a Decision Support System for each Patagonian Province; 4. Training and equipping of personnel; 5. Interdisciplinary assistance for producers (technical, economical, group processes); 6. Institutional coordination and cooperation; 7. Compilation, analysis and evaluation of legal norms with respect to the sustainable use of natural resources.

INTA, the institute that co-executes the PRODESAR project with GTZ, reports directly to the Secretary of Agriculture, Animal Husbandry and Fishery.

Within the strategy of PRODESAR to find economic alternatives in the region and diversify land use, the issue of carbon sequestration is highly relevant. Afforestation and reforestation activities within the region, with a potential to reduce desertification, could become economically more attractive if they generated additional income from carbon sequestration. However, little experience in this area existed. PRODESAR therefore requested more information on the ecological and economic potential and impact of afforestation and reforestation activities within the context of carbon sequestration projects.

1.1.1 Description of study areas

Ecuador

Ecuador has a surface area of 283,000 km^2. It has three major eco-regions in which 25 Holdrige life-zones have been identified (Cañadas, 1983). The Andean mountain range (Sierra) runs from north to south through the country with peaks that reach maximum heights of about 6000 m above sea level (masl). East of the Sierra is the Amazon region (Oriente), consisting of humid tropical lowland, while west of the Sierra lies the coastal area. In 2000, 12.6 million people lived in Ecuador, of which 62% in urban areas (World Bank, 2002). The great majority of the population live in the coastal area and in the Sierra. The population growth rate is 2.4%.

Ecuador has suffered a major economic crisis since 1999, with the collapse of the financial system and negative GDP growth of about -8%. At the end of 2000, the public debt was about US$ 17 billion, representing 120% of the GDP. The economic crisis has caused high migration rates to Europe and the United States and has increased poverty. In 2000, an estimated 60% of the total population and 80% of the rural population were living under the poverty level. Of the total population, 44% suffer from malnutrition.

There is a high degree of pressure on the natural resources of the country. Ecuador is considered a mega-diverse country with respect to biodiversity (Myers, 2000) but its remaining forests are being deforested at a high rate, due to the expansion of the agricultural frontier, and directly through logging. Of the total forest area (about 10.6 million ha in 2000) an estimated 137,000 ha are lost annually, which represents a deforestation rate of 1.2%, the highest in South America (FAO, 2001). Another major problem - especially in the Andes - is erosion, causing the degradation of soils and desertification.

Some of the main causes of the degradation of natural resources are extractive economic activities and low productivity, weak implementation and control of environmental policies, failing price and market structures, a lack of technologies for sustainable management, and the absence of accounting systems for externalities of productive activities on natural resources (GTZ, 2000).

The study area for this project was located in the north-western part of Ecuador, covering the whole of the province of Esmeraldas and the most north-western part of the province of Pichincha, within the geographical coordinates of 80°05´W, 1°30´N (north-western corner) and 78°40´W, 0°05´S (south-eastern corner) (Figure 1). The area is roughly delimited in the East by the Western Cordillera of the Andes, in the West by the Pacific Ocean, in the North by the national border with Colombia, and the South by the province of Manabí.

The altitude of the study sites varies between sea level and 1,600 masl, corresponding to an average temperature between 25.6 °C and 21.5 °C, respectively. Yearly annual precipitation varies from 1,000 mm near the city of Esmeraldas to over 5,000 mm in the sub-montane area of the western Cordillera of the Andes. Most of the vegetation of the area is classified within the Holdrige life-zone system as humid tropical forest, with the exception of a coastal strip north and south of the city of Esmeraldas that is classified as dry tropical forest (Cañadas, 1983).

Figure 1. Study area Ecuador

The natural vegetation is a continuation of the Colombian *Chocó* and is known as one of the world’s hot spots of biodiversity (Myers, 1988; Conservation International, 2001), because of its species richness, the high levels of endemism and the strong pressure of human activities. Knowledge is still limited, but rough estimates of biodiversity in the Ecuadorian *Chocó* indicate that this region contains about 25% of the diversity of the national flora, which means about 6,300 species, with an endemism between 13% and 20% (Conservation International, 2001, Gentry, 1986). Further estimates indicate a total number of bird species of around 800, of which 40 are endemic to coastal Ecuador; 142 mammal species, of which 15 are regionally endemic; and 60% of all amphibian species found in the country (Conservation International, 2001).

The soils can broadly be divided into 2 groups. The soils on the foothills of the Western Cordillera (most eastern part of the area) and some lower-lying valleys are of volcanic origin, while the soils of the undulating coastal lowlands are sedimentary (MAG/ORSTOM, 1980). The volcanic soils are relatively young soils developed on ashes with a mineralogy characterised by the presence of allophane. They are generally acidic or slightly acidic, have a high level of water retention, low bulk density, a sandy or loamy texture, a base saturation under 35 meq/100g and are of medium fertility. The sedimentary soils are more developed, with a clayey or loamy clay texture. In the most humid areas, iron and aluminium oxides are present and clay minerals are dominated by kaolinite, while in dryer areas montmorillonite clay minerals dominate. Kaolinite is generally associated with low fertility and montmorillonite with medium fertility. The sedimentary soils shrink and swell according to soil moisture conditions. The following USDA Soil Taxonomy sub-orders can be found in the study area: Tropepts, Aquents, Orthents, Fluvents, Udalfs, Udolls and Psaments (MAG/Orstom, 1980, Clirsen/Patra, 1998).

Land use is very dynamic in the region with the highest deforestation rates within the country due to timber extraction and conversion to agricultural land (Sierra and Stallings, 1998). The estimated forest cover (primary and secondary) in the province of Esmeraldas is - depending on the source - between 50% (source: Clirsen/Patra, 1998) and 73% (source: INEC, 1995). Most agricultural land is grassland for cattle grazing (between 20% and 50%, depending on the source), followed by permanent crops such as oil palm, banana, cacao, plantain and coffee. Small areas of temporary crops exist, such as maize, rice and cassava, mostly for local consumption.

Most grassland was established after the cutting and/or burning of native - in many cases intervened - forest. Stocking densities are low, on average around one animal per ha. When grazing and occasional clearing is stopped, rapid regrowth of secondary forest takes place. This vegetation is called "monte" or "rastrojo" in the region.

The area of forest plantations is limited (approximately between 7,000 and 10,000 ha) and is owned by a small number of companies.

Argentina

Argentina has a surface area of 2.8 million km^2 stretching from latitude 22 south to latitude 55 south. It has a variety of ecological zones, ranging from tropical forest in the north to the productive pampa in the centre of the country, and to the temperate and mountainous Patagonian Andes in the South. In 2000, Argentina had 37 million habitants (World Bank, 2002) and an average population growth rate of 1.2%.

In 1991, Argentina's currency (the peso) was coupled directly to the US dollar. However, a severe economic and political crisis starting in 2001 has forced the de-coupling of the peso and its subsequent devaluation. Poverty and unemployment have increased steeply since the beginning of the crisis. Furthermore, the large public debt (approximately US$ 150 billion in 2000, representing 54% of the GDP) hampers the recovery of the economy.

The study area for this project was located within the north-western part of Patagonia (Figure 2). Patagonia has clearly differentiated biogeographic regions, such as mountains, steppe and temperate forests, that are the result of the varied geomorphic and climatic conditions. The dominant economy in the 20th century was sheep and cattle grazing, an activity that has declined strongly during the last 40 years due to a structural crisis in the sector and degradation of the pastures due to overgrazing (León and Aguiar, 1985; Soriano and Movia, 1986). Around

84% of the surface of Patagonia presents moderate to very severe degrees of desertification (del Valle et al., 1997).

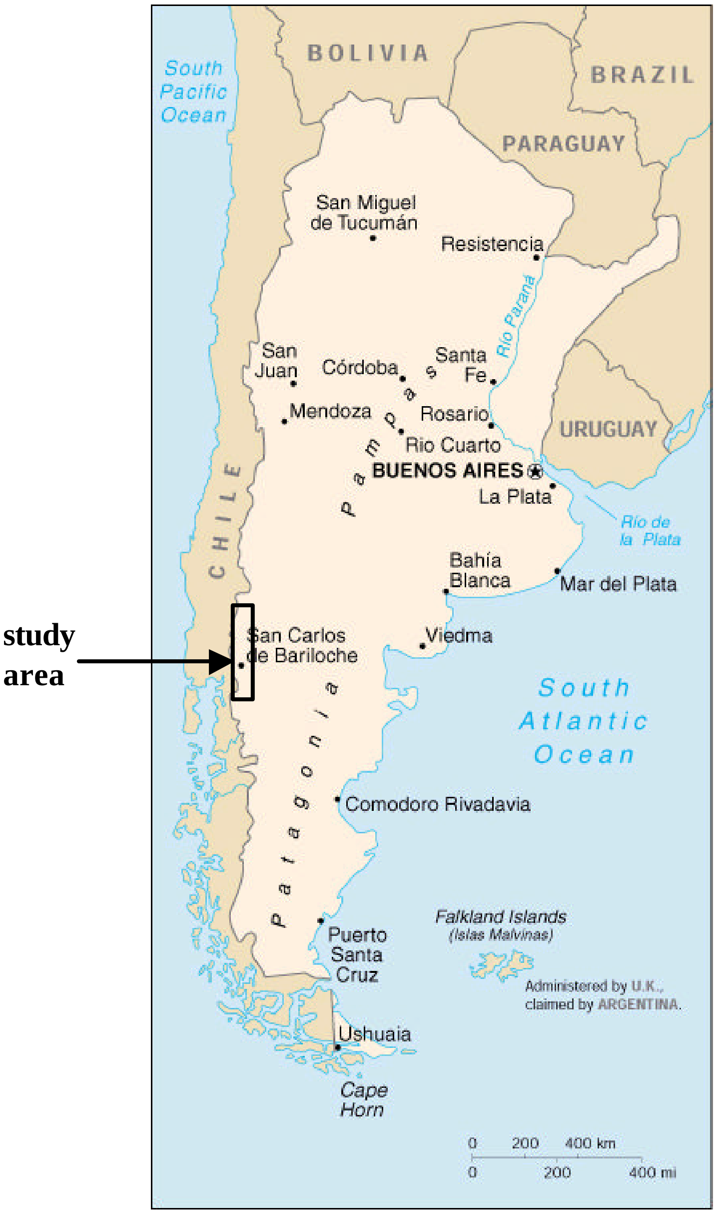

Figure 2. Study area Argentina

The north-western part of Patagonia, between latitude 36° and 46° and limited to the west by Chile and the east by the isohyet of 500 mm, has the appropriate conditions for native forest growth, ranging from the Andean *Cordillera* bordering Chile to the steppe. This region, with a total area of 4,500,000 ha, has ample biological and economical potential for the management of native forests as well as forest plantations. The current area of (mostly native) forests is 1,685,000 ha, of which 1,425,000 ha are within the national parks of Lanín, Nahuel Huapi and Los Alerces (Laclau, 1997).

Rural productive activities are cattle grazing, forest plantations, the sporadic use of native forests and deer grazing. Tourism and recreation are increasingly gaining in importance.

Outside the protected areas, 2,835,000 ha are marginally to very suitable for forest conifer plantations (Laclau, 1997). However, in spite of financial incentives offered by the government, only 70,000 ha of plantations exist, although the area growth rate is steady: 7,000 to 8,000 ha yearly (Laclau et al., 2002b).

The chosen study area was selected within north-western Patagonia and comprises a stretch of land parallel to the Andean *Cordillera* area between latitude 39º 56´S and 42º13´S and longitude 70º49´W and 71º35´W. In most of the area, the altitude varies between 650 and 1200 masl, except for the very south where the altitude goes down to about 250 masl. Most of the area is between the isohyets of 600 mm and 1200 mm - east from the dense *Cordillera* forests and west from the steppe - an area also known as the *ecotono* (Schlichter and Laclau, 1998). The area has a degree of high potential for forest plantations as well for cattle grazing. The native forests in the area mainly contain *Nothofagus spp*, as well as cypress (*Austrocedrus chilensis*). The climate is temperate, with an annual average temperature of about 10ºC, average maximum temperatures between 16ºC and 18ºC, and average minimum temperatures between 3ºC and 6ºC. Precipitation is concentrated between May and September, sometimes in the form of snow. Generally the frost-free period is less than 100 days.

The dominant soils are the result of volcanic activity and are classified as Andisols. On top of rocky outcrops and glacial geoforms, volcanic ashes have been deposited that have developed into soils with non-crystalline allophanic clays. The amount of allophane is generally higher in humid and well-drained soils, where development has been faster than in the dryer areas. In the dry eastern part of the region, a transition takes place, with soils with more crystalline clays found (Molisols) (Colmet Dâage et al, 1995). These eastern soils have also been modified by transport and have been mixed with fluvial and colluvial limes and sand material (Etchevehere, 1972).

The main type of pasture in this area is natural steppe pasture dominated by *Festuca pallescens* and, to a lesser extent, *Stipa speciosa* var *Major*. Forest patches that are sparse at the eastern extreme of the area become more dominant when annual precipitation exceeds 900 mm (Somlo and Bran, 1994).

Native cypress forests can be pure or associated with *Lomatia hirsuta* (radal), *Nothofagus antarctica* (ñire) or *Nothofagus dombeyi* (coihue), and are the most oriental woody formations of the Andean Patagonian forests, due to their resistance to water stress (Loguercio, 1999). Cypress wood is highly appreciated; furthermore, these forests have environmental functions such as soil and water conservation. Dezzotti and Sancholuz (1991) classify cypress forests as marginal in the steppe region, compact between 900 mm and 1,600 mm of precipitation, and mixed forests associated with coihue in more humid areas. The cypress forests have an irregular diameter structure and a high degree of variability in the relation between age and diameter (Dezzotti and Sancholuz, 1991).

Forest plantations consist of pine species, mostly *Pinus ponderosa*, and to a much lesser extent, *Pinus contorta* var *latifolia* and *Pseudotsuga menziesii*. Plantations are homogeneous, and are mostly not older than 25 years, although some plantations of over 60 years exist. Most plantations are established on former pasture. When the forest canopy closes - after 15 to 20 years - the herbaceous vegetation generally disappears. Early plantations used very high planting densities (2500 plants/ha), but since then more flexible production models have evolved, with much lower planting densities. Combinations also exist with cattle grazing in silvopastoral models (Schlichter et al., 1999).

The land use in the study area - with a total surface of about 1,150,000 ha – is as follows: pastures: 445,000 ha; pure and mixed cypress forests: 80,000 ha; pine plantations: 25,000 ha; other forests and shrubs, high altitude grassland, rocky areas and water bodies: 600,000 ha.

1.2 Problem analysis

Changes in land use in South America have had important effects on natural resources through deterioration of soil and water quality, loss of biodiversity and influence on the global climate system. Two of the most prominent results of uncontrolled land use are desertification and deforestation.

Arid and semi-arid zones cover 75% of Argentina's land area, and generate about 50% of the country's agricultural output (crops and livestock). However, Argentina's agricultural sector is beset by serious problems caused by falling world market prices for agrarian products, as well as by a national policy which formerly devoted too little attention to developing rural areas. Coupled with the negative impacts of inappropriate land use systems and large-scale clearing of natural forests, this has resulted in soil degradation, erosion and salinization. Approximately 40% of Argentina's territory already exhibits symptoms of severe degradation. Patagonia, where more than 70% of the area is affected by erosion and desertification, is a particularly negative example.

Ecuador has great agro-ecological diversity. In the past, agriculture was mainly concentrated in the more densely populated Andean eco-region, but since 1900 the colonisation of the tropical lowlands has taken place, especially in the coastal eco-region. Since the 1970s, agricultural exploitation of the Amazonian eco-region has increased. Historical land use data reveal that the increase in agricultural land was mainly due to an expansion of extensively managed pastures, which were established on areas previously occupied by natural forest. The productivity of these pastures is mainly based on the ‘mining’ of nutrients, which become available during the first years following forest clearing. Obviously, this system does not guarantee sustainable production. After several years, production drops and some of these areas are abandoned, resulting in the regrowth of secondary vegetation.

The Kyoto Protocol of 1997 has established the basis for international negotiations on reducing the amount of greenhouse gases in the atmosphere. In the Conferences of the Parties (COP) of the United Nations Framework Convention of Climate Change (UNFCCC), criteria are defined for the amounts of reductions needed for the first commitment period (2008-2012) for Annex 1 countries, as well as on flexibility mechanisms than can be used to achieve these reductions. Of special relevance for developing countries is the Clean Development Mechanism (CDM), which allows industrialised countries to mitigate greenhouse gas emissions by financing projects in the energy or forestry sectors in developing countries. CDM projects have to support sustainable development in the country of implementation (Fearnside, 1999; Chomitz et al., 1999, Smith et al., 2000).At the COP6 meeting in Bonn in 2001 it was agreed that industrialised (Annex 1) countries should have the flexibility to mitigate part of their CO_2 emissions (1% of their estimated 1990 CO_2 emissions, i.e. 183 million t CO_2 (incl. USA) (Jotzo and Michaelowa, 2000)) through sequestration in afforestation and reforestation projects within CDM. A number of criteria were set at the COP-7 Marrakesh meeting in 2001 and will be further elaborated in upcoming COP meetings.

The definitions for afforestation and reforestation used in the Marrakesh agreement (UNFCCC, 2001) are:

"Afforestation is 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 is the direct human-induced conversion of non-forested land to forested land through planting, seeding and/or the human-induced promotion of natural seed sources, on land that was forested but that has been converted to non-forested land. For the first commitment period, reforestation activities will be limited to reforestation occurring on those lands that did not contain forest on 31 December 1989."

Carbon sequestration in forestry projects has received a lot of attention in recent years in Ecuador and Argentina. Payment for carbon sequestration would make forestry projects more interesting, especially if income could be obtained during the initial years of a forestry project in order to overcome the long period before forest products can be harvested. Within the GTZ's PPF-RN and PRODESAR projects, it was recognised that carbon sequestration projects can bring additional benefits, such as the protection of biodiversity, the conservation of soils and the prevention of desertification, and can contribute to socio-economic development.

For carbon sequestration projects, reliable estimates of the amount of carbon that can be sequestered in forest biomass and soil are essential (IPCC, 2000). Concerning below-ground carbon changes in particular, little information was previously available, and this therefore became a priority research field of this project, especially as carbon storage in soils has additional benefits for soil conservation and helps prevent desertification, important themes in Ecuador and Argentina as explained above. It was therefore considered important to develop a reproducible methodology to estimate carbon sequestration in soils.

Furthermore, GTZ was interested in the cost of carbon sequestration projects to estimate their feasibility and the economic benefits they generate for individual landowners, motivated by GTZ's objectives to alleviate poverty in rural areas.

For the design and implementation of carbon sequestration projects, it is necessary to calculate base-line and project additionality, perform a cost-benefit analysis, and evaluate processes such as leakage (IPCC, 2000).

The specific research questions for Ecuador and Argentina were:

- How much carbon can be sequestered by secondary forests and plantation forests established in former grassland, especially in the soil?
- What is the economic value of carbon sequestration in these forests?
- What is the potential of carbon sequestration projects and what are their advantages and limitations?

1.3 State of the art

1.3.1 Soil carbon changes in land conversions

Various studies exist on the impact of land use conversion on soil organic carbon (SOC), especially the effect of the conversion of tropical forest to agricultural land (see reviews by Detwiller, 1986; Veldkamp, 2001; Powers, 2001; Post and Kwon, 2000). In the case of tropical Central and South America, the most extensive and most studied conversion is from forest to grassland. In many of these studies, decreases in SOC after deforestation have been reported. Veldkamp (1994) reports SOC losses of up to 21 t/ha (17% of original SOC) -

depending on soil type - in the top 50 cm after deforestation followed by 25 years of pasture in Costa Rica. Guggenberger and Zech find a decrease in SOC content after forest to pasture conversion - from 5.8% to 7.2% in the topsoil - which can recover within 18 years to the original forest SOC levels through forest regrowth. For pasture establishment after deforestation in the Brazilian Amazon, Fearnside and Barbosa (1998) estimate that at the landscape level 12 t/ha of SOC are lost over several decades in the top 8 m of soil. For tropical sub-montane Ecuador, Rhoades (2000) measures a decrease in SOC of 17% after 15 years of mixed pastures, representing a loss of 10 t/ha, which can be recovered to native forest SOC levels after 20 years of secondary forest regrowth. However, for some forest to pasture conversions SOC increases have been reported, such as in Brazil by De Moraes et al. (1996), Feigl et al. (1995) and Koutika et al. (1999), and in Costa Rica by Powers (2002). Neill et al. (1997) attribute changes in Brazil mainly to management, with increases in well-managed grassland and decreases in degraded grassland. Flint Hughes et al. (2000) do not find major changes at ecosystem level in Mexico.

In Patagonia the climate is strongly seasonal with humid cold winters and dry warm summers. In a comparison between pastures, native vegetation and pine plantations in north-western Patagonia in Argentina, Gobbi et al. (2002) conclude that the effect of pine plantations on soil fertility depends on inherent soil fertility. In their study, pine plantations maintained or improved chemical soil quality in less fertile soils but caused impoverishment of chemical fertility, including organic C, in nutrient rich soils. The strong precipitation gradient within Patagonia is also likely to influence the effect of vegetation on soil quality. For example, Buamscha et al. (1998) have demonstrated the precipitation-dependent nutrient use efficiency of cypress trees.

Land use change-induced SOC dynamics are related to the fractionation of carbon over the stable and labile SOC pools (Post and Kwon, 2000) and their controlling factors, especially soil texture and soil mineralogy. The light fraction organic carbon is free and highly decomposable. After decomposition, carbon is stabilised by organo-mineral complexes with mainly clay and silt sized fractions, by organo-metal complexes, especially with iron and aluminium, and through the formation of complexes with non-crystalline minerals such as allophane in volcanic soils (Feller and Beare, 1997; Torn et al., 1997; Shoji et al., 1993). The form in which carbon is stabilised determines the carbon turnover time. For example, silt and clay-associated carbon is more stable than sand-associated carbon, while a comparison between clay and silt with respect to higher or lower stability depends on the type of soil (Feller and Beare, 1997; García-Oliva et al., 1994; Koutika et al., 2000).

Net SOC amounts are the result of the balance between carbon input through litter fall and fine roots - and thus net primary production - and the carbon turnover time in the soil. Turnover time depends on temperature and soil moisture conditions (Amelung et al., 1998; Townsend et al., 1995), which affect microbial activity, and on the stability of the carbon pools as determined by texture and mineralogy. Land use change can influence the carbon turnover rate through changes in moisture and temperature conditions as well as through changes in the partitioning of carbon over its different pools (e.g. Balesdent et al., 1998; Desjardins, 1994)

Considerable uncertainty remains about the factors related to soil, climate and management that determine the size and rate of soil carbon changes after land use conversion. Furthermore, the literature has predominantly focussed on soil carbon changes after the cutting of native forest, mainly to estimate the impact of deforestation on the global climate and local soil quality. Much less information exists on soil carbon changes after human-induced forest (re-) growth on tropical agricultural land. Soil carbon changes measured in deforestation studies are not simply reversible, because these depend on the partitioning of carbon over the different stable and less stable pools.

Point data of most studies are also insufficient for estimating regional carbon budgets or for the purpose of planning carbon sequestration activities. For these applications, a regionalisation of soil carbon changes is necessary by determining the relation between the land use induced SOC changes and the biotic and abiotic factors that vary over distance within the area of interest.

1.3.2 Costs of carbon sequestration

Faced with global climate change, various measures can be taken in order to prevent the world from the possible negative effects this change will bring. Figure 3 shows some alternative reactions. They start with a simple “wait and see” attitude, move on to the “protection” –approach, and finally reach the active reduction of atmospheric CO_2. This reduction can be achieved by avoiding emissions or by sequestering CO_2. These alternatives are not mutually exclusive. It is possible, for example, to reduce emissions “at home” or in other countries by Joint Implementation projects (JI), and at the same time sequester carbon “at home” or by using the Clean Development Mechanism (CDM), and to protect the people and regions most vulnerable to damages caused by global warming. The “wait and see” attitude could also be combined with more intensive research related to the climate change phenomenon. As shown in Figure 3, all alternatives will generate costs and benefits, some of which occur today and others in the future. In recent years various studies have been conducted to estimate the total costs of measures against global warming in order to compare them with the expected benefits, defined as avoided damages.

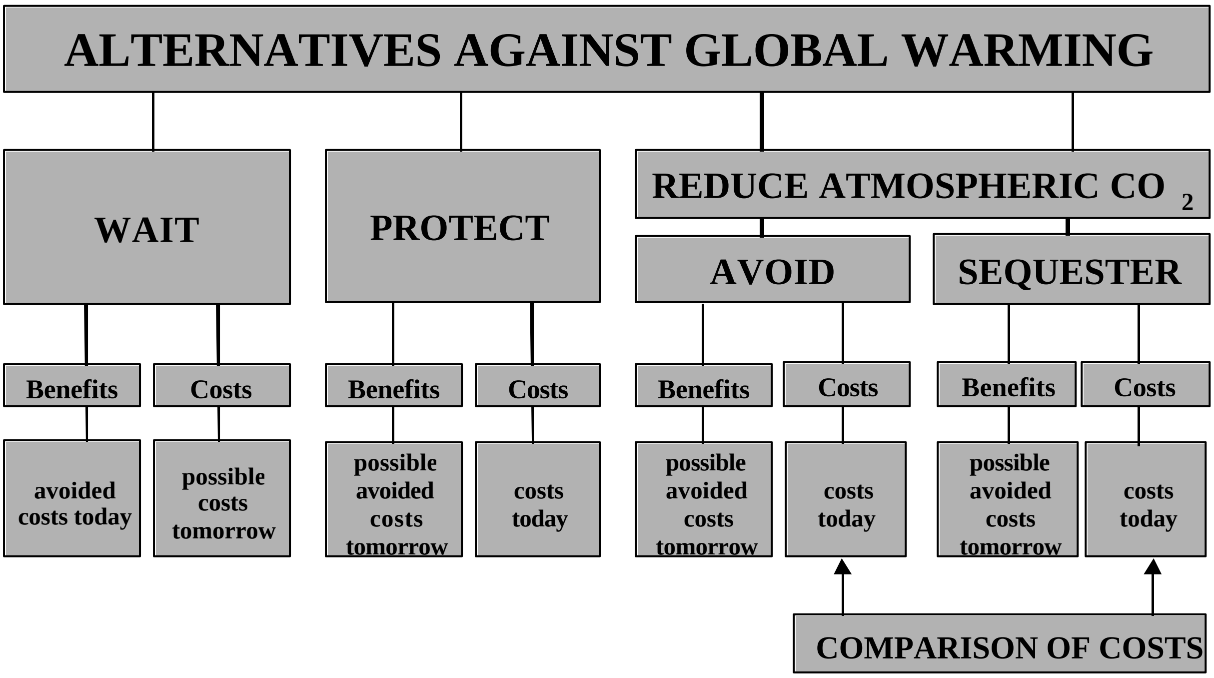

Figure 3. Alternatives against global warming.

When determining future damages, two approaches can be distinguished (Fankhauser, 1995). The first one, which might be called the “enumerative approach”, analyses all harmful aspects separately and calculates the total damage by simply summing up the respective values. The second approach, also called “integrated damage assessment”, uses a general equilibrium model to show the impact of climate change on a system of interacting markets.

For the estimation of total abatement costs, “bottom-up” and “top-down approaches” are used (Cline, 1992). Bottom-up models are based on detailed microeconomic data and technical information, whereas the top-down approach refers to a higher abstraction level.

The comparison of total costs and benefits provides useful information when seeking to decide whether measures against global warming should be taken or not. However, even if these measures are taken, there is no guarantee that the negative effects of climate change can be avoided.

Assuming that waiting and protecting is not enough, the Kyoto Protocol was created in order do something to combat global warming, emphasising the importance of the reduction of greenhouse gases such as CO_2. Article 3 of the Kyoto Protocol requires the so-called Annex 1 countries[1] to reduce their aggregate emissions by at least 5% below their 1990 levels in the commitment period 2008-2012 (UNFCCC 1998). Once such a decision is made, the question is: "How can this political target be achieved in an efficient way?"[2] The answer can be given by a comparison of costs: the costs of avoiding emissions and the costs of fixing carbon as illustrated in Figure 3. For such an analysis, marginal instead of total costs have to be estimated in order to determine the most cost-efficient solution.

Figure 4 shows a country's obligation to reduce CO_2 as the horizontal line. Reading the figure from right to left, the marginal costs of emission avoidance can be identified. The first units of reduced CO_2 emissions might even be realised without any additional costs by so-called "no regret" projects. Reading the figure from left to right, the marginal costs of sequestering CO_2, e.g. by afforestation projects, can be estimated. In both cases we assume rising marginal costs, which means that the additional costs increase with further efforts to reduce atmospheric CO_2.

---

[1] Countries listed in Annex 1 of the United Nations Framework Convention on Climate Change.

[2] For a discussion of the environmental effectiveness of this political target, especially after the U.S. withdrawal from the Protocol, see Böhringer (2001).

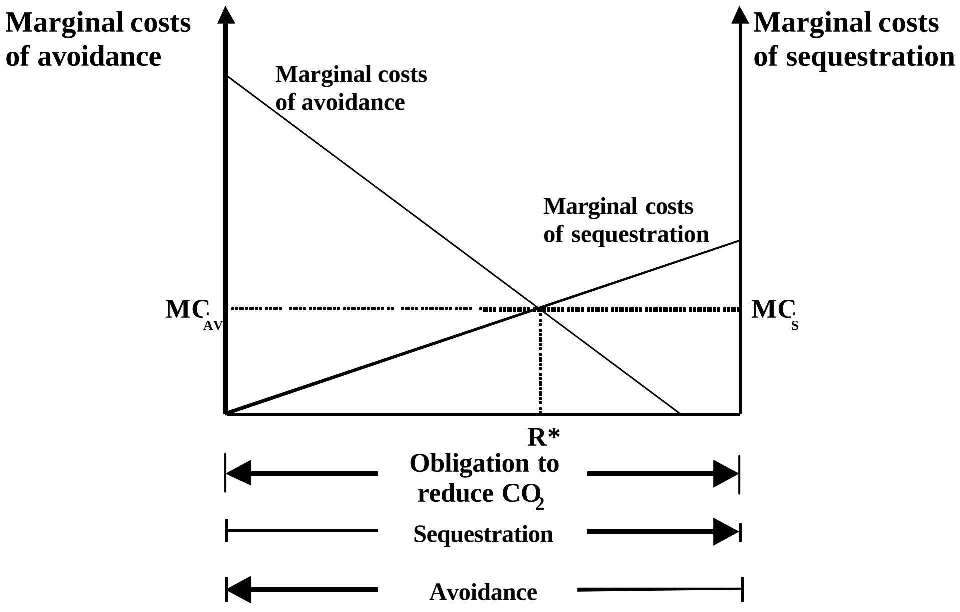

Figure 4. Marginal costs of avoidance and sequestration.

If it is possible to estimate these marginal cost curves, the optimal point R* can be determined, which shows the most cost-efficient solution to fulfil a country's reduction obligation. The emission units from R* to the right should be avoided "at home". From R* to the left it is cheaper to sequester CO_2 than to avoid further emissions "at home".[3] Figure 4 could be extended, including JI and other non-sequestration CDM measures. This would probably lead to a flatter marginal avoidance cost curve and a shift of the optimum point R* to the left. Our analysis focuses on the marginal costs of sequestration, i.e. the costs that occur on the supply side of Certified Emission Reductions (CER).[4] A number of recent

---

[3] If a political decision is made to reduce half of the overall target "at home", comparison of the areas below the marginal cost curves between R* and the 50% level gives an estimate of the additional costs of this political constraint.

[4] A CER is defined to be equal to one metric tonne of carbon dioxide equivalent UNFCCC (2001).

studies have examined this matter but often exclude (or simply make assumptions about) soil organic carbon.[5] Our goal is to estimate the marginal costs of CO_2 sequestration by afforestation/reforestation projects (plantation forest and secondary forests) in different climate zones in South America, including changes in SOC.

The results of this kind of study can be used for several purposes. On one hand, sequestration costs (in Non-Annex 1 countries) can be compared with the costs of avoidance (in Annex 1 countries), thereby determining how the Kyoto Protocol commitments can be fulfilled in an efficient way. On the other hand, the costs of carbon fixation in countries from different climate zones can be compared. This is important because Non-Annex 1 countries act as competitors on the supply side of a future CER market. Finally, Non-Annex 1 countries can use a study like this to find out in which of their home regions carbon sequestration generates the lowest opportunity costs. The last point is important because our study is not restricted to valuation of carbon sequestration but provides the basis for making decisions on the right incentives, i.e. how much to pay for this ecosystem service.

---

[5] See for example Sedjo et al., 1994, Sedjo, 1999, van Kooten et al., 1999, Stavins, 1999, de Jong et al., 2000 #38

2 Conceptual approach

2.1 Objectives

2.1.1 Overall objective

The overall objective was to determine the ecological and economic feasibility of carbon sequestration projects in secondary forests and plantation forests in Ecuador and Argentina.

For the GTZ projects in Ecuador and Argentina (PPF-RN and PRODESAR), such an assessment helps in defining the role carbon sequestration can play in forest management, forest policies, sustainable development, local economies, soil conservation and the combating of desertification.

The objective of the project is also to support the political decision-making process concerning CDM sink projects within the Ministry of Environment in Ecuador and the Secretary of Agriculture, Animal Husbandry and Fishery in Argentina, as well as the Climate Change Offices in both countries.

2.1.2 Research objectives

- Estimation of the measurable and verifiable above- and below-ground carbon sequestration potential after conversion of pastures to pine tree plantations or native cypress forests in Patagonia, and after conversion of pastures to laurel tree plantations or secondary forest in Ecuador.

- Carry out a cost-benefit analysis - comparing the net benefits of forest systems with grassland systems - including carbon sequestration in forest systems as a potential benefit.

These objectives directly address the information needed for the evaluation of CDM sink projects and the implications for political decision-taking.

2.1.3 Project results and activities

- A statistical model has been developed that describes the total biomass in tree plantations and secondary forests as a function of climate, soil characteristics and vegetation age.

- A statistical model has been developed that describes the below-ground carbon sequestration potential of forests that grow on former pastures as a function of water availability, forest productivity, landscape position, land use history and soil characteristics.

- A comparative cost-benefit analysis has been carried out for secondary forests, plantation forests and grasslands (grazing) in order to determine the net benefits, taking into account carbon sequestration.

- The carbon sequestration function of forestry – as part of the benefits resulting from forestry activities – has been evaluated within the framework of the instruments given by the Kyoto Protocol. Advice is given in order to transform these findings into national policy, considering the background of the country in question and the requirements for sustainable development.

2.2 Methodology

2.2.1 Site selection

Experiments that monitor change in soil organic matter following land conversion require decades to provide conclusive results and were therefore not a feasible option. We chose pairwise pasture/forest comparisons in different biophysical settings, which provided more timely results, but was subject to the risk of confounding natural spatial variation with differential effects of land conversions (Rhoades et al., 2000). Proper site selection was therefore critical and was done with much care.

Within the study areas in Ecuador and Argentina, sites were selected where a grassland plot was found next to or very close - less than 1 km - to one (in Ecuador and some Argentinean sites) or two (in most Argentinean sites) forest plot(s). The size of the grassland and forest plots was at least 1 ha. Care was taken to obtain soil and terrain conditions as similar as possible for the plots within a site, in this way allowing for pairwise comparisons between pasture and forest plots.

The sites were selected in such a way that the variation in soil and climate conditions with the study area was represented as well as possible, within the limitations posed by the study design to find a grassland and forest plot next to each other. Furthermore, sites were selected so that grasslands and forests of different ages were included, allowing for the reconstruction of changes over time by means of chrono-sequences.

In Ecuador 40 sites were selected (Figure 5). At 34 of these sites, grassland plots were paired with a secondary forest plot, at 6 sites with a forest plantation plot. All secondary forests and plantation forests were established after the abandonment or conversion of former grassland. All grasslands were established after the cutting and/or burning of former forest, with subsequent sowing of grassland. Different grass species were being used over the 40 sites. In the grasslands no fertiliser was being applied. In many grasslands some trees remaining from the former forest were still scattered around.

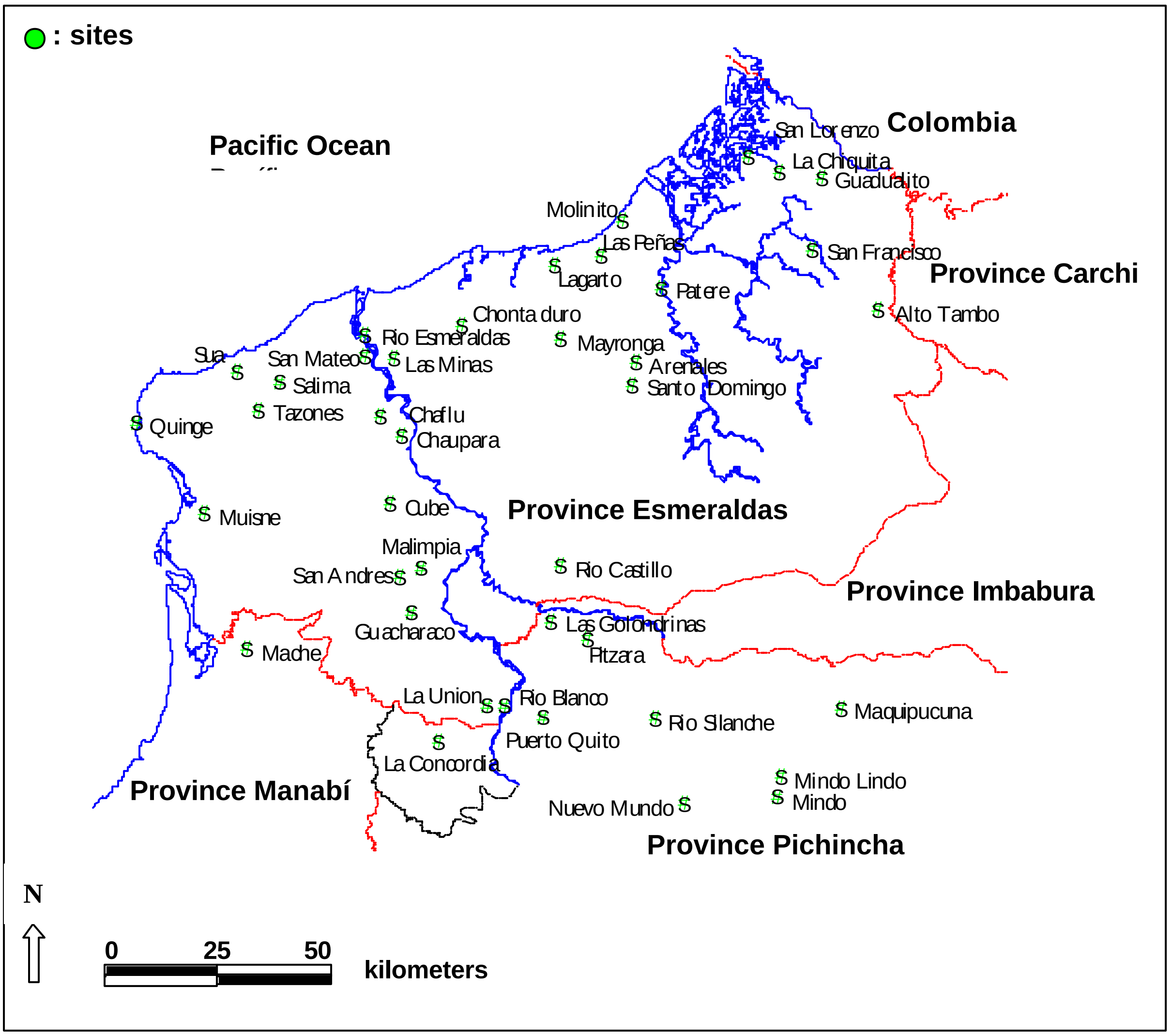

Figure 5. Sampling sites within the study area, Ecuador.

In Argentina, 39 sites were selected (Figure 6). At 28 sites a natural pasture plot was paired with a pine plantation plot and a cypress plot, at 6 sites a natural pasture plot was matched with 2 pine plantation plots of different ages, at 2 sites a natural pasture plot was matched with 2 cypress plots of different ages, and at 3 sites a natural pasture plot was matched with one pine plantation plot.

The pine plantations were established through planting in natural grassland. All cypress forests are the result of natural growth.

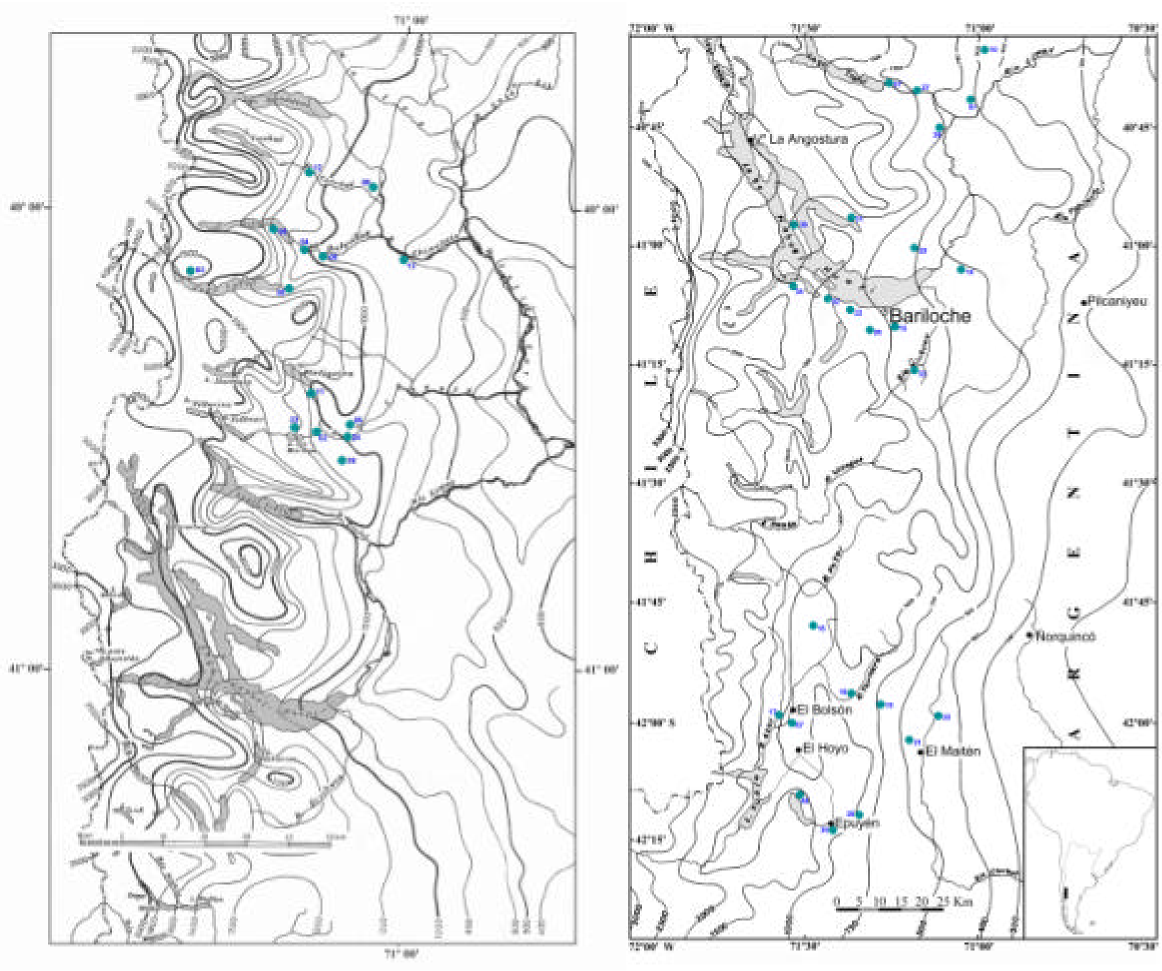

Figure 6. Sampling sites (indicated with numbers) within the study area, Argentina.

2.2.2 Data collection

Soils and biomass

Soil samples were collected according to a stratified random sampling scheme (López et al., 2002, de Urquiza et al., 2002). In each plot, at fixed distances of 0, 16.6, 33.3, and 50 m along a transect and at both sites of the transect, soil samples were taken at random distances between 1 and 25 m from the transect. At the 8 sample points thus determined, samples were taken with a steel auger from two soil layers: 0-25 cm and 25-50 cm, this way collecting in total 16 samples per plot. These samples were prepared for laboratory analysis by air-drying them and subsequently passing them through a 2 mm sieve.

At the four sample points at both sides of the 0 m and 50 m points of the transect, bulk density samples were taken from the two soil layers. These samples were taken with metal rings with a volume of 250 cm^3, avoiding distortion of the soil, and then dried in a stove for 24 hours at 105 °C and weighed in order to calculate dry soil mass per volume. This soil material was not further analysed. At the same four sample points where bulk density samples were taken, the pH of the two soil layers was determined in the field with a portable field potentiometer.

The following site and terrain characteristics were reported for all plots: geographical coordinates, altitude, slope, orientation, stoniness, drainage, evidence of erosion, and visual observations of soil characteristics. Land use history and actual land management was obtained through interviews with land owners. In the Argentinean forest plots, tree age at breast height was determined by counting year rings of a wood sample taken with an auger at breast height (130 cm).

In the forest plots in Ecuador, tree biomass was estimated by means of non-destructive inventories in areas varying from 600 m^2 to 1000 m^2, within the transect area where the soil samples were taken. Of all trees with a diameter at breast height (dbh) of at least 5 cm, dbh and tree height were measured, and the tree species noted. Using secondary information on specie-specific wood densities and form factors, individual trunk biomass dry weight was calculated as follows:

$$Bt = \frac{1}{4} \pi (DBH)^2 * TH * D * Ff \qquad (1)$$

Bt = Biomass dry weight of the trunk of a tree (ton)

DBH = Diameter at breast height (m)

TH = Tree trunk height (until crown) (m).
D = Specific wood density (g/cm^3)
Ff = Form factor (relation between the real trunk volume and the volume of a cylinder with the same diameter)

Total trunk biomass (Btt) dry weight per ha was obtained by summing the Bt's of all individual trees within the inventory area and subsequently extrapolating to biomass per ha. Total biomass dry weight per ha was estimated by multiplying the Btt with a biomass expansion factor (Bef). The Bef was taken from the literature (Brown et al., 1997):

For a total biomass less than 190 t/ha: Bef= Exp(3.213-0.506*ln(Btt))
For a total biomass of more than 190 t/ha: Bef = 1.74

The estimation of biomass in Ecuador has been documented in detail by López et al. (2002).

Biomass in the forest plots in Argentina was estimated with specific allometric regression equations developed for the region on the basis of destructive sampling methods (Laclau, 2002; Laclau et al., 2002a). For pine as well as cypress, individual trees were selected in order to cover all diameter classes between 5 cm and 35 cm: these trees were harvested, and their structural variables measured (diameter, height). Of these trees, the fresh weight of leaves/needles, branches and roots was determined, and sub-samples were dried for 96 to 120 hrs at 65-70 ºC in the laboratory to determine the dry weight. Trunk dry weight was determined by multiplying volume (calculated on the basis of diameter and height of various small segments of the trunk) by specific wood density. A density of 0.434 kg/dm3 was used for pine and 0.512 kg/dm3 for cypress. The weight determination numbers for pine trees were 65 for trunks, 30 for branches, 34 for needles, 62 for pen-roots and 62 for main roots. For cypress, 35 determinations were made for all compartments (trunks, branches, leaves, pen-root and main roots). With these data, regression equations were developed to relate structural variables to total biomass dry weight (Laclau at al., 2002a).

At the 39 plots selected in Argentina for this study, structural variables were measured in a 500 m^2 area within the same area where the soil samples had been taken. The allometric regression equations were applied in order to estimate total biomass (dry weight) per ha. These biomass estimations were used to investigate the relationship between tree biomass and soil organic carbon. For the economic analysis (Chapter 3), growth curves for pine plantations in relation to management and site index were used on the basis of documented studies for the study area (Laclau et al., 2002a).

In this study it is assumed that the amount of carbon is 50% of the biomass dry weight (IPCC, 2000).

Additionally, litter weight was estimated in the forest plots in Argentina by taking 12 samples with an iron frame of 40 by 50 cm within each plot. At fixed distances of 0, 10, 20, 30, 40 and 50 m along the transect, samples were taken at random distances between 1 and 25 m from the transect on both sites of the transect. The fresh weight of the 12 litter samples was determined in the field with a balance. Total dry weight was determined by taking a sub-sample that was subsequently dried in a stove at 60 ºC for 24 hours.

Geographical coordinates were used to derive additional information from existing digital maps. For Ecuador, information from 20 weather stations in the study area was collected in order to spatially interpolate precipitation data. The interpolated precipitation map was used to estimate annual precipitation for each site. Temperature was not considered separately as it is linearly related to altitude in the study area. For Argentina existing maps of isohyets were used.

Economic data

Economic data were collected through interviews with the owners of the land where soil and biomass data were collected. These data were completed with additional interviews in the study area and, in the case of Argentina, with existing data available at INTA from former studies with landowners, several of whom were in the sample of the current study. Additional information on prices and market developments was collected from secondary data sources. In this way, typical land use systems were identified and used for the economic analysis. For all forestry projects, a joint production of timber and CO_2 sequestration was assumed.

In the case of Ecuador, the study area was very diverse with respect to economic conditions. For the economic analysis, the study area was therefore stratified into 4 different zones as indicated in Figure 7 and Table 1 (Benítez et al., 2001). Zone 1 is characterised by a high percentage of land without agriculture, the importance of activities based on wood extraction, an increasing presence of oil palm plantations, low to medium accessibility to roads, low population densities, and low land prices. Zone 2 has intermediate land prices, large areas of relatively extensively managed pastures, and medium to high accessibility to major roads. Zones 3 and 4 have the highest agricultural productivity, which is reflected in the highest land prices. Access to major roads is good in these zones, especially in zone 4, which is close to Quito (approximately 2 hours). Zone 3 has a large percentage of agricultural crops, mainly oil palm plantations and banana plantations. In zone 4 cattle grazing is the most important agricultural activity.

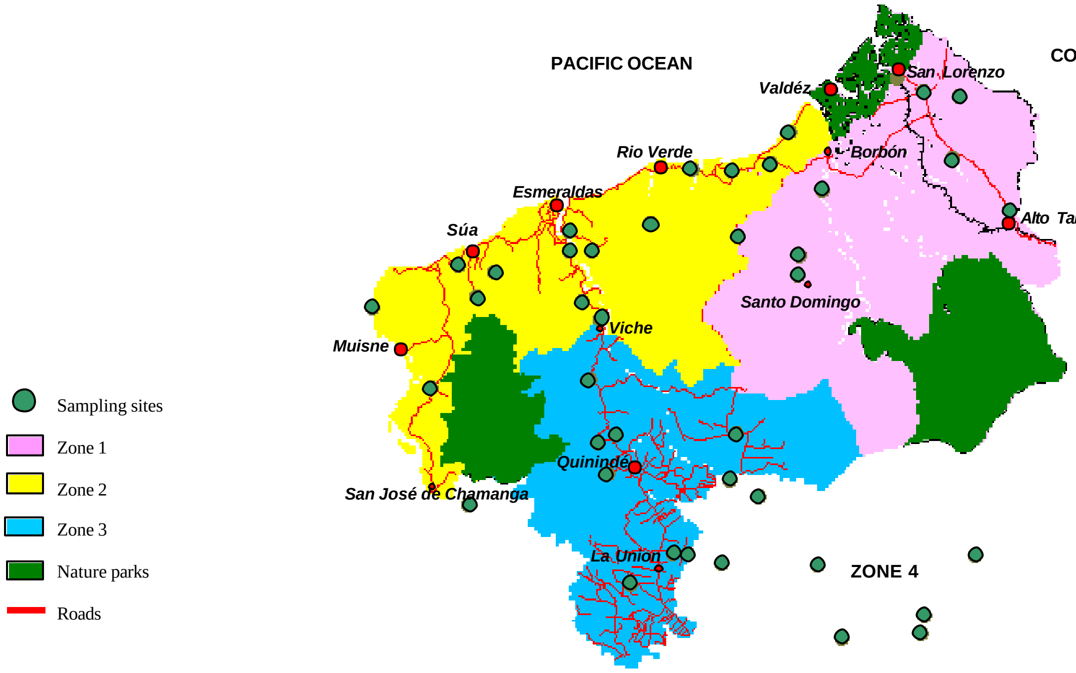

Figure 7. Economic zonification of the study area, Ecuador.

Table 1. Characteristics of the four economic zones within the study area, Ecuador.

Zone	***Area (1000 ha)***	***cantóns (administrative division)***	***Dominant land uses***	***Land use area in 1991 (source INEC) (Percentage of total area)***			***Access to roads***	***Rural inhabitants $(/km^2)$ (1990)***	***land price ($/ha)***
				pasture	crops	prim./sec. forest			
1	490	▪ San Lorenzo ▪ Eloy Alfaro (except La Tola)	▪ Forest: wood extraction ▪ Oil palm	5%	2%	93%	medium /low	4	$150 - $500
2	420	▪ Muisne ▪ Atacames ▪ Río Verde ▪ Esmeraldas ▪ Eloy Alfaro: la Tola	▪ Pasture: dual purpose cattle ▪ banana, plantain, cocoa	37%	10%	53%	high/ medium	20	$400 - $1000
3	450	▪ Quinindé ▪ Puerto Quito	▪ Oil palm, banana, cocoa ▪ Pasture: dual purpose cattle	28%	25%	47%	high	14	$800 - $2000
4	330	▪ Los Bancos ▪ Pedro V. Maldonado	▪ Pasture: dual purpose cattle ▪ Permanent crops	27%	8%	65%	high	7	$800 - $2000

2.2.3 Laboratory analyses of soil samples

Soil samples were analysed in the laboratory of the Institute of Soil Science and Forest Nutrition of the University of Goettingen, Germany. Part of the soil material of the individual samples was used to make composite samples for each layer per plot consisting of mixed material from the corresponding 8 samples. Carbon and nitrogen was analysed in all individual samples, while the other soil characteristics - used to explain soil carbon levels - were analysed for the composite samples.

For the individual soil samples (180 plots x 16 samples per plot = 2880 samples), the carbon and nitrogen content was determined by means of dry combustion with a Carlo Erba NA 1500 auto-analyser.

For the individual soil samples of Ecuador, the carbon isotope ratios were determined. Tropical grasses are a C4-type vegetation, while the forests are predominantly a C3-type vegetation. C4 and C3 plants have a different photosynthetic pathway. In C3 plants the first stable compound in the photosynthetic pathway contains 3 C-atoms, while in C4 plants the first stable compound contains 4 C-atoms. C3 plants discriminate more against ^{13}C occurring naturally in the atmosphere than C4 plants in the photosynthetic uptake of CO_2 (Balesdent et al., 1988), resulting in a lower $^{13}C/^{12}C$ ratio. In case of a conversion from C3 vegetation to C4 vegetation or vice versa, the carbon isotope ratio of soil organic matter can be used to determine which fraction of the soil organic matter originates from either vegetation. The carbon isotope ratios are expressed as $\delta^{13}C^0/_{00}$ (Balesdent et al., 1988) where:

$$d^{13}C = \left[\frac{(^{13}C/^{12}\ C)sample}{(^{13}C/^{12}\ C)reference} - 1 \right] * 1000 \qquad (2)$$

The reference value is the PDB carbonate standard. C3 vegetation has $\delta^{13}C$ values of around $-27^{0}/_{00}$ and C4 vegetation has $\delta^{13}C$ values of approximately - $12^{0}/_{00}$.

After a conversion from C3 forest to C4 pasture, the amount of soil organic carbon derived from forest and the amount of soil organic carbon derived from pasture can be calculated as follows (Dejardins et al., 1994)

$$C\mathrm{dp} = \left[\frac{(d^{13}Csp - d^{13}Csf)}{(d^{13}Cp - d^{13}Csf} \right] * Ct \qquad (3)$$

$$C\mathrm{df} = Ct - Cdp \qquad (4)$$

When:

Cdp = soil organic carbon derived from pasture

Cdf = soil organic carbon derived from forest

δ^{13}Csp = δ^{13}C value ($^{0}/_{00}$) of the pasture soil samples

δ^{13}Csf = δ^{13}C value ($^{0}/_{00}$) of the forest soil samples

δ^{13}Cp = δ^{13}C value ($^{0}/_{00}$) of litter material of pasture

Ct = total carbon content (t/ha) of the pasture soil

To determine their ^{13}C value, the ground soil samples were treated with HCL to remove any $CaCO_3$ and afterwards dried in a stove at 80 ºC. About 1 g of sample material was at 900 ºC. CO_2 and NO_x were trapped in liquid air (-186 ºC). O_2 was evacuated, and NO_x reduced to N_2 through copper. The remaining pure CO_2 was trapped with liquid N_2 and used to calculate the C content. The ^{13}C 5value was analysed with a mass spectrometer.

The ^{13}C value was also determined for litter material collected at each of the pasture and forest plots. The average ^{13}C value for pasture vegetation and forest vegetation was calculated and used for the calculation of fractions of carbon derived from pasture and forest.

No isotope analysis was used for Argentina, as both the pastures and forests in the study area comprise C3 vegetation.

The texture of composite samples (180 plots x 2 samples per plot = 360 samples) was determined with the pipette method, distinguishing the three fractions of clay (particle size < 0.002 mm), loam (particle size between 0.002 mm and 0.063 mm) and sand (particle size between 0.063 mm and 2 mm).

Mineralogy of composite samples was examined through extractions of aluminium (Al), iron (Fe) and silica (Si) with acid-oxalate and extractions of Al, Fe and Carbon (C) with pyrophosphate. Oxalate extractions of Al, Fe and Si indicate all active components of Al, Fe and Si, dissolving non-crystalline minerals such as allophane, imogolite, amorphous and poorly crystalline oxides like ferrihydrite as well as organo-mineral Al- and Fe- humus complexes (Mizota and Van Reeuwijk, 1993). Pyrophosphate extractions of Al, Fe and C detect selectively all Al, Fe, and C present in organo-mineral humus complexes (Shoji et al., 1993). Oxalate extractions were conducted using a 0.2 M ammonium oxalate solution buffered at pH 3 with oxalic acid, with a 1:50 soil:solution ratio. The solutions were shaken for 4 hours and centrifuged at 2500 rpm. The amount of Al, Fe and Si in the transparent solutions was analysed using inductively coupled plasma emission spectrometry (ICP).

Pyrophosphate extractions were conducted with a 0.1 M sodium pyrophosphate solution at pH 10, using a 1:100 soil:solution ratio. The solutions were shaken for 16 hours, and 25 ml of the solution was centrifuged during 15 minutes at

2500 rpm. The amount of Al, Fe and Si in the transparent solution was analysed with ICP. For the analysis of C, 10 ml of the transparent solution was centrifuged during 30 more minutes at 4000 rpm. Afterwards, 50 µl was put in capsules and left to dry for 1 hour. Subsequently carbon was determined by means of dry combustion with the Carlo Erba NA 1500 auto-analyser.

For Ecuador only, the light fraction was determined through suspension of soil material in a NaF solution.

2.2.4 Economic analysis

How to determine the costs of CO_2 sequestration?

Our analysis focuses on the marginal costs of sequestration, i.e. the costs that occur on the supply side of Certified Emission Reductions. By doing this we take the viewpoint of a typical landowner. The costs of CO_2 sequestration can be defined as the minimum financial compensation a landowner has to receive for changing, for example, one hectare of land from pasture to forestry for sequestration purposes. This compensation can be estimated by a comparison of costs and benefits of the different land use types. The criterion used is the Net Present Value (NPV), defined as:

$$NPV = PV(Benefits) - PV(Costs) \tag{5}$$

Benefits (B) and costs (C) occur at different times (t) and are subject to discounting (d=discount rate) in order to make them comparable:

$$NPV = \sum_{t=0}^{T} \frac{B_t}{(1+d)^t} - \sum_{t=0}^{T} \frac{C_t}{(1+d)^t} = \sum_{t=0}^{T} \frac{B_t - C_t}{(1+d)^t} \tag{6}$$

A profit maximising and risk-neutral landowner would switch from pasture to forestry if the NPV of the forestry alternative is higher or at least as high as the

NPV of pasture. In the latter case s/he has no preference for either of the two alternatives.

$$NPV_F \geq NPV_P \tag{7}$$

CO_2 sequestration (as a service produced by the landowner) could lead to extra revenues ($p_{CER} \cdot CER$) for the forestry alternative if CERs are traded on a market and purchased by Annex 1 countries. The present value (PV) of these revenues can be added to the inequation as follows:

$$NPV_F + PV_F[p_{CER} \cdot CER] \geq NPV_P \tag{8}$$

where *CER*= Certified Emission Reduction units measured in metric tonnes of CO_2 fixed by the forestry alternative and p_{CER} the market price of one CER. $PV_F[p_{CER} \cdot CER]$ calculates the present value of the CER revenues.[6] Equation *(8)* implicitly assumes a joint forestry production generating timber and CER revenues. Forests established only for CO_2 sequestration are not considered.

If both sides are set equal and the equation is solved for p_{CER}, we get:

$$P_{CER} = \frac{NPV_P - NPV_F}{PV_F\,[CER]} \tag{9}$$

This formula determines the minimum compensation, measured in US$ per CER, as the financial incentive for landowners necessary to switch from pasture to forestry.[7] This compensation can be interpreted as the "minimum price" of

---

[6] $$PV_F\,[\,p_{CER} \cdot CER] = \sum_{t=0}^{T} \frac{p_{CER} \cdot CER_t}{(1+d)^t} = p_{CER} \cdot \sum_{t=0}^{T} \frac{CER_t}{(1+d)^t} = p_{CER} \cdot PV_F\,[CER]$$

[7] The calculation of $PV_F \cdot [CER]$ is explained in the "CER Discounting" section.

carbon sequestration and can be calculated for different land use systems and regions based on an economic cost-benefit analysis.

What influences the "minimum price" of carbon sequestration?

The NPV of pasture and forestry appear in the numerator. If pasture is highly productive and leads to high net revenues per hectare, the resulting p_{CER} will also be high, because the incentive to change to forestry has to be relatively strong. If forestry generates a high NPV_F because of high timber revenues and low costs, the financial compensation can be lower because NPV_F has a negative sign. If NPV_F is both higher than zero and higher than the NPV of pasture, forestry is the better alternative and there is no need for compensation.[8] In this case we suppose that the profit-maximising landowner would switch to forestry even without CER revenues and would not fulfil the additionality criterion in Article 12 (5) of the Kyoto Protocol (UNFCCC, 1998)[9].

The denominator is the present (discounted) value of the Certified Emission Reductions. Consequently, the "minimum price" of sequestration will be relatively low if the forestry project allows a high and fast sequestration of CO_2 per hectare.

How can the present values be calculated?

The analysis includes benefits and costs of the different land use types within the project horizon.

---

[8] In case of a negative NPV_P, for the calculation of p_{CER} the NPV_P is set to zero, assuming that a potential compensation depends only on the respective NPV_F.

[9] In practice other factors may cause farmers not to switch to forestry, such as cultural factors, lack of technical assistance or perception of risk.

1. Pasture:

$$\begin{aligned} NPV_P = \; & PV_P\,(Pasture\ Revenues) \\ & - PV_P\,(Management\ Costs) \\ & - PV_P\,(Capital\ Opportunity\ Costs) \end{aligned} \tag{10}$$

2. Forestry:

$$\begin{aligned} NPV_F = \; & PV_F\,(Net\ Timber\ Revenues) \\ & - PV_F\,(Establishing\ Costs) \\ & - PV_F\,(Management\ Costs) \\ & - PV_F\,(Capital\ Opportunity\ Costs) \end{aligned} \tag{11}$$

The landowner's capital opportunity costs include the costs of holding land for production purposes. Otherwise s/he could sell the land and earn interest revenues on his or her bank account. According to equation *(9)* these costs – with the same value for pasture and forestry - appear in the numerator, but with different signs and thus add up to zero. Apart from this, a comparison of forestry alternatives shows that - in the case of secondary forest - only low costs (or even none at all) for establishing the forest have to be taken into account.

CER Accounting

When estimating CER benefits, an accounting approach and a financing procedure have to be decided on. The accounting approach refers to the way of calculating the carbon units sequestered by forestry alternatives and the minimum duration the carbon has to remain stored in order to be acknowledged. The financing procedure deals with the way in which payments for sequestration are organised (Moura Costa, 2000a). The chosen accounting and financing approaches have an influence on the revenues from carbon sequestration and, consequently, on its attractiveness for landowners. Various accounting and financing methods are possible (Fearnside, 2000). In the following, the average net storage method is used based on the formula below (Moura Costa, 2000b):

$$CER = \left[\frac{\sum_{t=0}^{100} (tons\,CO2\ stored\ in\ forestry - tons\,CO2\ stored\ in\ pasture)}{100} \right] \qquad (12)$$

The calculation is based on the assumption that permanence of carbon storage is achieved for a period of 100 years, and is used to estimate the amount of CO_2 stored on average during this period. This is done by summing up the respective annual net storage (forestry – pasture) of CO_2 per hectare divided by 100 years.

It is assumed that all carbon (in biomass and soil) is released immediately after finishing the project. This restrictive assumption reflects a conservative estimation of the sequestration potential and is in accordance with the "Revised 1996 IPCC Guidelines for National GHG Inventories", which - up to now - have excluded carbon fixed in products (IPCC, 1996).

The 100 years timeframe is presented in the IPCC report on "Land-use, Land-Use Change and Forestry" as one possible way of accounting, which is in accordance with the "100 years approach" of calculating the global warming potential (GWP) (IPCC, 2000). Later, a sensitivity analysis will show the impact on the results when using an alternative approach, assuming a shorter period of 46 years, which is called "equivalence-adjusted average storage" (Moura Costa, 2000c). This approach takes into account the fact that emitted carbon units do not stay in the atmosphere for 100 years, but will disappear earlier through natural processes (Fearnside, 2000).

CER Financing

After determining the CO_2 units stored by the different alternatives, a decision on the financing mechanism has to be made. One possible way would be to pay only for those units that have actually been stored for 100 years. This, of course, would make carbon sequestration extremely unattractive for landowners, as payments would not be generated until 100 years after switching from pasture to forestry. In the present study, payments are assumed to be generated according to the annual net increment of CO_2 fixation until the average net storage, determined by formula *(12),* is reached.

CER Discounting

The last step to determine the variable in the denominator of equation *(9)* is to calculate the present value of CER units. This is achieved by listing the annual net increment of CO_2 storage of the respective years (t = 0,…,a) until the average net storage is reached (in period t=a), and discounting these physical CER units according to the following formula:

$$PV_F\,[CER] = \sum_{t=0}^{a} \frac{(\text{annual net increment of CO2 storage in forestry})_t}{(1+d)^t} \qquad (13)$$

The procedure of discounting future benefits and costs at some positive real interest rate is widely accepted, as far as projects with timeframes of 30 to 40 years are concerned (Portney and Weyant, 1999). Discounting of project effects that lie beyond this horizon is subject to discussion, because this deals with intergenerational equity aspects rather than intragenerational saving and consumption decisions. When discounting long-term project effects (e.g. related to biodiversity or climate change), the outcome might seem to be ethically unacceptable. Nordhaus (1999) argues that a society may decide that such effects are "intrinsically important in a way that cannot be captured by market valuations". In this case, the “manipulating of a discount rate is […] a very poor substitute for policies that focus directly on the ultimate objective”, e.g. conserving biodiversity or avoiding climate change.

As pointed out in Figures 3 and 4, the approach of the present study does not evaluate future damage caused by climate change, but compares the costs of alternative measures in reaching a political target set by the Kyoto Protocol. All calculations are based on the viewpoint of the landowner when estimating the minimum compensation. Thus, the interest rate d used for discounting the physical CER units is the same as the one used for calculating the Net Present Values of the land use alternatives of forestry and pasture, based on equation *(8).*[10] The discount rate has a strong influence on the project’s results, which makes the determination of this rate critical:

Benefits and costs as well as CO_2 fixation occur at different times. They can be compared by discounting them to a base period. The question is, however, which interest rate should be used for discounting. As the calculation of NPV_F and NPV_P is based on 2001 market prices, i.e. using real instead of nominal prices, the interest rate must also be adjusted for inflation. Consequently, the real interest rate has to be calculated using the following formula:

$$i_t^r = \frac{i_t^n - p_t}{1 + p_t} \qquad (14)$$

where i_t^n is the nominal interest rate and p_t is the rate of inflation.

---

[10] For a further discussion of discounting physical CER units, see Richards (1997) and van Kooten et al. (1999).

Both in Ecuador and Argentina the determination of the real interest rate is a difficult task. Both countries are in a process of transition. In 2000 Ecuador changed the Sucre for the US Dollar as its official currency, while by the end of 2001 Argentina gave up its US Dollar parity (established by a currency board in 1991) to switch to a free-floating Peso. In both countries no fixed-interest bonds with a duration of about 20 to 30 years are issued, that could serve as an indicator for the long-term nominal interest rate.[11]

The Ecuadorian inflation rate reached about 91% in 2000 and about 22% in 2001 (Banco Central del Ecuador, 2002). According to a forecast by the Economist Intelligence Unit (2000), the reduction of inflation, which is one of the main goals of dollarisation, will be reached at an average level of 7.7% in the medium term. Comparison with the nominal reference interest rate of 15.23% stated by the Ecuadorian National Bank (Banco Central del Ecuador, 2002) results in a real interest rate of about 7%.

Argentina´s inflation was close to zero or even negative during the last few years (CEPAL, 2002). In the future, rising inflation may be expected due to the Peso devaluation and increasing governmental expenditure. In February 2002, inflation was about 4% on an annual basis (The Economist, 2002). According to the Central Bank of Argentina (2002), the interest rate for loans over a 10-year term is about 13% on average. If an average inflation rate of about 5% is assumed, a real interest rate of approximately 7% results. Using this rate as the discount rate (d = i = 0,07) would allow comparison with the Ecuadorian results, based on the same

---

[11] Interest rates of long term bonds are used for an approximation of the consumers' "time preference rate" or for the "opportunity cost rate" of investments. For a discussion of this procedure, especially when discounting intergenerational effects, see: Cline (1993), Lind (1995), and Schelling (1995).

discount rate. Due to uncertainty about future developments, a sensitivity analysis using different interest rates is conducted in this study.

2.3 Project participants and partners

2.3.1 Scientific supervision

Goettingen University provided the scientific supervision. The supervision of soil organic carbon research was in the hands of Prof. Dr. E. Veldkamp of the Institute of Soil Science and Forest Nutrition. Soil sample analysis was also completed in the laboratory of this institute. Economic supervision was provided by Dr. R. Olschewski of the Institute of Forest Economics.

Overall project coordination was the responsibility of Dr. F. de Koning, based at GTZ Ecuador.

2.3.2 Financial support

The project was financed by the Tropical Ecology Support Program (TOEB) of GTZ and supported by the following TOEB staff: Elisabeth Mausolf, Michaela Hammer, Rudiger Wehr, Dorothé Otto, Claus Bätke and Michael Tampe.

2.3.3 Local partners and counterparts

In Ecuador the project was executed within the PPF-RN project of GTZ (project leader Wolfgang Lutz), which has a direct counterpart in the Ministry of Environment of Ecuador. Two Ecuadorian professionals - soil scientist M. López and environmental economist P. Benítez - were employed within the project.

In Argentina, the project was executed at INTA (Instituto Nacional de Tecnología Agropecuaria) in Bariloche in direct relation with the PRODESAR project (project leader W. Moosbrugger). Two Argentinean professionals from INTA -

forest economist P. Laclau and ecologist M. de Urquiza - were employed within the project and supported by Dr. T. Schlichter, head of the forestry department of INTA.

2.3.4 Students

Four students from Goettingen University participated in the project, each producing their MSc research project resulting in an MSc thesis. Carsten Schusser and Friderike Oehler investigated soil carbon changes in Ecuador and Argentina, respectively, and Cornelia Dreyer and Carsten Huljus executed cost-benefit analyses for different land use types in Ecuador and Argentina, respectively.

3 Presentation of results

3.1 Biomass in forest systems

3.1.1 Biomass in forest systems in Ecuador

In the 34 secondary forest plots in Ecuador, 124 different tree species were found among the 1,645 trees measured. Of these, 21 species comprise 70% of the total amount of trees (Appendix 1). The most frequently encountered tree species are laurel (*Cordia alliodora*), Guabo (*Inga coruscana*), Chilca (*Vernonia baccharoides*) and Cordoncillo (*Piper aduncum*).

The frequency distribution of the estimated above-ground biomass for the 34 secondary forests is illustrated in Figure 8. The class from 150-175 t/ha has the highest amount of secondary forests (11), followed by the classes 125-150 t/ha and 175-200 t/ha, respectively.

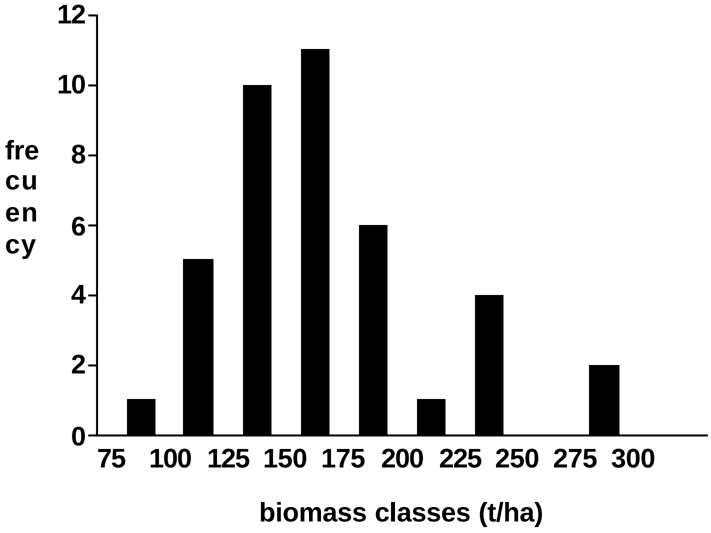

Figure 8. Above-ground biomass dry weight frequency distribution in secondary forests in Ecuador.

By means of regression analysis, the relation between biomass and the independent variables precipitation, soil texture, soil density, soil pH and forest age was investigated. No significant univariate and multivariate models could be constructed with climate and soil variables. However, a significant logarithmic regression model was found with age as the independent variable:

$$\text{Biomass} = 81.7 * \ln(\text{age}) - 54.7 \qquad (15)$$

The coefficient of determination of this regression model is 0.58. The model and the estimated biomass for each forest plot are plotted in Figure 9. According to the regression model, on average a total biomass of about 220 t/ha is reached after 30 years.

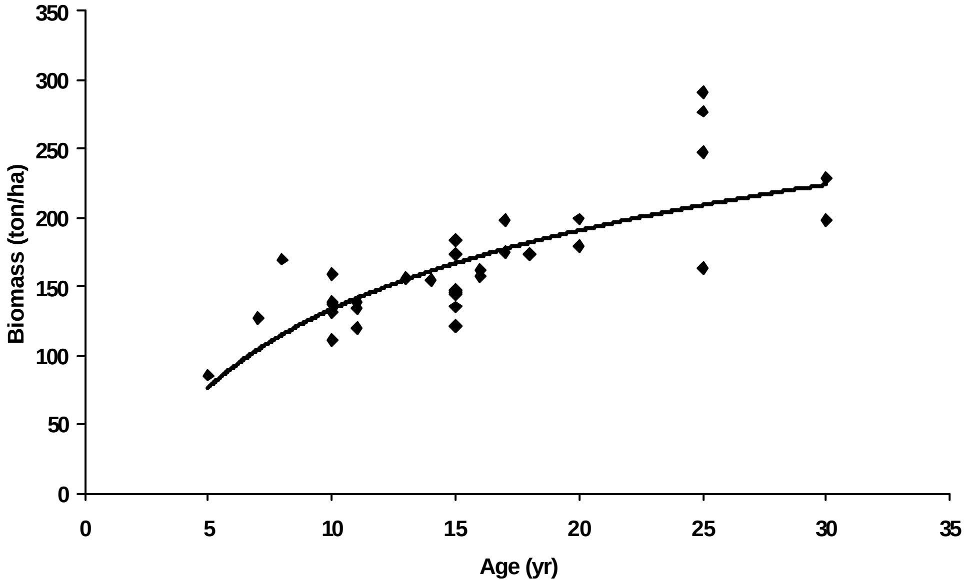

Figure 9. Relation between tree biomass dry weight (t/ha) and age of secondary forests, Ecuador.

If the secondary forest sites are stratified in 2 groups according to precipitation - less than 2500 mm/yr (18 sites) and more than 2500 mm/yr (16 sites) - a higher R^2

of 0.74 is obtained for the humid zone and a lower R^2 (0.40) for the drier zone (López et al., 2002), with faster biomass growth in the humid zone. However, it was decided not to stratify for the economic analysis and only use the more conservative biomass growth curve for the zone with less rainfall, which estimates a biomass of 200 t/ha after 30 years (see Section 3.3).

The biomass estimations for the 6 plantation forests are given in Table 2. Biomass estimations for all plantations are somewhat higher than the biomass estimation of secondary forests at the same age as estimated with the regression model of Figure 9. In particular, the estimated biomass for the teak plantation is high. However, the basal area measured in this plantation corresponds well with data from the literature for this area (INEFAN, 1996).

Table 2. Biomass estimations for forest plantations in Ecuador

Site name	Common name	Scientific name	Age (yr)	Biomass (T/ha)
Mayronga	Teca	*Tectona grandis*	9	184
Silanche	Tangaré	*Carapa guianensis*	21	213
Río Castillo	Cutanga	*Parkia multijuga*	15	194
Golondrinas	Laurel/Sande/Coco*	*Cordia alliodora/* *Brosimun/Virola sp.*	17	229
Concordia	Caucho injerto	*Hevea brasilensis*	7	108
Pitzara	Mascarey	*Hyeronima chocoensis*	10	155

* = mixed plantation.

Insufficient data were available from the plantation forest sites to reconstruct the increase of biomass over time for the study area. For this reason, literature data for north-western Ecuador on the biomass increments of laurel plantations (Alder and Montenegro, 1999) were used for the economic cost-benefit analysis. In the study area, laurel is the plantation tree species for which most information is available. Furthermore, a market exists for laurel wood. The biomass increment curves for 2 planting densities of laurel, estimated on the basis of Alder and Montenegro (1999) as described by Benítez et al. (2001), are shown in Figure 10. These are estimates based on medium site quality (site index 22).

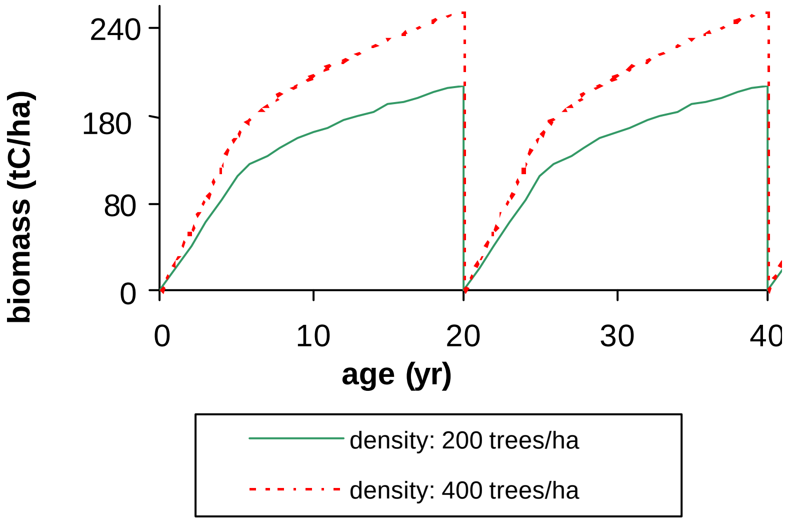

Figure 10. Growth curves for 2 planting densities of a plantation of laurel (*Cordia alliodora*), site index 22, Ecuador. (source: Alder and Montenegro (1999). Biomass expansion factor according to Brown (1997). Until year 5, linear growth is assumed.

3.1.2 Biomass in forest systems in Argentina

On the basis of the data from the destructive sampling, regression equations for individual pine and cypress trees were developed that predict the biomass dry weight in different compartments, using trunk volume as independent variable (Laclau et al., 2002a). Regression equations of the form $y=ax^b$ were used, where y is the biomass dry weight (g) of a compartment, x is the value of the independent variable trunk volume (m^3) calculated on the basis of DBH and height, and a and b are regression coefficients. The parameters of these regression equations are indicated in Table 3.

Table 3. Regression equations for biomass dry weight of different compartments of individual pine and cypress trees

Compartment	n	coef. a	coef. b	R^2
Pine				
Trunk	65	424434	0.988	0.99
Branches	30	74611	0.845	0.93
Needles	34	23643	0.455	0.66
Main roots	62	23525	0.810	0.74
Pen root	62	54941	0.787	0.83
Cypress				
Trunk	35	506011	0.966	0.99
Branches	35	73412	0.786	0.89
Leaves	35	15061	0.529	0.68
Main roots	35	23439	0.677	0.92
Pen root	35	23552	0.749	0.96

For pine, the models for biomass in trunks and branches have high coefficients of determination (R^2), while the lowest R^2 are for needles. The models for cypress have the lowest R^2 for leaves, and a high R^2 for all other compartments.

The regression models were used to estimate the total tree biomass per ha of all the forest plots of the study area, using the data of the structural variables (DBH, altitude) measured at the 500 m^2 sample area within the forest stands. Figure 11 shows the estimated above-ground biomass as a function of age at breast height (ABH).

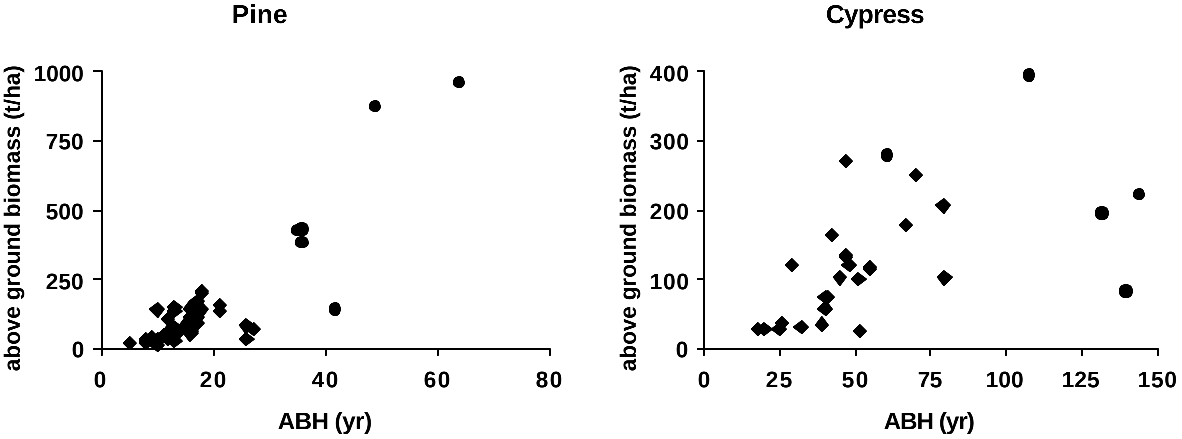

Figure 11. Above-ground biomass dry weight (t/ha) as a function of age in pine and cypress stands, Argentina. ABH= Age at Breast Height (see text). Filled circles indicate that diameters fall outside range of equations of Table 3.

In some older stands, the diameters fell outside the range (5-35 cm) for which the equations of Table 3 were developed. For this reason, the results for these stands have to be interpreted with caution. A possible error is associated with the estimations for branches and needles/leaves, as the trunk biomass is estimated on the basis of the volume. In the case of cypress, trees of different ages are found within one stand, and for the situations presented in Figure 11 the ABH represents the oldest cypress trees within a stand. The differences in age within a stand and the large differences in tree density between stands explain the larger variation within age classes for cypress than for pine. It can be observed that at similar ages, the above-ground biomass is much higher for pine than for cypress.

For the pine stands, above-ground biomass is also positively correlated with precipitation. A significant regression equation could be constructed explaining above-ground biomass on the basis of age (yr) and annual precipitation (mm) with an adjusted R^2 of 0.806:

$$\text{Above-ground biomass} = 12.6*\text{ABH} + 0.135*\text{precipitation} - 235.8 \qquad (16)$$

For cypress no significant correlation was found with precipitation.

Trunks are the most important biomass compartment of individual trees, occupying a percentage of total tree biomass (including roots) of 40% for pine and 55% for cypress for small trees (diameter 5-10 cm), and 65% for pine and 75% for cypress for trees with a diameter between 30-35 cm.

The root biomass is on average 19.5% of the total biomass for the pine stands and 11.4% of total biomass for cypress stands.

The needles/leaves occupy a high percentage of total biomass in small trees (45% and 25% for pine and cypress respectively), but this share decreases with diameters over 30 cm, where trunks, branches and roots together constitute more than 80% of the total biomass.

For the economic analysis, growth curves for pine developed within INTA were used (Laclau et al., 1999). These curves describe growth of pine plantations for different site indices in the study area, taking into account pruning, thinning and harvesting of the stands at the most appropriate age. Figure 12 shows the growth curves for three site indices, indicating total biomass as a function of age after planting. Indicated age is the number of years after planting. ABH is 3, 4 and 5 years higher than the age after planting for SI 19, SI 15 and SI 11, respectively. SI 19 indicates very suitable sites, SI 15 suitable sites and SI 11 slightly suitable sites.

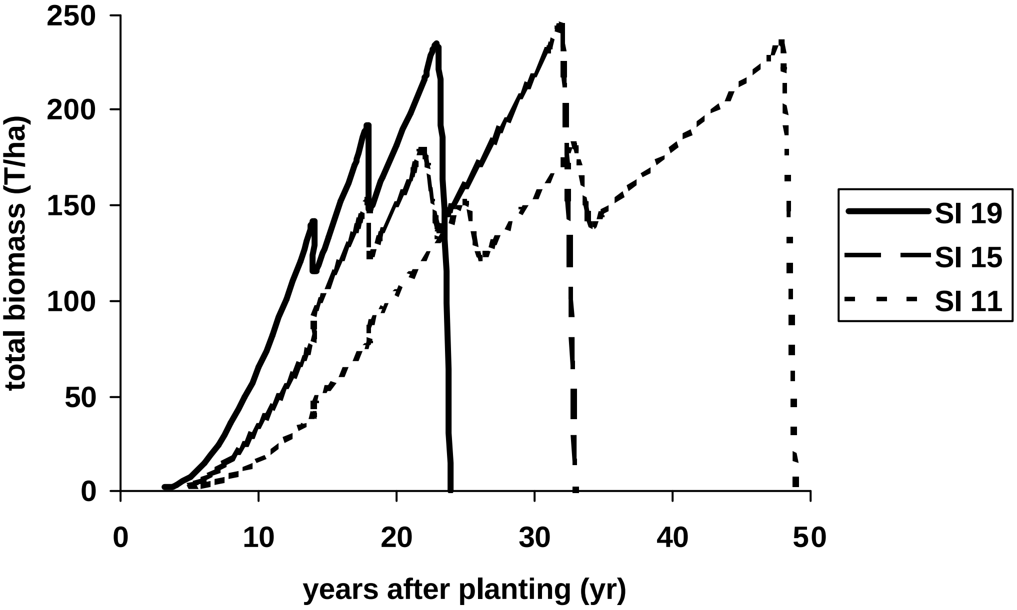

Figure 12. Growth models for pine for three site indices, Argentina.

3.2 Soil organic carbon in grassland and forest systems

3.2.1 Soil organic carbon in grassland and forest systems in Ecuador

Site characteristics in Ecuador

The general characteristics of the 40 sites in Ecuador are summarised in Appendix 2. Annual precipitation generally increases with altitude, and altitude in turn is related to soil characteristics. Volcanic soils are located at higher altitudes and sedimentary soils at low altitudes. This is illustrated in Table 4, which shows Spearman rank correlations between altitude and site characteristics, such as precipitation, slope, texture and mineralogy (as expressed by oxalate and pyrophosphate extractions) of the 0-25 cm layer, for the pasture and forest sites. Site 40 was excluded from analysis because it is outlying. Non-parametric correlation was chosen as not all variables were normally distributed. Some derived variables were used. The total of clay and silt percentages indicates the soil mineral fraction that predominantly stabilises soil carbon. Pyrophosphate extracted aluminium (Alp) divided by oxalate extracted aluminium (Alo) is an indicator for allophane content, with values close to zero indicating the predominance of allophane, and values close to one indicating the predominance of aluminium-humus complexes. Soils with Alp/Alo values lower than 0.5 are generally considered allophanic (Mizota and Van Reeuwijk, 1993; Shoji et al., 1993). Similarly, Alo minus Alp is an indicator for non-crystalline minerals, with high values indicating high contents of these minerals.

The correlation coefficients in Table 4 for both pastures and forests clearly demonstrate the positive relation between altitude and precipitation and associated changes in texture and mineralogy. At higher altitudes, soils increasingly show volcanic properties with increasing total amounts of aluminium, iron and silica and decreasing fractions of humus-associated aluminium and iron. This gradient is accompanied by decreasing amounts of clay and silt. Similar coefficients are found for pastures and forests, reflecting the fact that within sites the biophysical characteristics were similar for the pasture and the forest plot.

Closer analysis through scatter plots indicated that the two main soil groups - volcanic and sedimentary soils - belong to two different soil systems with characteristics of texture and mineralogy that do not form a continuum over the 40 sites (López et al., 2002). Volcanic soils constitute a separate group with clearly lower levels of clay and silt and higher levels of non-crystalline minerals, indicated by high values for Sio, and Alo-Alp, and low values of Alp/Alo. For this reason, these groups will be treated independently in some of the following analyses.

Table 4. Spearman rank correlation between altitude and other site characteristics, Ecuador. (*: p-value < 0.05, **: p-value < 0.01).

	Pastures	**Forests**
slope	0.27	0.31
precipitation	0.48**	0.43**
clay	-0.56**	-0.52**
sand	0.55**	0.49**
silt	-0.38*	-0.29
clay+silt	-0.55**	-0.49**
Alo	0.62**	0.60**
Feo	0.52**	0.50**
Sio	0.59**	0.57**
Alp	0.64**	0.65**
Fep	0.25	0.37
Alp/Alo	-0.26	-0.19
Alo-Alp	0.57**	0.49**

Soil carbon and nitrogen in pastures and forests in Ecuador

Appendix 3 lists the carbon and nitrogen concentrations of the 40 pasture and forest plots in the 0-25cm and 25-50 cm layers with the coefficients of variation (CV), as well as the C/N ratio. With exception of site 40, which has atypically high values - probably as result of frequent inundations - carbon contents in the 0-25cm layer range between 1.2% and 6.9% in pastures and 1.6% and 6.5% in forests. In the 25-50 cm layer, carbon contents are clearly lower, ranging between 0.3% and 3.4% in pastures and between 0.3% and 3.5% in forests. In most sites the carbon content in the deeper layer is 2 to 3 times lower than in the top layer. C/N ratios are on average close to 10.

Carbon contents are determined by site characteristics as illustrated by the Spearman rank correlation coefficients listed in Table 5 for the two soil groups separately, as well as all sites lumped together. As expected, high correlations are found in the 0-25 cm layer between total carbon and carbon in organo-metal complexes (indicated by Cp). Negative correlations with bulk density indicate the higher carbon contents, with increasing volcanic properties accompanied by lower bulk density. This is also illustrated by the significant positive correlation coefficients between carbon and both altitude and precipitation when all sites are considered. With respect to texture, carbon is positively associated with silt and clay contents, and negatively with sand contents, as expected. These texture-related associations are strongest in sedimentary forest soils, while none of the coefficients for pasture is significant. In pastures, carbon contents decrease with age, while in forests the opposite occurs, especially in volcanic soils.

Table 5. Spearman rank correlation between carbon contents and site characteristics, 0-25 cm layer, Ecuador. (*: p-value < 0.05, **: p-value < 0.01).

	pastures			**forests**		
	sedimentary	**volcanic**	**all**	**sedimentary**	**volcanic**	**all**
altitude	0.15	0.15	0.52**	0,26	0.31	0.60**
slope	-0.20	-0.20	0.11	-0,04	0.16	0.03
precipitation	0.29	0.06	0.54**	-0,004	0.06	0.40*
clay	0.16	-0.01	-0.41	0.57**	0.04	-0.27
sand	-0.27	-0.45	0.28	-0,5**	-0.28	0.22
silt	0.07	0.43	-0.07	0,15	0.43	-0.13
clay+silt	0.27	0.45	-0.28	0,52**	-0.28	-0.22
pH	-0.09	-0.07	-0.30*			
bulk density	-0.70**	-0.69*	-0.76**	-0,65**	-0.76**	-0.77**
age	-0.23	-0.46	-0.35*	0,02	0.38	0.11
biomass				-0.09	0.78**	0.08
Alo	0.41*	0.88**	0.70**	0.40*	0.85**	0.69**
Feo	0.37	-0.38	0.54**	-0.02	-0.27	0.39*
Sio	0.26	0.77**	0.62**	0.16	0.81**	0.58**
Alp	0.38	0.93**	0.69**	0.16	0.97**	0.61**
Fep	0.27	0.43	0.52**	0.12	0.39	0.40*
Alp/Alo	-0.05	-0.78**	-0.41**	-0.04	-0.77**	-0.35*
Alo-Alp	0.32	0.85**	0.68**	0.14	0.83**	0.56**
Cp	0.78**	0.89**	0.85**	0.74**	0.88**	0.84**

In volcanic forests, a strong positive correlation exists with biomass. Indicators for mineralogy show in general stronger and more significant correlations than texture variables, especially in volcanic soils. Particularly strong is the positive relation of carbon with total and humus-associated aluminium in volcanic soils. The negative relation with Alp/Alo indicates increasing carbon contents with increasing levels of allophane. The results of Table 5 indicate that in volcanic soils carbon is stabilised in organo-metal complexes as well as in complexes with allophane and with clay and silt minerals. Positive correlations with Fep confirm the occurrence of carbon in carbon-iron complexes. For the 25-50 cm soil layer, patterns are similar as for the top 25 cm but correlations are weaker (not indicated in Table 5).

In order to determine which are the best predictor variables for soil carbon, multivariate regression models were constructed using stepwise variable selection. The models are provided in Table 6.

Table 6. Multiple regression models for the prediction of carbon content in the 0-25 cm layer under pastures and forests, Ecuador. n=12 for volcanic soils, n=24 for sedimentary soils. Units used**:** Alo, Alp, Sio, Fep, clay and silt: %; C: %.

PASTURES:			
Soil group	**model**	**p-value model**	**R^2**
All soils	Log (C%) = 0.103 + 0.74 * Alp + 0.0019 * (clay + silt)	0.00	0.71
Volcanic	C% = -0.32 + 7.2 * Alp + 0.79 * Sio	0.020	0.97
Sedimentary	C% = 1.62 + 2.97 * Alo	0.000	0.21
FORESTS:			
Soil group	**model**	**p-value model**	**R^2**
All soils	Log (C%) = 0.36 + 0.14 * Alo	0.023	0.61
Volcanic	C% = 0.45 + 9.34 * Alp - 4.58 * Fep	0.020	0.95
Sedimentary	C% = 0.45 + 0.049 * clay + 5.55 * (Alo-Alp)	0.000	0.39

For all pasture soils, 71 percent of carbon variation is explained with the pyrophosphate-extracted aluminium and the total of clay and silt fractions. For volcanic pasture soils the independent variables Alp and Sio indicate the importance of both organo-metal complexes and allophane and imogolite for the prediction of total carbon contents, with a coefficient of determination of 0.97. The model for sedimentary pasture soils explains less of the soil carbon variation, with oxalate-extracted aluminium as the only independent variable. For forest soils the coefficients of determination are similar to the models for pasture.

Soil carbon differences between pastures and forests in Ecuador

In Appendix 3, soil organic carbon differences between pasture and forest are given per site for carbon percentages and total carbon content in the top 50 cm expressed as t/ha. In order to be able to compare the same mass of soil for pasture and forest within a site, the bulk density (average value of 4 sample points per layer) of forest at the site was used for forest as well as pasture in order to correct for compaction in pasture. For the differences between percentages C, significant differences as calculated with a t-test (8 observations per soil layer) are also indicated in Appendix 3. Positive differences indicate higher carbon concentration in the forest than in the pasture. The average difference in carbon content (%) in the 0-25 cm layer is positive at 0.25%. So the average carbon content in forests is 8.3% higher than the average carbon content in pastures in this layer (Figure 13). In the 25-50 cm layer the average difference is 10 times smaller, indicating an average carbon content in forests 1.6% higher than the average carbon content in pastures in this layer.

In the 0-25 cm layer 27 sites have a positive difference, of which 9 are significant ($p < 0.05$). Of the 13 negative differences, only 1 is significant ($p < 0.05$). In the 25-50 cm layer, 21 sites have a positive difference, of which 4 are significant (p < 0.05), while 19 sites show a negative difference of which 6 are significant (p < 0.05).

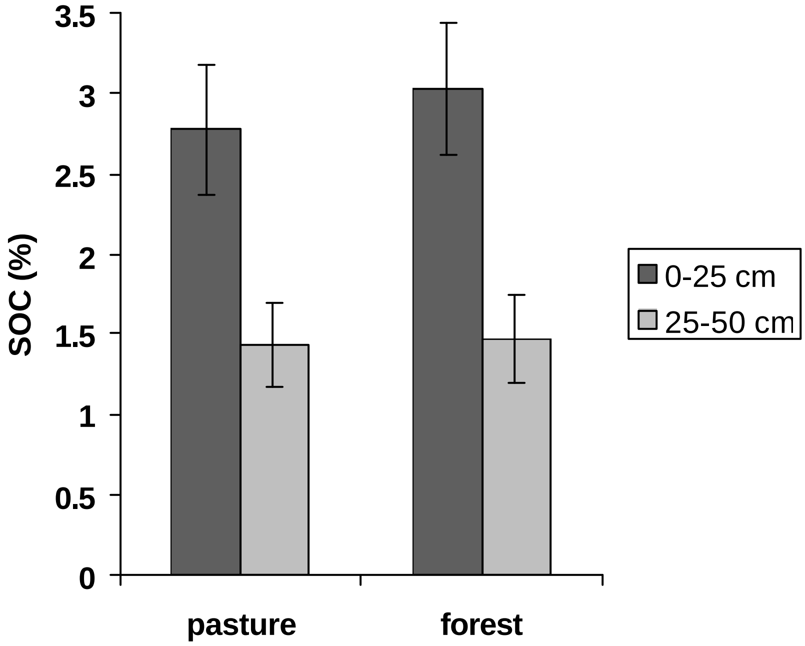

Figure 13. Average soil organic carbon contents (%) in 0-25 cm and 25-50 cm layers of pastures and forest, Ecuador. Error bars indicate 95% confidence intervals.

In terms of carbon inventories for the top 50 cm expressed as t/ha, site differences between pasture and forest range between -51.3 and 50.9 t/ha (SOC forests minus SOC pastures). The average amount of total carbon in pastures is 100.9 t/ha and in forests 107.9 t/ha, an average difference of 7 t/ha, representing a total amount of carbon in forests on average 7% higher than in pastures. The differences between pastures and forests are greater in volcanic soils (9.7 t/ha) than in sedimentary soils (5.7 t/ha) (Figure 13), although relative differences - expressed as a percentage of pasture carbon - are comparable: 7.5% and 6.6% for volcanic and sedimentary soils, respectively.

The amount of carbon in the 0-25 cm layer extracted by pyrophosphate (Cp) - a measure of the carbon in organo-metal complexes - was on average 31% of total carbon for pastures and 30% for forests. The light fraction represented only a small percentage of total carbon in the 0-25 cm layer: 4.1% for pastures and 4.8% for forests.

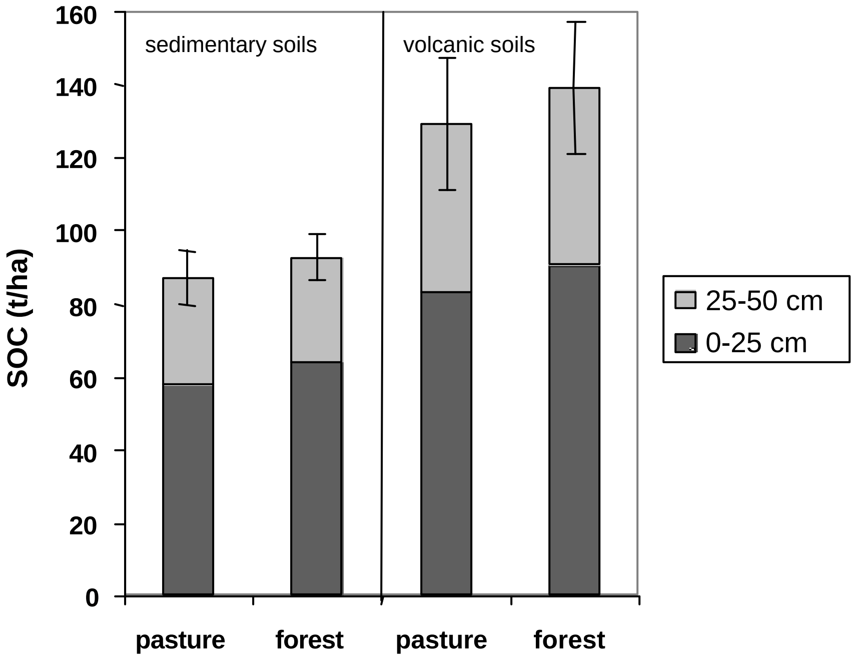

Figure 14. Average total soil organic carbon (t/ha) in 0-25 cm and 25-50 cm layers of pasture and forest, for sedimentary soils and volcanic soils, Ecuador. Error bars indicate 95% confidence intervals of total carbon (t/ha) 0-50 cm.

The effect of land use on soil carbon and bulk density was tested by means of a paired t-test (Table 7). The difference in soil carbon - expressed as percentages as well as t/ha - over the 40 sites is significantly positive in the 0-25 cm layer but not for the 25-50 cm layer ($p < 0.05$). The positive total soil carbon difference in the top 50 cm is significant as well. Significant differences in bulk density indicate compaction of grasslands due to cattle grazing. Differences in pyrophosphate-extracted carbon (Cp) in the top layer are not significant. Differences in total carbon minus Cp, however, are significant. Differences in carbon light fraction in the top layer are significant, but represent only a small part (12%) of the total difference in carbon percentage.

Table 7. Results of the paired t-test, Ecuador. (n=40, *: p-value < 0.05)

variable	**difference** (mean value pasture minus mean value forest)	**significance level (p-value)**
C (%) 0-25 cm	-0.25	0.026*
C (%) 25-50 cm	-0.024	0.726
C (t/ha) 0-25 cm	-6.27	0.018*
C (t/ha) 25-50 cm	-0.74	0.656
C (t/ha) 0-50 cm	-7.01	0.046*
bulk density (g/cm^3) 0-25 cm	0.046	0.018*
bulk density (g/cm^3) 25-50 cm	0.078	0.024*
Cp (%) 0-25 cm	-0.046	0.329
C (%) minus Cp(%) 0-25 cm	-0.204	0.017*
C light fraction (%)	-0.032	0.031*

*: p-value < 0.05

The paired t-test can be used to test the average effect of land use, but it does not account for specific site characteristics that influence the effect, especially vegetation age. Therefore, the differences per site were analysed for their relation with site characteristics. The effect of vegetation age was verified by grouping the sites according to pasture age (Figure 15). Secondary forests that are paired with pastures of less than 10 years have on average 9.3 t/ha (7.9%) less soil carbon than the pastures. When paired with pastures between 10 and 20 years, secondary forests have on average 5.2 t/ha (4.8%) more soil carbon than pastures, which increases to 18.8 t/ha (20.7%) for pastures between 20 and 30 years and decreases slightly to 15.8 t/ha (18.7%) for the oldest pastures. The 95% confidence intervals are large, indicating high variability within pasture age classes.

This variability decreases with pasture age. When the SOC difference for each age class is expressed as difference divided by forest age, this value increases strongly from -0.47 t/(ha yr) for the youngest pastures to 1.32 t/(ha yr) for the pastures between 20 to 30 years. Thereafter the value slightly increases to 1.42 t/(ha yr), indicating that differences are starting to level off.

Figure 15. Differences in the amount of total soil organic carbon (t/ha) in the 0-50 cm layer between pastures and forests in dependence of pasture age class, Ecuador. Positive differences indicate higher content in forests than in pastures. Errors bars indicate 95% confidence interval. Number of observations: age class < 10: n=11; age class 10-20: n=8; age class 20-30: n=10; age class >30: n=10.

In order to investigate the relative importance of pasture age and abiotic site characteristics, multivariate stepwise regression was applied for the dependent variable soil carbon differences per site (forest carbon minus pasture carbon, expressed as t/ha) (Table 8). For all soils lumped together, as well as for volcanic soils, pasture age and altitude are selected. None of the soil texture or mineralogy variables is selected, although altitude is related to soil characteristics. For volcanic soils, 84% of the variation in carbon differences can be explained, while the figure for sedimentary soils is only 23%. For sedimentary soils the only selected variable is Alo.

Table 8. Multiple regression models for the prediction of differences in total SOC (0-50 cm) between pastures and forests, Ecuador. n=12 for volcanic soils, n=24 for sedimentary soils. Dif C is SOC in the top 50 cm soil layer of forest minus pasture. Units: pasture age: yr; altitude: masl, Alo: %.

soil group	model	p-value model	R^2
All soils	Dif C (t/ha) = 0.98 * (pasture age) + 0.0249 * altitude - 17.31	0.002	0.38
Volcanic	Dif C (t//ha) = 1.66 * (pasture age) + 0.032 * altitude - 35.79	0.001	0.84
Sedimentary	Dif C (t/ha) = -119.87 * Alo + 32.69	0.009	0.23

Determination of carbon origin with ^{13}C isotope analysis in Ecuador

The average soil ^{13}C values for each plot and each depth were used to calculate the fraction of total soil organic carbon derived from pasture and from forest in the pasture plots as well as the forest plots, as explained in Chapter 2. As Chapter 2 states, all pasture plots were previously forests, just as all forest plots were previously pastures. The land use sequence of the pasture plots is therefore: native (intervened) forest - pasture, and the land use sequence of the forest plots is: native (intervened) forest - pasture - secondary or plantation forest. The results of the isotope analysis are shown in Figure 16.

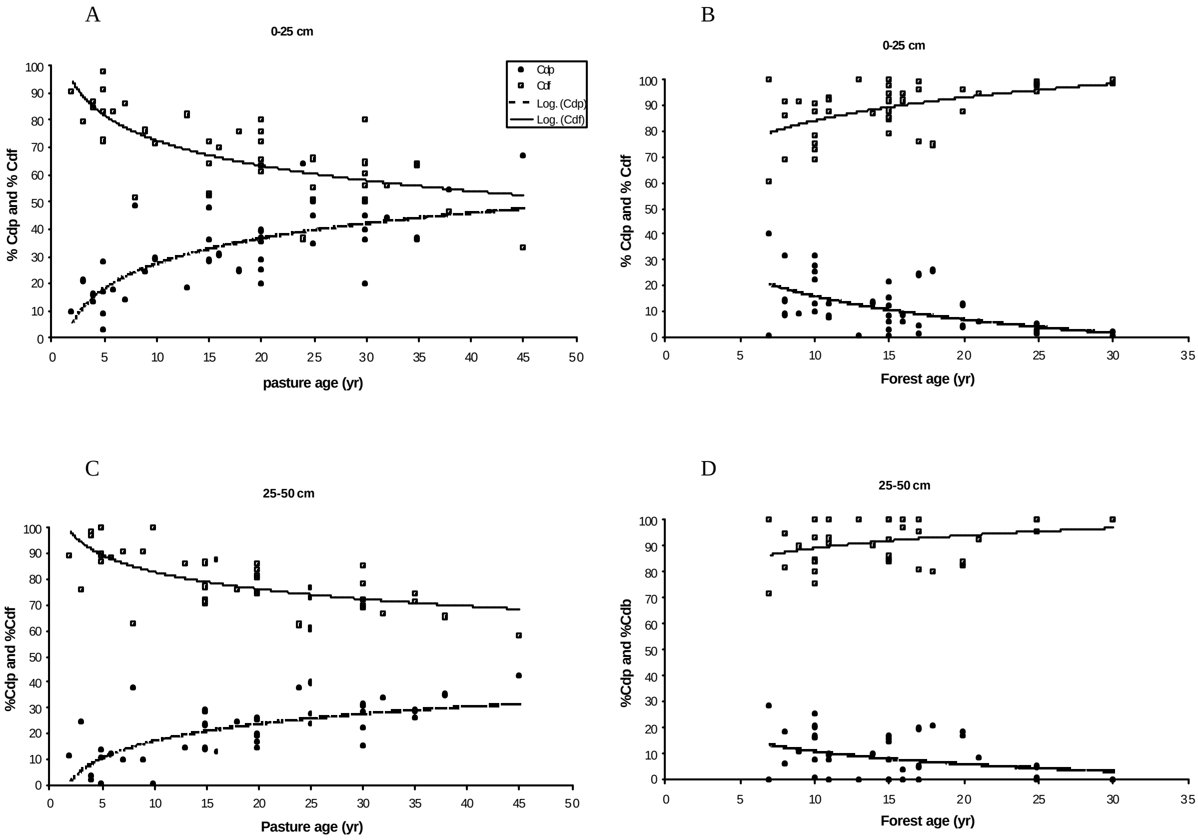

Figure 16. Fractions of carbon derived from forest and pasture as a function of vegetation age in 0-25 cm and 25-50 cm layers at pasture plots (Figures A and C) and forest plots (Figures B and D), Ecuador.

Figure 16A and 16C indicate the fractions of pasture-derived (Cdp) and forest-derived (Cdf) carbon in pasture plots as a function of pasture age for the 0-25 cm and 25-50 cm soil layers, respectively. A logarithmic curve is fitted through the calculated Cdp and Cdf values for the range of pasture ages encountered in the selected plots. In the 0-25 cm soil layer in very young pasture plots, virtually all soil organic carbon originates from the forest that was cut for pasture establishment. However, in the first years of pasture growth, the fraction of pasture-derived carbon increases quickly and, accordingly, the fraction of forest-derived carbon decreases quickly with pasture age. After about 20 years, rates of change decrease, and after 45 years of pasture the fraction of carbon originating from the forest reaches a more or less stable level of around 50% of total carbon. This forest-derived carbon is apparently not degradable over the rather large time-span considered, and can therefore be regarded as stable carbon (Veldkamp, 1994). The labile fraction is the amount of carbon that can be manipulated through land management, and is therefore of interest for carbon sequestration projects.

In the second layer, the changes in Cdp and Cdf over time are substantially lower. This could be due to the fact that the roots of the pastures are concentrated in the top 25 cm, as well as to lower mineralisation rates at greater depths. Trumbore et al. (1995) have shown that the passive carbon fraction increases with depth.

In the forest plots (Figures 16B and 16D), the fraction of pasture-derived carbon is small and virtually disappears after about 30 years. The forest-derived carbon consists of the newly incorporated carbon after the pasture was abandoned, the stable forest carbon that still remained from the former forest before the pasture was established (which is about 50% of the soil carbon content in the forest that existed before the pasture, as indicated in Figure 16A and 16C), and some labile forest carbon from the former forest. This last amount depends on how long the pasture existed between the two forest covers, and could not be determined. The amount of pasture-derived carbon in these forest plots depends on the total time the previous pasture plot existed.

3.2.2 Soil organic carbon in grassland and forest systems in Argentina.

Site characteristics, Argentina

The general characteristics of the 39 sites in Argentina are summarised in Appendix 4. In general, annual precipitation decreases from west to east. Precipitation ranges from 550 mm to 1700 mm with the exception of the Quechuquina site, which has a precipitation of 2450. In contrast to the sites in Ecuador, no clear soil groups can be distinguished for the sites in Argentina. The soils all have volcanic characteristics, with a large sand fraction and a small clay fraction similar to the volcanic soils of Ecuador. The Argentinean soils have allophanic properties with Alp/Alo ratios (with the exception of 1 plot) ranging from 0.14 to 0.51 and an average Alp/Alo ratio of 0.28. Soils with Alp/Alo values lower than 0.5 are generally considered allophanic (Mizota and Van Reeuwijk, 1993; Shoji et al., 1993).

Table 9. Spearman rank correlation between precipitation and other site characteristics, Argentina. (*: p-value < 0.05, **: p-value < 0.01).

	pasture	cypress	pine
altitude	0.273	0.181	0.312*
clay	-0.357*	-0.096	-0.273
sand	0.107	-0.045	-0.20
silt	0.057	0.108	0.137
Alo	0.499**	0.081	0.586**
Feo	-0.137	-0.244	-0.258
Sio	0.386*	0.056	0.480**
Alp	0.528**	0.123	0.633**
Fep	0.276	0.171	0.251
Alp/Alo	0.03	0.394*	-0.034
Alo-Alp	0.440*	0.050	0.496**

Table 9 shows Spearman rank correlations between precipitation and site characteristics such as altitude, texture and mineralogy - as expressed by oxalate and pyrophosphate extractions, and by Alp/Alo and Alo minus Alp (see Section 3.2.1) of the 0-25 cm layer, for the pasture and forest sites. There is a positive correlation between precipitation and altitude, though this is only significant for the pine plots. The negative relation between precipitation and clay content is only significant in the pasture plot. The strongest relations are found between precipitation and aluminium content (Alp as well as Alo) in pasture and pine plots, which is accompanied by a positive relation with the amount of Alo minus Alp, indicative for aluminium associated with non-crystalline minerals.

Soil carbon and nitrogen in pastures and forests in Argentina

Appendix 5 lists the carbon and nitrogen concentrations of the 50 pasture and forest plots in the 0-25cm and 25-50 cm layers with the coefficients of variation (CV), as well as the C/N ratio. Pastures at sites 6, 16, 17, 21, 34 and 39 were located in so-called *mallines*, which are pastures that are part of the year inundated as indicated by their hydromorphic characteristics. The inundations result in organic matter accumulation and high carbon contents. Although indicative of carbon contents under these conditions, these sites were excluded from the pasture-forest comparisons, as the forest sites were not located in areas with inundations. Carbon contents in the 0-25cm layer range between 0.7% and 9.9% in pastures, between 1.3% and 6.9% in cypress, and between 0.6% and 8.1% in pine. Carbon contents in the 25-50 cm layer are lower, but the difference in carbon contents between the two soils is less than in Ecuador. On average the carbon content in the 25-50 cm layer is 76%, 60% and 78% of the carbon content in the 0-25 cm layer in pasture, cypress and pine, respectively. C/N ratios are on average 12.1 in the 0-25 cm layer and 11.6 in the 25-50 cm layer for pasture, 14.2 in the 0-25 cm layer and 12.4 in the 25-50 cm layer for cypress, 13.1 in the 0-25 cm layer and 12.0 in the 25-50 cm layer for pine. These C/N ratios are higher than in Ecuador.

Carbon contents are determined by site characteristics as illustrated by the Spearman rank correlation coefficients shown in Table 10 for the three vegetation types (*mallines* excluded). As expected, high correlations are found in the 0-25 cm layer between total carbon and carbon in organo-metal complexes (indicated by Cp). Higher carbon content is associated with lower bulk density as indicated by the significant negative correlation coefficients. While for pasture and pine, carbon contents increase significantly with increasing precipitation, for cypress a stronger (negative) relation is found with altitude. With respect to soil texture, a rather strong negative relation is found between carbon contents and the size of the sand fraction, and a positive relation with the silt fraction for all vegetation types.

Table 10. Spearman rank correlation between carbon contents and site characteristics for three vegetation types, 0-25 cm layer, Argentina. (*: p-value < 0.05, **: p-value < 0.01).

	pasture	**cypress**	**pine**
altitude	-0.003	-0.461**	-0.110
precipitation	0.533**	0.197	0.501**
clay	0.151	0.650**	0.262
sand	-0.531**	-0.801**	-0.668**
silt	0.647**	0.779**	0.712**
pH	-0.607**	0.01	-0.489**
bulk density	-0.87**	-0.674**	-0.846**
age		0.417*	0.224
total biomass		0.312	0.354*
Alo	0.699**	0.672**	0.734**
Feo	-0.059	0.256	0.082
Sio	0.485**	0.582**	0.533**
Alp	0.841**	0.766**	0.926**
Fep	0.732**	0.761**	0.707**
Alp/Alo	0.262	-0.143	0.180
Alo-Alp	0.576**	0.624**	0.611**
Cp	0.967**	0.921**	0.972**

Carbon contents are also determined by soil mineralogy, as indicated by the positive relation with total aluminium as well as aluminium in organo-metal complexes and in non-crystalline clays. A positive relation is also found with iron in organo-metal complexes (Fep). Concerning vegetation characteristics in the forest systems, carbon contents increase significantly with cypress age, while in pine, carbon contents significantly increase with total tree biomass.

In order to investigate which are the best predictor variables for soil carbon, multivariate regression models were constructed using stepwise variable selection (Table 11.). For all pasture soils, 82% of carbon variation can be explained with indicators of mineralogy. For cypress forests, 87% of carbon contents can be explained with the sand fraction, aluminium in organo-metal complexes, forest age and precipitation. Carbon contents in pine forests can be best predicted with the amount of aluminium in organo-metal complexes and non-crystalline clays and sand fraction, obtaining a coefficient of determination of 96%.

Table 11. Multiple regression models for predicting the carbon content in the 0-25 cm layer under pasture, cypress and pine, Argentina. Units**:** Alo, Alp and Sio: %; C: %; prec: mm/yr; biomass: Mg/ha; sand: %.

vegetation	**model**	**p-value model**	**R^2**
pasture (n=32)	C(%) = 2.25 + 13.41*Alp - 17.28*Sio + 7.65*(Alo-Alp)	0.000	0.82
cypress (n=29)	C(%) = 4.3 - 0.062*sand + 6.179*Alp + 0.00127*age + 0.0011*prec	0.000	0.87
pine (n=41)	C(%) = 2.39 +13.42*Alp - 1.21*(Alo-Alp) - 0.029*sand	0.000	0.95

Soil carbon differences between pastures and forests in Argentina

In Appendix 3, soil organic carbon differences between pasture and forest are given per site for carbon percentages and total carbon content in the top 50 cm expressed as t/ha. In order to be able to compare the same mass of soil for pasture and forest within a site, the bulk density (average value of 4 sample points per layer) of cypress forest at the site was used for forests as well as pasture. For the differences between percentages C, significant differences as calculated with a t-test (8 observations per soil layer) are also indicated in Appendix 3. Positive differences indicate a higher carbon concentration in the forest than in the pasture.

On average the percentage of carbon in the 0-25 cm layer is 2.7% in the pastures and 3.8% in the cypress forests (Figure 17). This difference of 1.1% means that the carbon concentration is 40% higher in cypress forests than in pastures. The soil carbon content in the 0-25 cm layer in pine forests is 2.5%, which is slightly lower than in pastures (Figure 17). The same trend can be seen in the 25-50 cm layer, but with lower soil carbon contents.

Excluding the *mallines*, in the 0-25 cm layer 23 cypress sites have a positive difference, of which 16 are significant ($p < 0.05$). Of the 5 negative differences, 3 are significant ($p < 0.05$). In the 25-50 cm layer, 16 cypress sites have a positive difference, of which 7 are significant ($p < 0.05$), and 12 sites have a negative difference of which 5 are significant ($p < 0.05$). In the 0-25 cm layer 13 pine sites have a positive difference of which 6 are significant ($p < 0.05$). Of the 24 negative differences, 12 are significant ($p < 0.05$). In the 25-50 cm layer, 15 pine sites have a positive difference, of which 11 are significant ($p < 0.05$), and 22 sites a negative difference of which 12 are significant ($p < 0.05$).

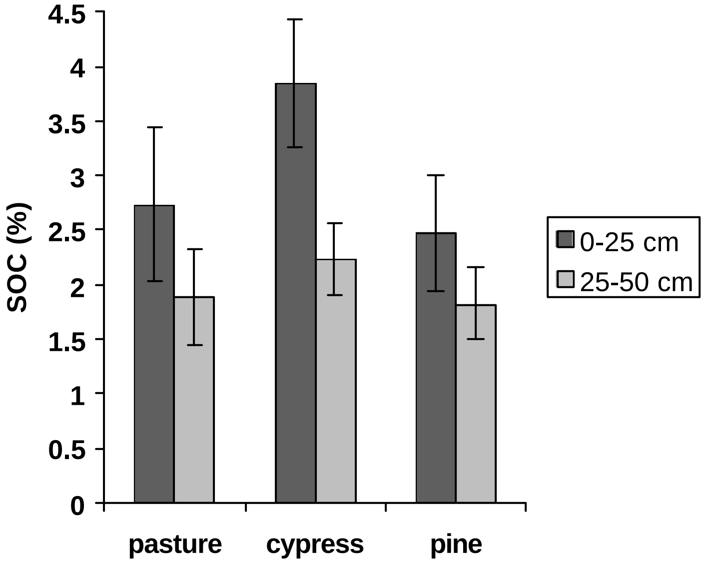

Figure 17. Average soil carbon contents (%) in 0-25 cm and 25-50 cm layers of pastures, cypress forest and pine plantations, Argentina. Error bars indicate 95% confidence intervals. 6 pasture sites were excluded because of inundations.

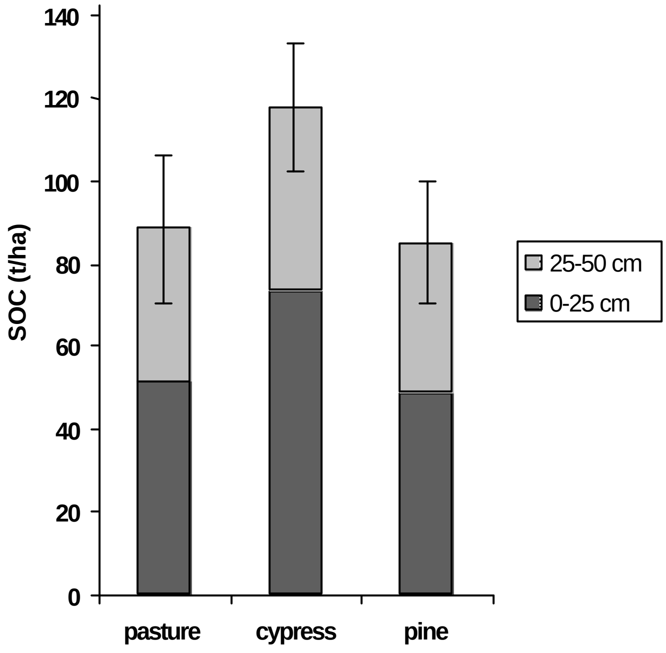

Figure 18. Average total soil organic carbon (t/ha) in 0-25 cm and 25-50 cm layers of pasture, cypress and pine, Argentina

In terms of carbon inventories for the top 50 cm expressed as t/ha, the average amount of total carbon in pastures is 88.5 t/ha, in cypress forests 117.6 t/ha, and in pine forests 85.1 t/ha (Figure 18). This means that the amount of soil carbon in cypress forests is on average 33% higher than in pastures, while the amount of soil carbon in pine forests is on average 4% lower than in pastures.

Table 12. Results of the paired t-test, Argentina. (n=28 for cypress, n=36 for pine)

	Cypress	**Pine**
Variable	**P-value**	**P-value**
C (%) 0-25 cm	0.013*	0.042*
C (%) 25-50 cm	0.568	0.3
C (t/ha) 0-25 cm	0.006*	0.034*
C (t/ha) 25-50 cm	0.43	0.256
C (t/ha) 0-50 cm	0.046*	0.072
bulk density (g/cm^3) 0-25 cm	0.000*	0.1*
bulk density (g/cm^3) 25-50 cm	0.000*	0.014*
Cp (%) 0-25 cm	0.149	0.313
C (%) minus Cp(%) 0-25 cm	0.009*	0.031*

*: p-value < 0.05

The paired t-tests (Table 12) for the site differences between pasture and cypress and between pasture and pine indicate that the differences in soil carbon - expressed as percentages as well as t/ha - are significantly different from pastures in the 0-25 cm layer for both cypress and pine. The average differences for pine (see Figures 17 and 18) are, however, very small. For the 25-50 cm layer differences in carbon are not significant for both cypress and pine. The total amount of carbon in the 0-50 cm layer is, in the case of cypress, significantly different from pastures, but not in the case of pine. Significant differences in bulk density indicate compaction of grasslands due to cattle grazing. As in Ecuador, differences in pyrophosphate-extracted carbon (Cp) in the top layer are not significant, whereas differences in total carbon minus Cp are.

Bivariate rank correlation between the site-specific abiotic and biotic variables and the site differences in total carbon (0-50 cm) between cypress and pasture and between pine and pasture indicates no significant correlation between forest age, forest biomass or precipitation and carbon differences for both forest types. Of the texture and mineralogy variables, only pine has two variables significantly (negatively) but weakly correlated: Fep and AlpAlo.

Multivariate stepwise regression was applied to investigate the relative importance of biotic and abiotic site characteristics for the dependent variable site carbon differences (forest carbon minus pasture carbon).

The regression models are indicated in Table 13. For pine a low coefficient of determination is obtained, with iron contents as the determining variables. For cypress about half of the variation in differences is explained, with aluminium contents and cypress biomass as the determining variables.

Table 13. Multiple regression models for predicting differences in carbon content (t/ha) between pastures and forests, Argentina. n=25 for cypress, n=34 for pine. Dif C is SOC in the top 50 cm soil layer of forest minus pasture. Units: biomass: Mg/ha, Alp, Alo-Alp, Fep and Feo: %.

forest	**model**	**p-value model**	**R^2**
Cypress	Dif C (t/ha) = - 413.37 * (Alp) + 0.19 * (Cypress biomass) + 66.2 * (Alo-Alp)	0.001	0.52
Pine	Dif C (t/ha) = - 149.56 * (Fep) + 18.6 * (Feo) - 15.58	0.002	0.27

3.3 Monetary evaluation

3.3.1 Monetary evaluation for Ecuador

Monetary evaluation of the carbon sequestration potential in north-western Ecuador is based on the assumption that risk-neutral landowners have various land use alternatives. We have selected some typical land use systems for the following analysis. As shown in Figure 19, secondary forest and forest plantations are potential alternatives for landowners with pasture for the production of meat and milk. We assume that these landowners might commit themselves to participating in projects that last for 30 or 100 years, respectively.

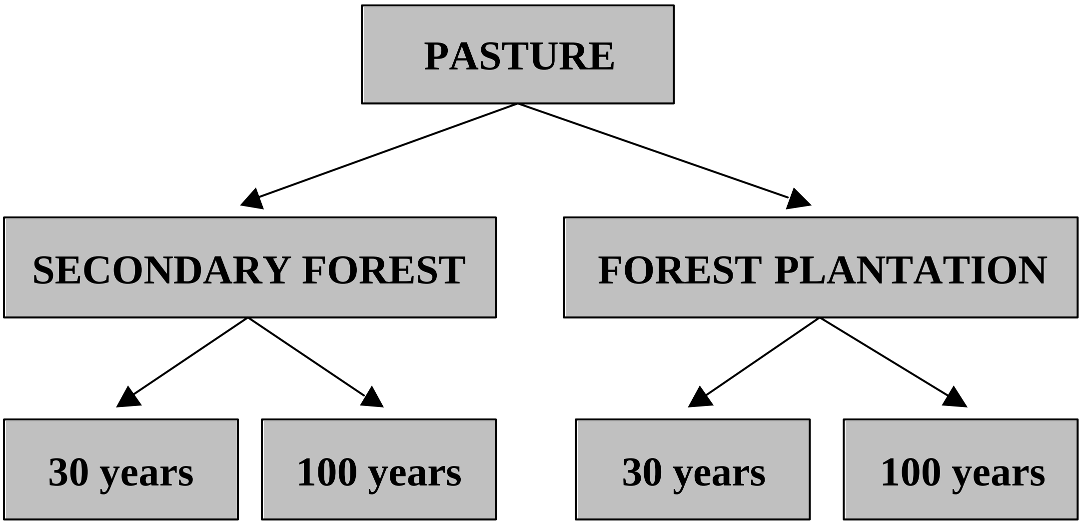

Figure 19. Considered land use alternatives for NW Ecuador.

30-year projects

Secondary forest – 30-year project

Based on the biomass and soil carbon estimates (see Sections 3.1 and 3.2), the cumulative carbon fixation per hectare is calculated for secondary forests, assuming that this forestry alternative is established on a relatively old pasture (20-30 years). We further assume that after year 10 a sustainable extraction of about 2 m^3/(ha yr) is possible, based on a simple management system. This system consists of a regular extraction of undesired tree species in order to favour commercial timber species (Benítez et al., 2001).

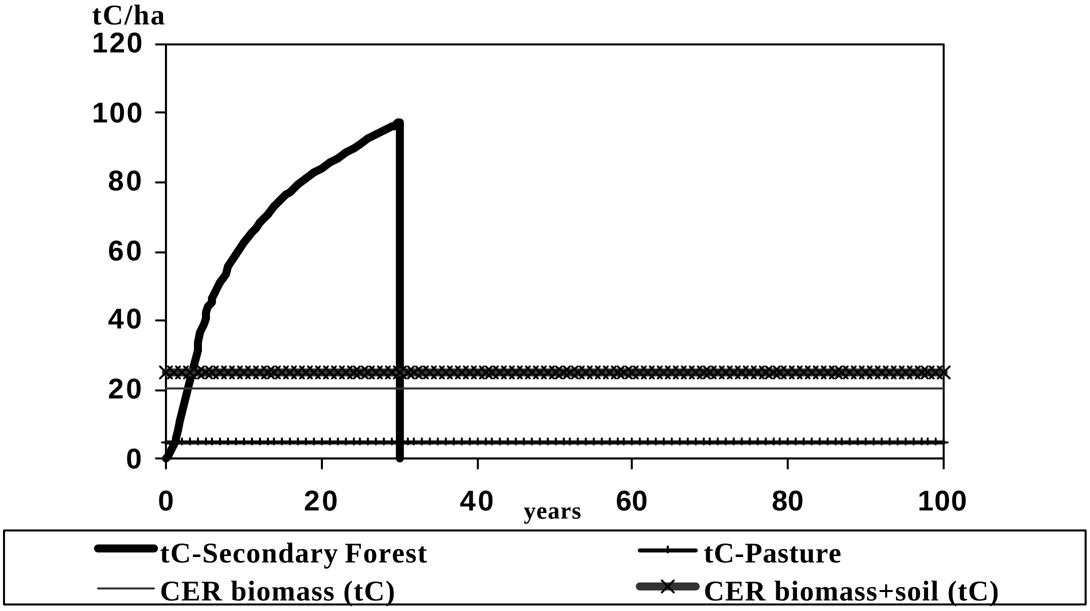

Figure 20: Carbon sequestration in secondary forest – 30-year project, Ecuador.

As shown in figure 20, sequestration in secondary forest biomass reaches the amount of about 100 tC/ha after 30 years.[12] The baseline is estimated at 5 tC/ha for pasture, including some shadow trees per ha (Palm et al., 2000; Benítez et al., 2001). The average carbon fixation in biomass over 100 years is about 21 tC/ha. The inclusion of soil carbon provides a total of 25 tC/ha. Multiplying this figure by 44/12 in order to obtain the amount of Certified Emission Reduction units expressed as CO_2 results in 92 tCO_2/ha.[13]

Sequestration of soil carbon makes up about 15% of the above-ground carbon sequestration. This has consequences for the calculation of the minimum price. Neglecting soil carbon leads to a lower CER value in the denominator of equation *(9)*, resulting in a 15% increase of the minimum price for the example given above.

Laurel plantation – 30-year project

The average C sequestration is calculated for a laurel plantation *(Cordia alliodora)* with a medium site index (SI 22) and a density of 400 trees per hectare. This calculation is based on a growth curve for laurel in Ecuador (see Section 3.1). For sites with a medium index, a planned rotation of 15-20 years is recommended (Alder and Montenegro, 1999).

---

[12] Biomass estimates did not allow an exact determination of the annual storage during the first few years after establishing a forest to be made. Thus, a linear increment was assumed during years 2 to 5. This runs the risk of overestimating CO_2 storage (and payments) in the early phase of a forestry project even if the average storage remains unaffected (Price, 1994). Therefore, a sensitivity analysis is conducted assuming various payment regimes (see chapter: Interpretation of Results).

[13] 44/12 (~ 3,67) is the ratio of the molecular CO_2 weight to the atomic C weight.

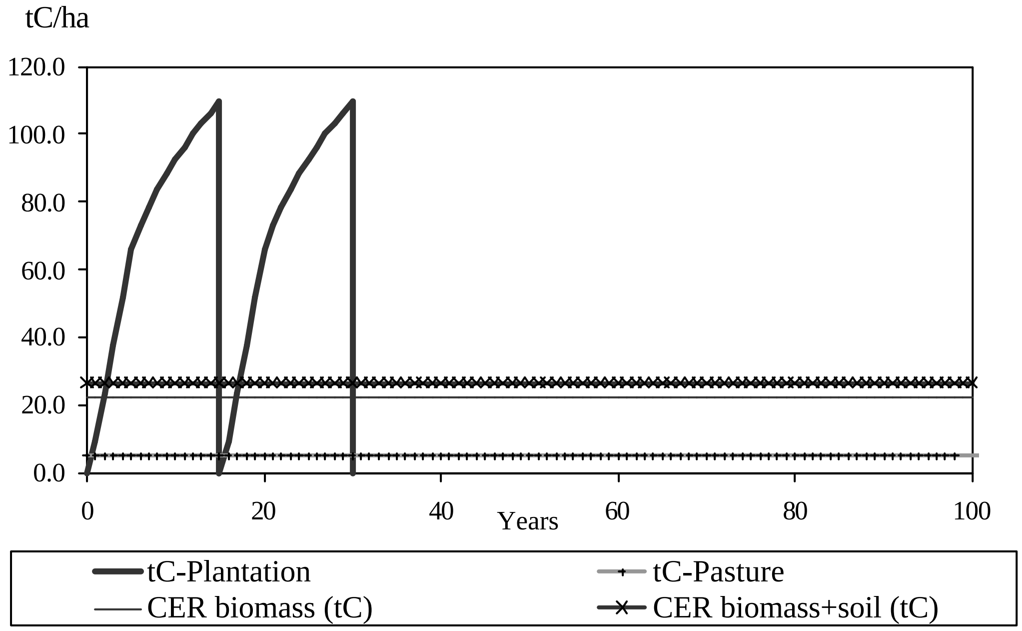

Figure 21. Carbon sequestration in a laurel plantation – 30-year project, Ecuador.

For a 30-year project we calculated 2 rotations of 15 years for zones 1-3 as shown in Figure 21. Zone 4 is not suitable for laurel plantation because of its high altitude.

Carbon sequestration in the biomass of a laurel plantation is estimated at about 110 tC/ha within 15 years. Taking the baseline into account and assuming a 100 years time horizon, this results in an average C-storage in biomass of 25 tC/ha for a 30 years project with two rotations. Inclusion of soil carbon results in an average of 27 tC/ha, and multiplying by 44/12 gives 100 tCO_2/ha CER units. Again, sequestration of soil carbon contributes about 15% of the above-ground carbon sequestration. Neglecting the soil when calculating the compensation results in a minimum price about 15% higher than if SOC is included.

The results of the accounting procedure have to be applied in equation *(9)*, i.e., the present CER values of the physical CO_2 units have to be calculated. This is done by listing the annual net increment of CO_2 storage of the respective years until the average net storage is reached. These physical CO_2 units are discounted according to equation *(13)*.

Calculating the "minimum price" for carbon sequestration by forestry projects of 30 years

After calculating the NPV of typical pasture land use systems in the four different areas of NW Ecuador as well as the NPV of the forestry alternatives and the discounted CER values, the minimum financial compensation can be estimated according to equation *(9)*. In the case of secondary forest, the NPV was calculated for "managed systems". This management encourages timber growth of commercial species that occur in the forest and includes thinning of undesired species. It generates higher costs than not managing the forest, but higher revenues, too, due to the increased volume of high-value timber species per hectare. In this way, commercial timber harvest of about $2m^3$/(ha yr) can be realised from year 10 onwards (Benítez et al., 2001).

Results are calculated at a 7% real interest rate and a standing timber value of \$20/m^3. Figure 22 shows that the lowest price for CO_2 sequestration of about \$1.5-3 per tCO_2 can be found in Zone 1. 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 5% of the total area is used for pasture, so there is only a minimal area available to switch from pasture to forestry. In Zones 3 and 4 the costs of sequestering CO_2 are relatively high (about \$16 per tCO_2). Zone 2 is most suitable for CO_2 fixation by forestry projects. The potential area for switching to forestry is high because about 40% of the total area is actually used for extensive pasture. The minimum price that would have to be paid to landowners in order to switch from pasture to forestry is about \$4-6 per tCO_2.

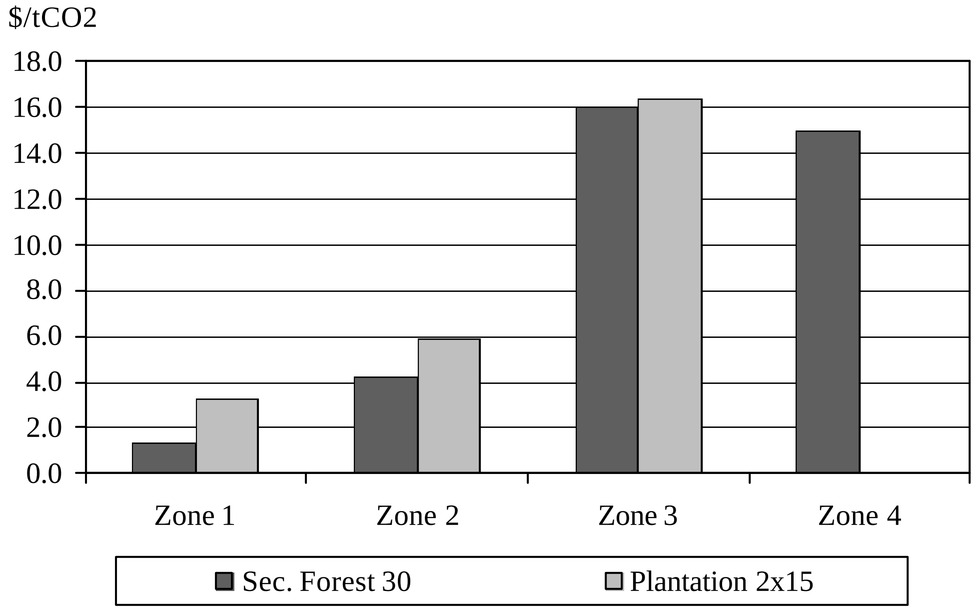

Figure 22. Minimum price of CO_2 sequestration in different zones - 30-year project, Ecuador.

An interesting aspect is that the minimum price for CO_2 fixation by secondary forest is lower than for sequestration by plantation forest. This is due to the low establishment costs and the relatively quick timber revenues from secondary forests.

Assuming that the required minimum prices of about $4 per tCO_2 for secondary forest projects and $6 per tCO_2 for plantation forest in zone 2 are actually paid, CER revenues per ha can be calculated.

Table 14 reflects the results of figures 20 and 21, and shows that the average CO_2 storage of both alternatives - 92 and 100 tCO_2/ha calculated on the basis of a

100 year timeframe - is already reached after 4 years.[14] The payments in periods 1 to 3 are the minimum financial incentives that would have to be paid to landowners in zone 2 in order to switch to forestry for economic reasons. Secondary forest stores about 8% less CO_2 per ha, but the required payments per ha for this alternative are only about two-thirds of the compensation for plantation forest. The costs per tCO_2 stored in secondary forest amount to 75% of the costs in forest plantation. In both cases a financial gap exists between the end of CER payments and the beginning of timber revenues.[15]

Table 14. Payment of "minimum prices" for carbon sequestration in zone 2 - 30-year project, Ecuador

	Secondary forest (30 years project)					Plantation forest (2x15 years)				
year	**biomass C** (tC/ha)	**SOC** (tC/ha)	**C total** (tC/ha)	**CO2 total** (tCO2/ha)	**payment** ($/ha)	**biomass C** (tC/ha)	**SOC** (tC/ha)	**C total** (tC/ha)	**CO2 total** (tCO2/ha)	**payment** ($/ha)
0										
1	4.1	1.3	5.4	19.8	83	9.3	1.3	10.6	38.9	227
2	9.1	1.3	10.4	38.1	160	14.3	1.3	15.6	57.2	334
3	8	1.3	9.3	34.1	143	1	0	1	3.7	21
total	**21.2**	**3.9**	**25.1**	**92.0**	**387**	**24.6**	**2.6**	**27.2**	**99.7**	**582**

---

[14] The "CO_2 total" column shows the annual net increment of CO_2 storage, which is multiplied in the "Payment" column by the minimum price of the respective land use alternative (secondary forest: \$4.20/tCO_2; plantation \$5.84/tCO_2).

[15] In the "Interpretation of the results" section, a sensitivity analysis shows the effect of other payment procedures, which can close this gap but lead to higher minimum prices.

100-year project

Secondary forest – 100-year project

Landowners in the different zones might also decide to commit themselves to carbon sequestration for a 100 year time period. In this case, we also assume that they would compare the costs and benefits of each land use alternative. The average C-storage in secondary forest biomass is about 87 tC/ha as shown in Figure 23. Including soil carbon (16 tC/ha on average if the forestry alternative is established on an old pasture) results in an average storage of 103 tC/ha, which multiplied by 44/12 gives 377 tCO_2/ha.

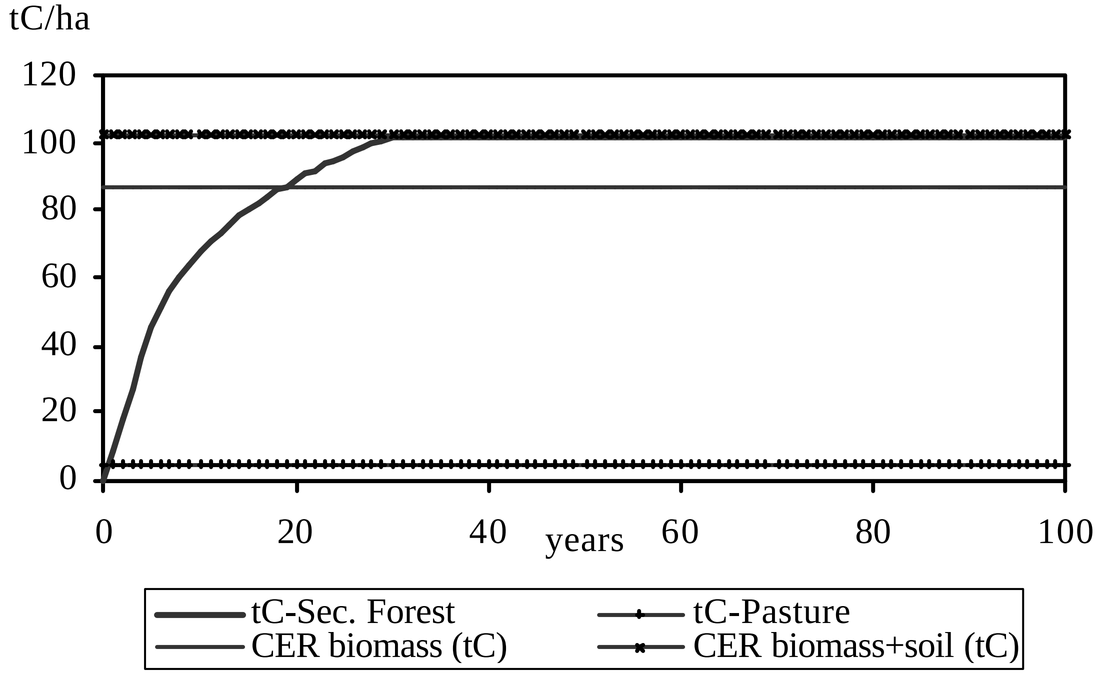

Figure 23. Carbon sequestration in secondary forest – 100-year project, Ecuador.

Laurel plantation – 100-year project

To calculate the plantation forest results, we assumed a rotation period of 20 years.[16] The average C-storage in biomass is about 81 tC/ha. Adding soil carbon sequestration (16 tC/ha) gives a total of 97 tC/ha (see figure 24) and a CER amount of 356 tCO_2/ha.

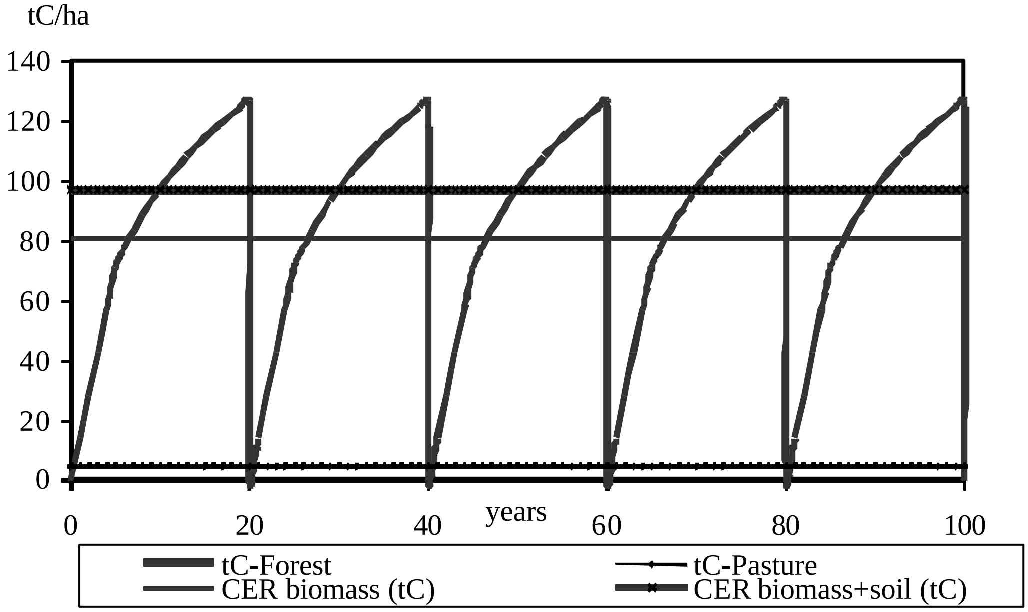

Figure 24. Carbon sequestration in a laurel plantation (5x20 years), Ecuador.

Based on this calculation and the respective NPV for pasture and forestry alternatives, the minimum prices for 100-year projects are calculated according to equation *(9)* (Figure 25).

---

[16] This rotation length is within the scope recommended by Alder and Montenegro (1999). Our own calculations showed that this would be the optimum cutting cycle, if a fictitious payment for CO2 sequestration of about $5/tCO2 is taken into account.

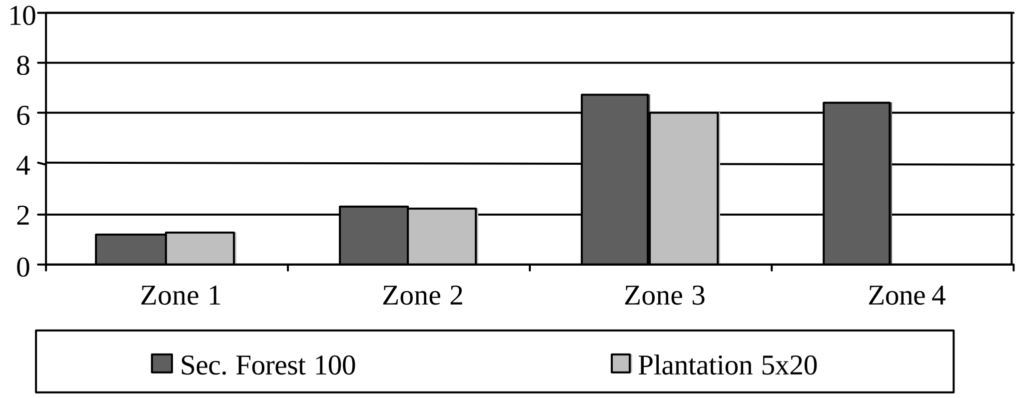

Figure 25. Minimum price of CO_2 sequestration in different zones - 100-year project, Ecuador

In each zone the minimum prices of both alternatives are about half the value of the 30-year projects. Again, zone 1 has the lowest minimum prices of about \$1.5/tCO_2. The costs in zones 3 and 4 remain relatively high at \$6-7/tCO_2. In zone 2 the minimum financial compensation for switching from pasture to secondary forest or to plantation would be about \$2.5/tCO_2. Due to the high percentage of extensively managed pasture and the relatively low minimum price, zone 2 is again the most suitable for CO_2 sequestration.

Compensation payments in zone 2, according to the financing mechanism with an annual net increment of CO_2 fixation until the average level is reached, would generate CER revenues as shown in Table 15.

Table 15. Payment of "minimum prices" for carbon sequestration in zone 2- 100-year project, Ecuador (secondary forest: \$2.30/tCO_2; plantation \$2.27/tCO_2).

	Secondary forest (100 years project)					Plantation forest (5x20 years)				
year	**Biomass C**	**SOC**	**C total**	**CO2 total**	**Payment**	**Biomass C**	**SOC**	**C total**	**CO2 total**	**Payment**
	(tC/ha)	(tC/ha)	(tC/ha)	(tCO2/ha)	($/ha)	tC/ha	tC/ha	tC/ha	tCO2/ha	$/ha
0	0.0	0	0.0	0	0	0	0	0	0	0
1	4.1	1.3	5.4	19.8	46	9.3	1.3	10.6	38.9	88
2	9.1	1.3	10.4	38.1	88	14.3	1.3	15.6	57.2	130
3	9.1	1.3	10.4	38.1	88	14.3	1.3	15.6	57.2	130
4	9.1	1.3	10.4	38.1	88	14.3	1.3	15.6	57.2	130
5	9.1	1.3	10.4	38.1	88	14.3	1.3	15.6	57.2	130
6	5.7	1.3	7.0	25.7	59	6.5	1.3	7.8	28.6	65
7	4.8	1.3	6.1	22.4	51	5.7	1.3	7.0	25.7	58
8	4.2	1.3	5.5	20.2	46	2.4	1.3	3.7	13.6	31
9	3.7	1.3	5.0	18.3	42		1.3	1.3	4.8	11
10	3.3	1.3	4.6	16.9	39		1.3	1.3	4.8	11
11	3.0	1.3	4.3	15.8	36		1.3	1.3	4.8	11
12	2.7	1.3	4.0	14.7	34		1.3	1.3	4.8	11
13	2.5	0.4	2.9	10.6	24		0.4	0.4	1.5	3
14	2.3		2.3	8.4	19					
15	2.2		2.2	8.1	19					
16	2.0		2.0	7.3	17					
17	1.9		1.9	7.0	16					
18	1.8		1.8	6.6	15					
19	1.7		1.7	6.2	14					
20	1.6		1.6	5.9	13					
21	1.5		1.5	5.5	13					
22	1.5		1.5	5.5	13					
total	**87**	**16**	**103**	**377**	**868**	**81**	**16**	**97**	**356**	**808**

In plantation forest the average sequestration of 356 tCO_2/ha is reached after 14 years. In secondary forest it takes 23 years to reach the average net storage of 377 tCO_2/ha, because from year 10 onwards about 2 m^3 of commercial timber is harvested per hectare. Although a managed secondary forest sequesters slightly more CO_2 on average, the overall compensation payments per hectare are higher for secondary forests than for plantation forest because of the slower C-storage process.

The annual values in Table 15 are influenced by the way carbon uptake in biomass is calculated. As the biomass estimates did not allow for an exact determination of the annual storage during the first few years after establishing a forest, a linear carbon uptake by both alternatives was assumed during years 2 to 5.

Carbon sequestration by postponing deforestation

According to the Marrakesh agreement (UNFCCC, 2001), carbon sequestration under CDM is limited to afforestation and reforestation projects, excluding the avoidance of deforestation as a means of reducing atmospheric CO_2. Nevertheless, it is interesting to calculate a minimum price for this alternative. Fearnside et al. (2000) argue that postponing deforestation is a “valid mitigation measure even if the forests in question are later cut for harvesting”. The result is “more like reducing fossil fuel C emissions than is C sequestration in plantations”.

The economic rationale behind a landowner’s decision could be as follows: comparing the NPV of forestry and pasture, forestry would be preferred - and thus deforestation avoided - if the sum of its NPV_F and the present value of CER revenues is higher or at least as high as the NPV_P of pasture. Inequation *(8)* can be used again, although this time two aspects have to be taken into account (Stavins, 1999):

1. Deforestation leads to immediate timber revenues if the commercial timber is sold in the same period. These windfall benefits from a clear-cut have to be added to the NPV of pasture.
2. Before starting pasture activities on former forest land, conversion costs are incurred and have to be subtracted from the NPV of pasture.

This leads to the following inequation:

$$\begin{aligned} NPV_F + PV_F\,[p_{CER} \cdot CER] \geq\ & NPV_P \\ & + \mathit{Clear\text{-}cut\ Benefits} \\ & - \mathit{Conversion\ Costs} \end{aligned} \tag{17}$$

If we assume that both sides are equal and solve the equation for p_{CER}, the following formula for calculating the minimum price of carbon storage by avoiding deforestation results:

$$P_{CER} = \frac{NPV_P - NPV_F + ClearcutB - ConversionC}{PV_F\ [CER]} \qquad (18)$$

The new variables appear in the numerator on the right side of equation *(18)*. Clear-cut benefits are an incentive for deforestation. Their level depends on the percentage of commercial timber volume in the forest to be cut. Data collection in managed secondary forests in NW Ecuador shows that - of a total timber volume of 115 m^3/ha - up to 75% might be commercially usable timber species. On the other hand, unmanaged secondary forests are assumed to contain only about 20% of commercial timber volume. The higher the commercial timber volume of a forest, the higher the windfall profit of a clear-cut and, consequently, the stronger the economic incentive must be to avoid deforestation.

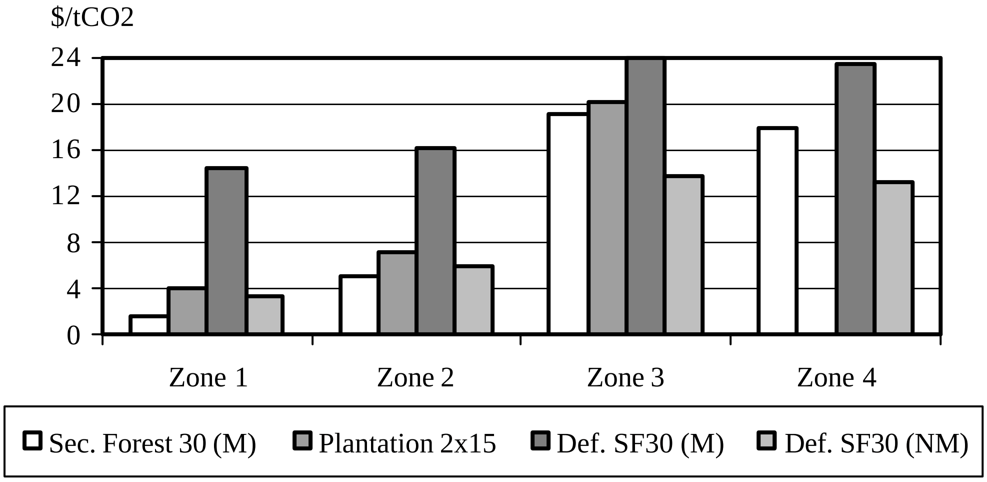

Figure 26. Minimum price of CO_2 sequestration considering afforestation and deforestation - 30-year project, Ecuador.

Conversion costs in the numerator have a negative sign and thus the higher they are, the lower minimum prices for CO_2 sequestration become. In Figure 26 the two columns on the left-hand side of each zone reflect the minimum prices of CO_2 sequestration by establishing managed secondary forest (Sec. Forest 30 (M)) and forest plantation (Plantation 2x15) (except zone 4) as calculated before. The calculated compensation for postponing deforestation is shown in the two columns at the right for each zone (Def.SF30(M) and Def.SF30(NM)).

As expected, the minimum prices for forests with a high percentage of commercial timber volume vary on a relatively high level between \$14 and \$24 per tCO_2. The result for unmanaged secondary forest is interesting: the minimum price that would have to be paid to maintain the forest is relatively low - at least in zones 1 and 2 with \$4-6 per tCO_2 – reaching about the same level as that needed to establish new forests. The same holds for the results of a 100-year project, shown in Figure 27. Postponing deforestation for 100 years would require a minimum payment of about \$2-3 per tCO_2 in zones 1 and 2 and about \$6-7 per tCO_2 in zones 3 and 4.

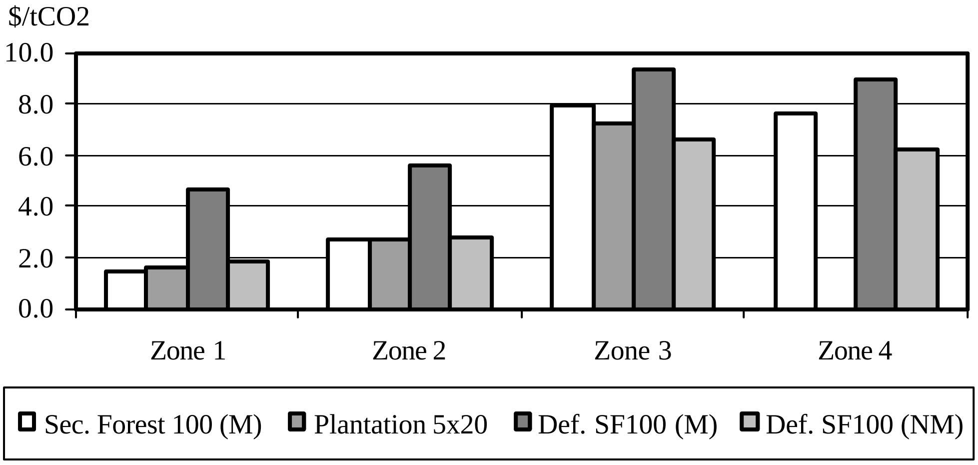

Figure 27. Minimum price of CO_2 sequestration considering afforestation and deforestation - 100-year project, Ecuador.

Our calculations are based on a comparison of forestry and pasture. An exemplary calculation for a 30 years project including oil palm plantation as an alternative land use in zone 2 led to minimum payments of about \$30-40 per tCO_2 needed to convince landowners not to cut down the forest.[17] This example shows that if postponing deforestation were to be included in the Kyoto framework, even a joint production of timber and CER would not make forestry a competitive land use alternative in comparison with oil-palm plantations.[18]

---

[17] Approx. \$30/tCO_2 would be the minimum price for avoiding deforestation of a not managed secondary forest, and \$40/tCO_2 for managed forest.

[18] This example considers neither the possible negative external effects of oil-palm plantations nor the potential positive external effects of forestry land use, other than CO_2 sequestration.

Summary of the Economic Results for Ecuador

The results of the economic analysis differ between the 4 zones presented in Section 2.2.2. Very low carbon sequestration costs are estimated for zone 1. At the same time only a small part of this zone is used for pasture. Consequently, the area which could be switched from pasture to forestry is very limited. Due to the high percentage of primary forests, payments for avoiding deforestation could be envisaged (even if not yet included in the Kyoto Protocol). The required minimum payments would be relatively high (\$14/tCO_2 for 30 years projects), even under the (conservative) assumption that the commercial timber volume in these forests is as high as in managed secondary forest.

Relatively high costs of carbon fixation by establishing forests are calculated for zones 3 and 4, because of high pasture productivity, resulting in a high NPV of the pasture alternatives.

The zone most suitable for carbon sequestration is zone 2, because of the large extension of grassland used for extensive pasture and the low opportunity costs of switching to forestry. Secondary forests and forest plantations have similar sequestration costs in this zone. The minimum price is about \$4-6/tCO_2 for 30-year projects and \$2/tCO_2 for 100-year projects. These results include soil carbon that contributes about 15 % of the average sequestration. Consequently, neglecting SOC would lead to a price increase of approximately 15%.

Assuming 30-year projects to be more feasible and realistic than 100-year projects leads to the conclusion that even in the most suitable area in NW –Ecuador, compensation payments of \$4-6/tCO_2 have to be reckoned with. Managed secondary forest seems to be competitive in comparison with forest plantation, because of its low establishing costs and quick timber revenues.

The applied minimum price calculation is based on opportunity costs, considering pasture as the relevant land use alternative. Much higher payments would be necessary if land uses with higher NPVs were taken into account. An exemplary calculation for oil-palm plantations led to a compensation of about \$30-40/tCO_2, showing that timber revenues and payments for CO_2 alone are not able to ensure the competitiveness of forestry compared to oil palm.

3.3.2 Monetary evaluation for Argentina

In NW Patagonia we used the same approach as in NW Ecuador to evaluate the carbon sequestration potential of different land use systems (Figure 28). The land use alternatives are pasture for cattle, cypress forest (*Austrocedrus chilensis*) and forest plantation (*Pinus ponderosa*). Again the underlying question is: what is the minimum payment per CER unit that would make a risk-neutral landowner switch for economic reasons from pasture to forestry? We compare the Net Present Values according to equation *(9)*, taking into account the amount of CO_2 sequestered by the different alternatives.

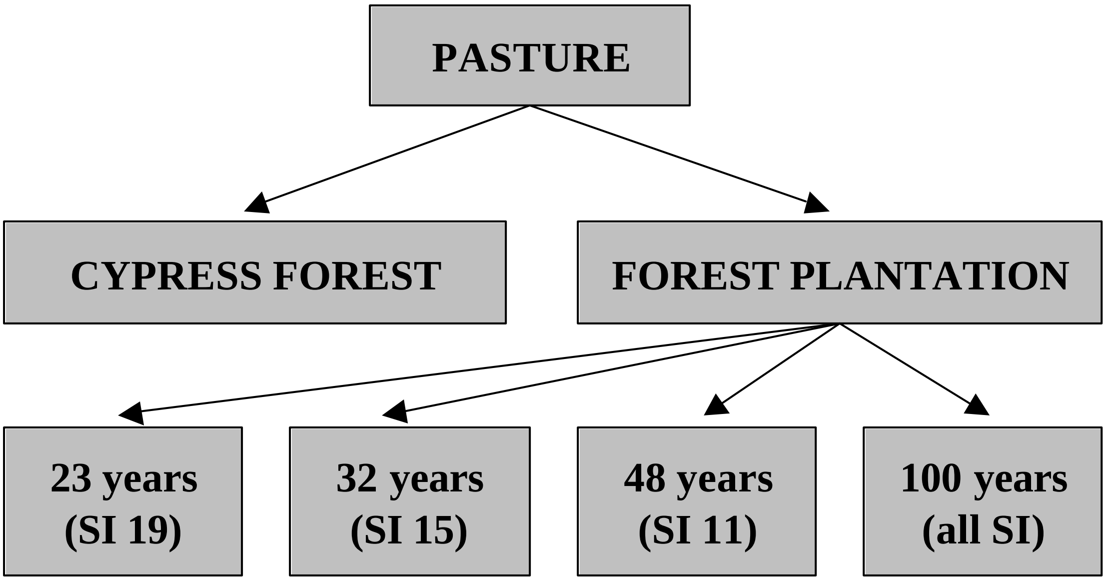

Figure 28. Considered land use alternatives for Argentina.

A precondition for official acceptance within the CDM is the “human induced activity” of establishing forests (UNFCCC, 2001). The problem that arose during the economic analysis for NW Patagonia was that no human-induced activity of establishing cypress forests could be identified. The relatively slow growth of cypress means that timber revenues occur relatively late. Carbon sequestration in cypress forests is also relatively slow. Both circumstances lead to landowners deciding that cypress is not a very attractive land use alternative. Consequently, as sporadic natural regrowth without the active participation of the landowners is not covered by the Marrakesh agreements, no payments can be expected for this type of land use. Furthermore, no growth models for cypress were available to simulate a complete rotation.

The economic analysis is therefore focussed on forest plantations of ponderosa pine. Plantations of different site indices were compared. The rotation period depends on the site index. In a relatively good site for ponderosa pine (SI 19), it takes about 23 years to reach harvesting age; in a medium site (SI 15) about 32; and at a site index of 11, about 48 years. For all sites we calculated one cutting cycle (23, 32, 48 years), and also a project period of about 100 years. The latter implies two rotations for a SI 11 (= 96 years), three rotations for a SI 15 (= 96 years) and four rotations for a SI 19 (= 92 years).

One rotation

As in the case of Ecuador, carbon fixation was calculated according to the average net storage method (equation *(12)*). In Figure 29 this approach is exemplarily demonstrated for plantations on the medium site (SI 15) and a cutting cycle of 32 years, including thinning after 19 and 23 years. Our calculation is based on a growth model used by Laclau (1999) in a previous study for Patagonia. A characteristic of ponderosa pine in NW Patagonia is its slow early growth, which has negative effects for potential CER revenues during the initial years of the rotation. After 32 years carbon storage reaches 121 tC/ha. The baseline is given by the pasture alternative with a C-storage of about 2 tC/ha (Laclau et al., 2002a). With a time horizon of 100 years, on average 17.5 tC/ha are stored. This corresponds to 64 tCO_2/ha, calculated on the basis of the above and below-ground biomass but without taking soil carbon sequestration into consideration.[19] As mentioned in Section 3.2, no significant change in soil carbon could be found for relatively young ponderosa pine plantations in the study area.

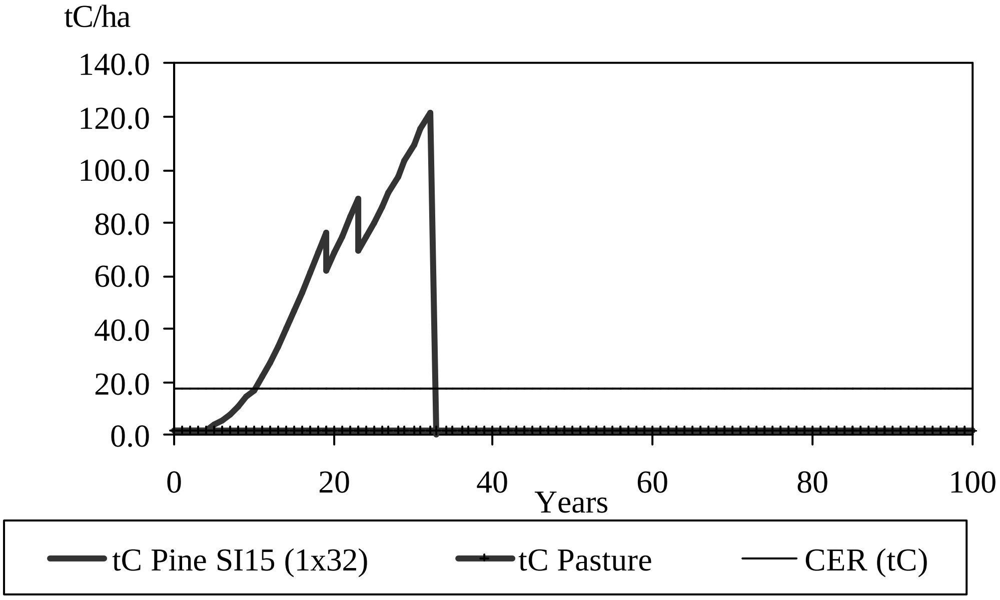

Figure 29. Carbon sequestration in a pine plantation (1x32 yr), Argentina.

CO_2 storage was calculated for the alternative sites, resulting in an average storage of 12.5 tC/ha (46 tCO_2/ha) for a SI 19 and of 26 tC/ha (96 tCO_2/ha) for a SI 11. The higher C-sequestration in a site with a low SI (more than twice the cycle at SI 19) can be explained by the longer cutting cycle, resulting in a higher average amount of carbon being sequestered.

---

[19] In contrast to the Ecuadorian analysis, in Argentina a detailed root analysis was possible and root carbon is included in the storage estimation.

In NW Patagonia no clearly distinct regional economic zones were identifiable as in Ecuador. Instead, a comparison was made between plantations of different pasture qualities, measured by productivity. A pasture was considered to have a low quality when producing about 1,200 kg/(ha yr) of forage dry matter. Medium pastures have about 2,400 kg/(ha yr), while good pastures produce about 3,600 kg/(ha yr). In all cases, the Net Present Value was calculated, based on a pasture land use model (Laclau et al., 2002b) and using a real interest rate of 7%. All pasture alternatives have an NPV of about zero or only slightly higher, taking opportunity costs of capital into account as explained above. This means that the minimum price for carbon sequestration - calculated according to equation *(9)* - mainly depends on the NPV of the forestry alternative and the average amount of CO_2 fixed. At a real interest rate of 7% all forestry alternatives, even the best sites, have a negative NPV, resulting in a necessary financial compensation higher than zero. Similar results were found by Sedjo (1999), who notes that "without substantial subsidies […], the private sector would not have the financial incentives to establish forest plantations in Patagonia."

The results are shown in Figure 30. The minimum price of carbon sequestration by forest plantations in the study area is about \$14-15/tCO_2 when planting ponderosa pine on a SI 11, and about \$10-11/tCO_2 on a SI 15. In the case of the high SI 19, the financial compensation to switch to forest plantation would be about \$1-2/tCO_2.

As mentioned above, on a SI 11 more carbon is fixed – on average - than on a SI 19. Nevertheless, due to the longer rotation period, the compensation on SI 11 is higher compared to SI 19, because of a): the more negative NPV_F of SI 11 in the numerator and b): the lower present value of CER units of SI 11 in the denominator of equation *(9)* used for the calculation of the minimum price.

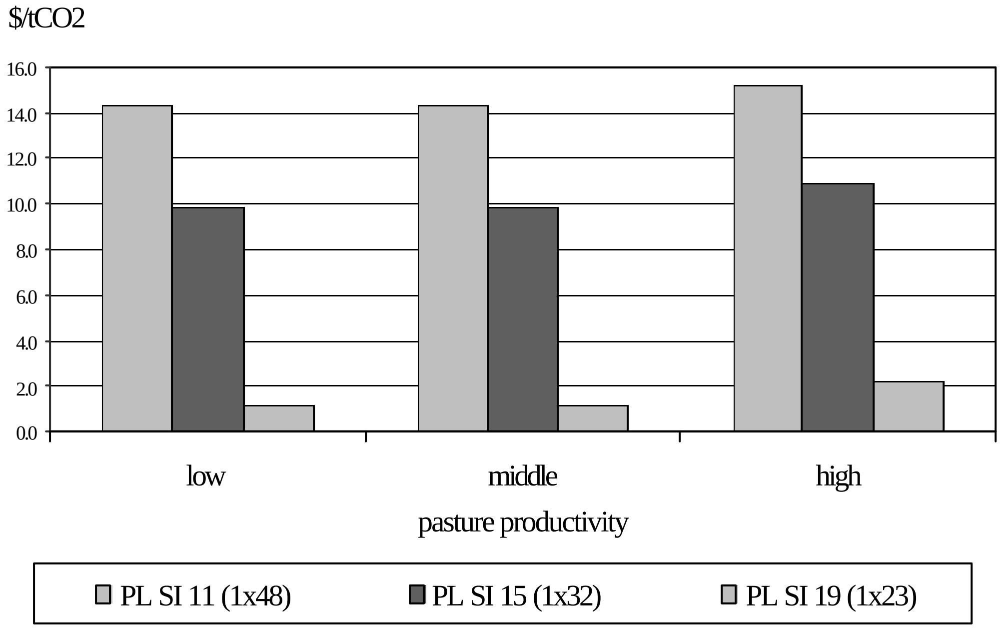

Figure 30. Minimum price of CO_2 sequestration in a pine plantation in different sites - 1 rotation, Argentina.

Table 16 shows that the not-discounted minimum compensation payments according to the annual net increment of CO_2 fixation until average storage vary between $55 (SI 19) and $1,386/ha (SI 11). Due to the slow early growth, there are no CER revenues to be expected during the initial years after establishing the plantation, due to the slow annual biomass increment.[20]

---

[20] A closed canopy can be expected approx. at the age of 10. It is assumed that – during the first rotation cycle - the average CO_2 storage according to the pasture baseline is maintained until age 10 and ends with the canopy closing, resulting in a lower net increment of CO_2storage in that year.

Table 16. Payment of "minimum prices" for carbon sequestration in plantation forest – 30-year project, Argentina (SI 11: \$14.3/tCO$_2$; SI 15: \$9.9/tCO$_2$; SI 19: \$1.2/tCO$_2$).

	1 rotation (48 years) SI 11					1 rotation (32 years) SI 15					1 rotation (23 years) SI 19				
year	**Biomass C**	**SOC**	**C total**	**CO2 total**	**Payment**	**Biomass C**	**SOC**	**C total**	**CO2 total**	**Payment**	**Biomass C**	**SOC**	**C total**	**CO2 total**	**Payment**
	(tC/ha)	(tC/ha)	(tC/ha)	(tCO2/ha)	(\$/ha)	(tC/ha)	(tC/ha)	(tC/ha)	(tCO2/ha)	(\$/ha)	(tC/ha)	(tC/ha)	(tC/ha)	(tCO2/ha)	(\$/ha)
0	0	n.a.	0	0	0	0	n.a.	0	0	0	0	n.a.	0	0	0
1	0.0	n.a.	0.0	0.0	0.0	0.0	n.a.	0.0	0.0	0.0	0.0	n.a.	0.0	0.0	0.0
2	0.0	n.a.	0.0	0.0	0.0	0.0	n.a.	0.0	0.0	0.0	0.0	n.a.	0.0	0.0	0.0
3	0.0	n.a.	0.0	0.0	0.0	0.0	n.a.	0.0	0.0	0.0	0.7	n.a.	0.7	2.6	3.1
4	0.0	n.a.	0.0	0.0	0.0	0.0	n.a.	0.0	0.0	0.0	1.2	n.a.	1.2	4.4	5.3
5	0.5	n.a.	0.5	1.8	26.3	1.5	n.a.	1.5	5.5	54.5	2.1	n.a.	2.1	7.7	9.2
6	0.9	n.a.	0.9	3.3	47.3	1.7	n.a.	1.7	6.2	61.7	3.5	n.a.	3.5	12.8	15.4
7	1.2	n.a.	1.2	4.4	63.0	2.4	n.a.	2.4	8.8	87.1	4.7	n.a.	4.7	17.2	20.7
8	1.5	n.a.	1.5	5.5	78.8	3.1	n.a.	3.1	11.4	112.5	0.3	n.a.	0.3	1.1	1.3
9	1.9	n.a.	1.9	7.0	99.8	3.8	n.a.	3.8	13.9	138.0		n.a.			
10	0.2	n.a.	0.2	0.7	10.5	2.5	n.a.	2.5	9.2	90.8		n.a.			
11	2.5	n.a.	2.5	9.2	131.3	2.5	n.a.	2.5	9.2	90.8		n.a.			
12	2.8	n.a.	2.8	10.3	147.0		n.a.					n.a.			
13	3.1	n.a.	3.1	11.4	162.8		n.a.					n.a.			
14	3.3	n.a.	3.3	12.1	173.3		n.a.					n.a.			
15	3.5	n.a.	3.5	12.8	183.8		n.a.					n.a.			
16	3.7	n.a.	3.7	13.6	194.3		n.a.					n.a.			
17	1.3	n.a.	1.3	4.8	68.3		n.a.					n.a.			
total	**26**	**n.a.**	**26**	**97**	**1386**	**18**	**n.a.**	**18**	**64**	**635**	**13**	**n.a.**	**13**	**46**	**55**

Various Rotations

According to the cutting cycles of the different SIs, project horizons vary between 92 and 96 years. In order to demonstrate the calculation of the average storage, we chose SI 15. Three rotations can be realised, including thinning at the respective ages (Figure 31). Average carbon storage in above and below-ground biomass is about 49 tC/ha (= 179 tCO$_2$/ha). Again, soil carbon is excluded for the reasons mentioned above, even though - at such a long project duration - additional soil carbon fixation could take place if during harvests the proper management were applied to protect the soils. On a SI 11 two rotations take place with an average storage of about 50 tC/ha (= 183 tCO$_2$/ha). On a SI 19 four rotations can be realised with an average storage of 47 tC/ha (= 172 tCO$_2$/ha).

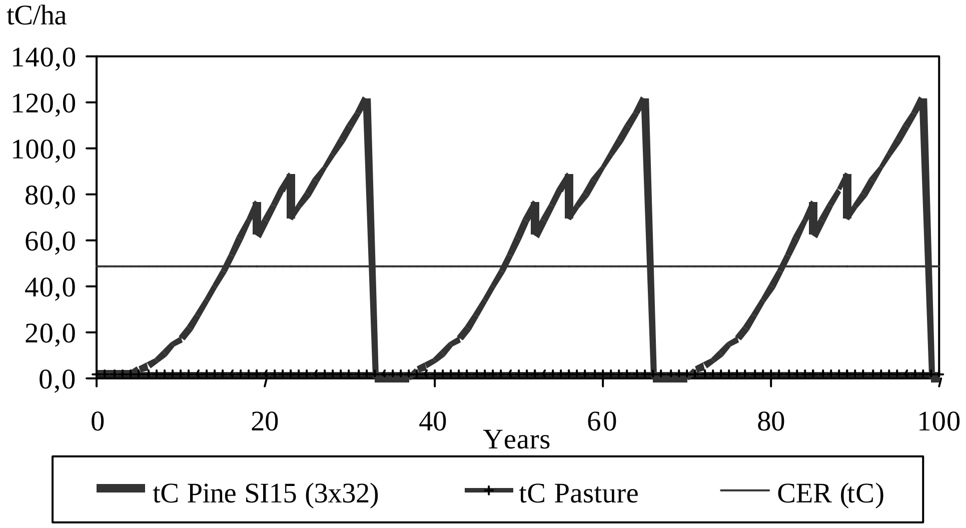

Figure 31. Carbon sequestration in a pine plantation - 3x32 yr, Argentina.

In the case of various rotations, the results also depend mainly on the NPV of the forestry alternatives. These NPVs are negative in all sites, resulting in a required compensation with a positive sign (Figure 32). In the good sites (SI 19) the minimum price of about \$0.5-1/tCO_2 is slightly higher than zero. The medium sites (SI 15) require a minimum payment of about \$5/$tCO_{2,}$ and the less appropriate sites (SI 11) of about \$10/$tCO_{2,}$ to persuade landowners to switch from pasture to forest plantation.

If such a minimum payment is realised, financial flows per ha as shown in Table 17 would be generated. All alternatives are able to fix approximately the same amount of carbon dioxide (about 175 tCO_2/ha), but the respective not-discounted compensation payments vary considerably between \$86 and \$1,760 per ha, depending on the suitability of the site for forest projects.

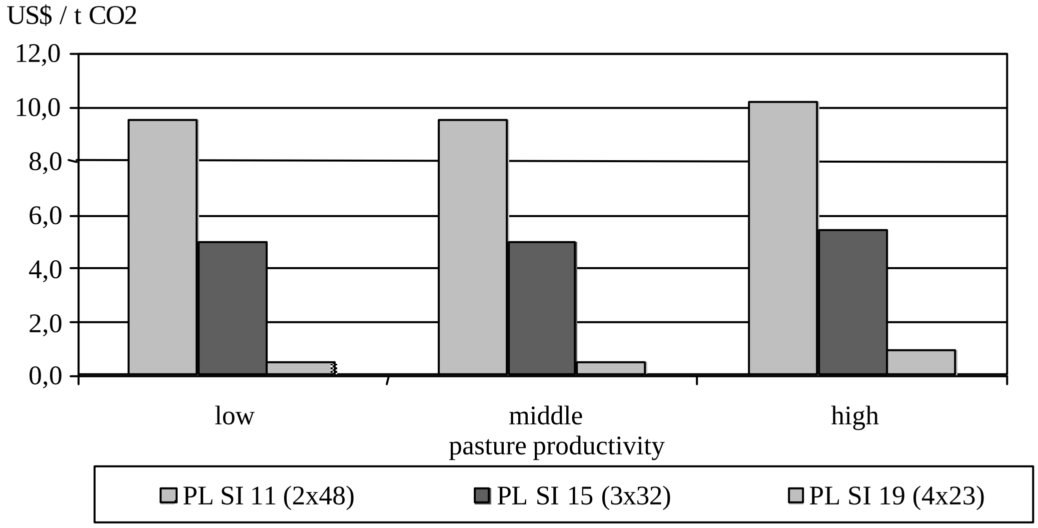

Figure 32. **Minimum price of CO_2 sequestration in pine plantations at different sites (100 years), Argentina.**

Table 17. Payment of “minimum prices” for carbon sequestration in plantation forest – 100-year project, Argentina (SI 11: \$9.6/tCO_2; SI 15: \$5.0/tCO_2; SI 19: \$0.5/tCO_2).

	2 rotations (2x48 years) SI 11					3 rotations (3x32 years) SI 15					4 rotations (4x23 years) SI 19				
year	Biomass C	SOC	C total	CO2 tota	Payment	Biomass C	SOC	C tota	CO2 total	Payment	Biomass C	SOC	C total	CO2 tota	Payment
	(tC/ha)	(tC/ha)	(tC/ha)	(tCO2/ha	($/ha)	(tC/ha)	(tC/ha	(tC/ha)	(tCO2/ha)	($/ha)	(tC/ha)	(tC/ha)	(tC/ha)	(tCO2/ha)	($/ha)
0	0.0	n.a.	0.0	0.0	0.0	0.0	n.a.	0.0	0.0	0.0	0.0	n.a.	0.0	0.0	0.0
1	0.0	n.a.	0.0	0.0	0.0	0.0	n.a.	0.0	0.0	0.0	0.0	n.a.	0.0	0.0	0.0
2	0.0	n.a.	0.0	0.0	0.0	0.0	n.a.	0.0	0.0	0.0	0.0	n.a.	0.0	0.0	0.0
3	0.0	n.a.	0.0	0.0	0.0	0.0	n.a.	0.0	0.0	0.0	0.7	n.a.	0.7	2.6	1.3
4	0.0	n.a.	0.0	0.0	0.0	0.0	n.a.	0.0	0.0	0.0	1.2	n.a.	1.2	4.4	2.2
5	0.5	n.a.	0.5	1.8	17.6	1.5	n.a.	1.5	5.5	27.5	2.1	n.a.	2.1	7.7	3.9
6	0.9	n.a.	0.9	3.3	31.7	1.7	n.a.	1.7	6.2	31.2	3.5	n.a.	3.5	12.8	6.4
7	1.2	n.a.	1.2	4.4	42.2	2.4	n.a.	2.4	8.8	44.0	4.7	n.a.	4.7	17.2	8.6
8	1.5	n.a.	1.5	5.5	52.8	3.1	n.a.	3.1	11.4	56.8	5.8	n.a.	5.8	21.3	10.6
9	1.9	n.a.	1.9	7.0	66.9	3.8	n.a.	3.8	13.9	69.7	6.8	n.a.	6.8	24.9	12.5
10	0.2	n.a.	0.2	0.7	7.0	2.5	n.a.	2.5	9.2	45.8	5.8	n.a.	5.8	21.3	10.6
11	2.5	n.a.	2.5	9.2	88.0	5.0	n.a.	5.0	18.3	91.7	8.6	n.a.	8.6	31.5	15.8
12	2.8	n.a.	2.8	10.3	98.6	5.5	n.a.	5.5	20.2	100.8	6.7	n.a.	6.7	24.6	12.3
13	3.1	n.a.	3.1	11.4	109.1	5.9	n.a.	5.9	21.6	108.2	1.0	n.a.	1.0	3.7	1.8
14	3.3	n.a.	3.3	12.1	116.2	6.3	n.a.	6.3	23.1	115.5		n.a.			
15	3.5	n.a.	3.5	12.8	123.2	6.7	n.a.	6.7	24.6	122.8		n.a.			
16	3.7	n.a.	3.7	13.6	130.3	4.4	n.a.	4.4	16.1	80.7		n.a.			
17	3.8	n.a.	3.8	13.9	133.8		n.a.					n.a.			
18	4.0	n.a.	4.0	14.7	140.8		n.a.					n.a.			
19	4.1	n.a.	4.1	15.0	144.3		n.a.					n.a.			
20	4.2	n.a.	4.2	15.4	147.9		n.a.					n.a.			
21	4.4	n.a.	4.4	16.1	154.9		n.a.					n.a.			
22	4.4	n.a.	4.4	16.1	154.9		n.a.					n.a.			
total	**50**	**n.a.**	**50**	**183**	**1760**	**49**	**n.a.**	**49**	**179**	**895**	**47**	**n.a.**	**47**	**172**	**86**

Summary of the Economic Results in north-western Patagonia

In NW Patagonia we concentrated on pine plantations and estimated the financial compensation according to the alternative qualities of pasture land. It was found that minimum prices of CO_2 sequestration hardly depend on pasture productivity (low, medium, high), as the NPVs of the considered pasture alternatives are about zero. The NPV of pine plantations is, even on the best sites, negative, resulting in a compensation higher than zero for switching from pasture to forestry.

The minimum price of sequestration in sites with a high SI is relatively low, about \$1/tCO_2 for 30-year projects and \$0.5/tCO_2 for 100-year projects. The minimum price of CO_2 sequestration in sites with a medium SI is about \$10/tCO_2 for 30-year projects, and \$5/tCO_2 for 100-year projects. Sites that are less suitable for pine plantations (SI 11) require higher payments of about \$15/tCO_2 for 30-year and \$10/tCO_2 for 100-year projects. Due to the slow biomass production, CER revenues are generated relatively late (approximately from year 4 onwards). In a medium site it takes about 11 years (for one rotation) and 16 years (for 3 rotations) until the average net storage level is reached.

These prices are calculated on the basis of the former Dollar-Peso-Parity. The Peso devaluation of about 70% after giving up the currency board has a strong impact on the results above. One immediate effect is that the Dollar values of the compensation calculated by using the new exchange rate are about 70% lower than their values calculated at Peso-Dollar-Parity. This statement holds for those cases where the NPVs of pasture and forestry are calculated exclusively on the basis of Peso prices. This situation is the case in the study region, as both pasture and forestry production output are traded on domestic markets. Long term secondary effects caused by the devaluation, which might have an impact on product markets, are not considered in the present study.

4 Discussion of the results

4.1 Carbon in biomass

Biomass estimates for secondary forests in Ecuador indicate that on average these forests can reach a biomass of just over 200 t/ha after 30 years. Steininger (2000) reports an average growth rate of 9-10 t/(ha yr) for young secondary forests during the first 12 years in Brazil. That is slightly lower than the growth rate estimated for the secondary forests in Ecuador in this study. This could be due to higher soil fertility in north-western Ecuador than in the Brazilian Amazon, as a result of the relative nearness of the Ecuadorian study area to the western *cordillera* of the Andes and the subsequent deposits of volcanic ash.

The variability of the estimated above-ground biomass of these secondary forests is large for the same age classes. This is the result of the variation in soil and climate conditions within the study area, as well as in species composition and management. Landowners occasionally fell some trees for construction work. Furthermore, all secondary forests were the result of the abandonment of pastures. In some of these pastures, trees - remnants of the previous native forest - may have remained scattered around and have become part of the secondary forests after pasture abandonment. These large trees, although few in number, can constitute an important amount of biomass.

The largest uncertainty in biomass estimations for secondary forests in Ecuador is introduced by the biomass expansion factor. This is derived from the literature, which in turn is based on a compilation of destructive sampling data from various tropical sites. For the study area in Ecuador, no specific data on biomass expansion factors for secondary forests are available, and for more detailed studies, destructive sampling in selected secondary forests is recommended.

The tree species for which most information is available for the study area is laurel, and for this reason the growth curves of this species (Alder and Montenegro, 1999) were used in the economic analysis of plantation forests. The biomass increment over time of laurel plantations is higher than that of secondary forests: 250 t/ha after 20 years as opposed to about 170 t/ha in secondary forests. The biomass estimated for the plantation that mainly consisted of laurel (the "las Golondrinas" site) - 229 t/ha after 17 years (Table 2) - corresponded well with the growth curve (Figure 9).

A comparison by Alder (1999) between plantation species in the study area, such as Chuncho (*Cedralina catenifomis*), Pachaco (*Schizolobium parahybum*), Cutanga (*Parkia multijuga*) and Jacaranda (*Jacaranda copaia*), indicates that these species can have an annual wood volume increment superior to that of laurel.

Biomass in understory growth and tree roots, and the carbon it contains, were not estimated for the Ecuadorian forests. Little information exists on root biomass in tropical forests, probably because of the large amount of work needed for good estimates. By means of a literature review including 39 examples of site data, Cairns et al. (1997) have calculated an average biomass in the roots of tropical forests of 24% of the above-ground biomass. The biomass of undergrowth in tropical forests is very variable but probably represents a rather limited amount of biomass (Kotto-Same, 1997; Fehse et al., 1999).

In contrast to Ecuador, biomass estimations in Argentina were based on destructive sampling of selected pine and cypress trees in the study area. In this respect, it proved a methodological advantage that only two tree species were considered as opposed to the high variety of species in Ecuador, allowing specie-specific allometric regression models to be constructed for Argentina. The destructive sampling method, which included harvesting the roots, also permitted the development of these models for each of the individual tree biomass compartments: trunk, branches, leaves/needles and roots. The models had high coefficients of determination, especially for trunks, branches and roots. It is therefore likely that biomass estimations for the two types of forests considered in Argentina are more reliable than the estimates for the secondary forests in Ecuador. Averaged over all sites, the biomass distribution of the compartments was different for pine and cypress, especially with respect to root biomass. Pine had a root/shoot biomass ratio of 19.5% as opposed to 11.4% in cypress, although cypress is more resistant to drought stress.

The diameter range considered in developing the models was 5-35 cm. Most trees in pine plantations in the study area fall within that diameter range, as the majority of these plantations have been established less than 30 years ago. This is due to the fact that only since the beginning of the seventies have forest plantations been stimulated at the national level through financial incentives. However, some of the pine plantations in the sample were older and had trees with diameters over 35 cm. For these plantations, biomass estimations for branches, needles/leaves and roots are less reliable. On the other hand trunk biomass, which is the main biomass compartment, was based on rather reliable volume estimations using DBH and altitude. The same applied to some of the oldest cypress forests.

At comparable ages total pine biomass in the selected sites was clearly higher than cypress biomass. Cypress stands are the result of natural regeneration through seed fall, and most of them have a very heterogeneous structure. Various age cohorts can be found within one stand, while the age measured in the field with a wood auger was that of the oldest trees. Other possible reasons for lower biomass in cypress stands - apart from physiologically determined growth rates - are that some landowners extract cypress wood for construction, while cattle have access to some stands.

Multiple regression analysis to predict biomass with soil and climate variables and age, using the site-specific data, resulted in a model for pine plantations which allowed about 80% of the variation in biomass to be predicted with the variables of age and precipitation. No other biophysical variables were selected in the model. Clear relations could not be found between biomass and biophysical variables in either secondary forests in Ecuador, or in cypress forests in Argentina. For both forest types, this is probably due to the heterogeneity of these forests discussed above, which is caused by other factors than soil and climate characteristics, such as management, species diversity and different age classes within one stand.

Site-specific biomass estimations were used for the explanation of soil carbon dynamics, and in the case of the Ecuadorian secondary forests, a growth curve was derived from these estimations to be used in the economic analysis. For the economic analysis of laurel and pine plantations, growth curves were derived from the literature and unpublished INTA data, respectively. For cypress trees no growth models were available, as the wood is not commercially produced by means of plantations, although some dense state forests are managed under silvicultural prescriptions. Cypress stands are not planted but the result of natural regeneration. Landowners do not value the standing stock of cypress wood on their land and do not manage the stands, but just use the wood when needed, for example in construction (Laclau et al., 2002b). For this reason no management models exist for the study area, although there seems to be an interesting market for cypress (Laclau et al., 2002b). The lack of reliable cypress growth data made us decide not to include cypress in our economic analysis.

For pine plantations, the site index greatly determines the growth rate. The necessary rotation length to reach a biomass of about 240 t/ha is, at the least suitable sites, more than twice the rotation length at the most suitable sites. When comparing growth curves, the biomass of pine after 30 years at the medium site index is comparable to the accumulated biomass in secondary forests in Ecuador. A laurel plantation with a low planting density (200 trees/ha) at a medium site index in Ecuador has after 20 years a biomass comparable to that of the pine plantation at the most suitable sites. However, laurel with a high planting density has a clearly higher biomass after 20 years than pine at the most suitable sites.

While the growth curves for Ecuador indicate decreasing annual growth over time, the site estimates for the biomass of pine and cypress stands suggest continuing growth over time. The highest estimated pine biomass is at the Isla Victoria site: 960 t/ha at an ABH of 64 years. Published data for the study area confirm that such a high biomass is indeed feasible. Lanciotti et al. (1995) report a trunk volume of 4000 m^3 for a humid dense *Pinus oregon* forest of 52 years, which - when applying a wood density of 0.43 kg/dm3 - would represent 1,720 t/ha of biomass in the trunk alone. These authors state that similar growth rates are feasible in *Pinus ponderosa*. In contrast, the reported above-ground biomass of native tropical forest is around 300-500 t/ha (López et al., 2002). Old Patagonian pine forests are therefore very interesting in terms of total carbon sequestration capacity, but their economic attractiveness depends on rotation length and wood quality.

4.2 Carbon in soils

Literature on the effects of land use conversion on soil organic carbon dynamics in South America has predominantly focussed on soil carbon changes after the cutting of native tropical forest, mainly to estimate the impact of deforestation on the global climate and local soil quality. Much less information exists on soil carbon changes after human-induced forest (re)growth on (tropical) agricultural land. However, these are the changes we are interested in for the purpose of carbon sequestration projects. Soil carbon changes measured in deforestation studies are not simply reversible, because these depend on the partitioning of carbon between the different stable and less stable pools. Also, much of the literature on the impact of land use conversions on soil characteristics deals with tropical South America, while less information is available for temperate regions such as Argentinean Patagonia. For this reason, soil carbon changes after forest (re)growth in agricultural land in the two contrasting climate regions of our study formed a central research theme in this project.

Our hypothesis was that soil organic carbon content increases after conversion of degraded pastures to forest systems, and that the amount of change depends on soil and climate characteristics.

For Ecuador the results did not offer a basis to conclude that secondary forests and plantation forests have a different impact on soil carbon dynamics. Therefore, the results of secondary forests and plantation forests were lumped together to generally represent forests growing after former pasture. In Ecuador the average amount of soil organic carbon in the 0-50 cm soil layer of forests was about 7 t/ha higher than in pastures. These differences are the result of higher carbon contents in forests in the 0-25 cm layer; in the 25-50 cm layer carbon contents are similar for the two land use types. Absolute differences between pastures and forests were on average higher in volcanic soils (9.7 t/ha) than in sedimentary soils (5.7 t/ha), although the relative differences were comparable for both soil types: around 7% more carbon (Mg/ha) in forests than in pastures. The higher absolute carbon contents in volcanic soils for both land use types are related to soil characteristics, as indicated by correlation analysis. Carbon contents for all sites grouped together increase with higher amounts of aluminium, iron and silica, decrease with Alo/Alp ratio and - within soil groups - increase with clay and silt fraction. This indicates the soil fractions that stabilise soil organic carbon: organo-metal complexes, clay and silt particles, and allophane.

In Ecuador, the paired site differences in soil organic carbon content in the 0-25 cm layer between pastures and forests were significant, as indicated by the paired t-test. The same test indicated that for this layer, differences in Cp were not significant, and neither were the differences in carbon light fraction. Cp represents the amount of carbon in organo-metal complexes. Differences in total carbon between the land use types are thus mainly associated with the non-organo-metal carbon fraction (indicated by the significant differences in C minus Cp), which is probably carbon associated with clay and silt minerals and, in the case of volcanic soils, also associated with allophanes.

Although the paired t-test indicated that land use type had an overall effect in Ecuador, this effect is modified by the age of the pastures with which forests are compared. It was shown that young pastures (< 10 yr) have on average higher soil organic carbon contents than nearby forests, while old pastures (> 20 yr) have on average clearly lower soil organic carbon contents than neighbouring forests. A possible explanation for these results is a change in the mineralisation rate after land conversion. Higher mineralisation rates in pasture because of exposure to higher temperatures can lead to an increase in soil carbon after recent pasture establishment due to the mineralisation of remaining litter and fine root material of the previous forest. After several years of pasture, the higher turnover rate and absence of vegetative material from the forest may result in decreasing carbon levels, lower than the original level at pasture establishment. This seems to be confirmed by the change of the C/N ratio with the age of the vegetation (Figure 33). Although variation is large, the C/N ratios in pastures show a tendency to decrease with age. In forests, the opposite occurs, with an accumulation over time of carbon compared to nitrogen. Another probable factor influencing C/N ratios is a difference in litter quality between pastures and forests. Woody debris generally has a higher C/N ratio than grass residues. For forests, the soil groups seem to behave differently (Figure 33), with higher C/N ratios in volcanic soils at increasing forest age, which can be due to the chemical composition of the vegetative material or caused by lower mineralisation rates in these soils.

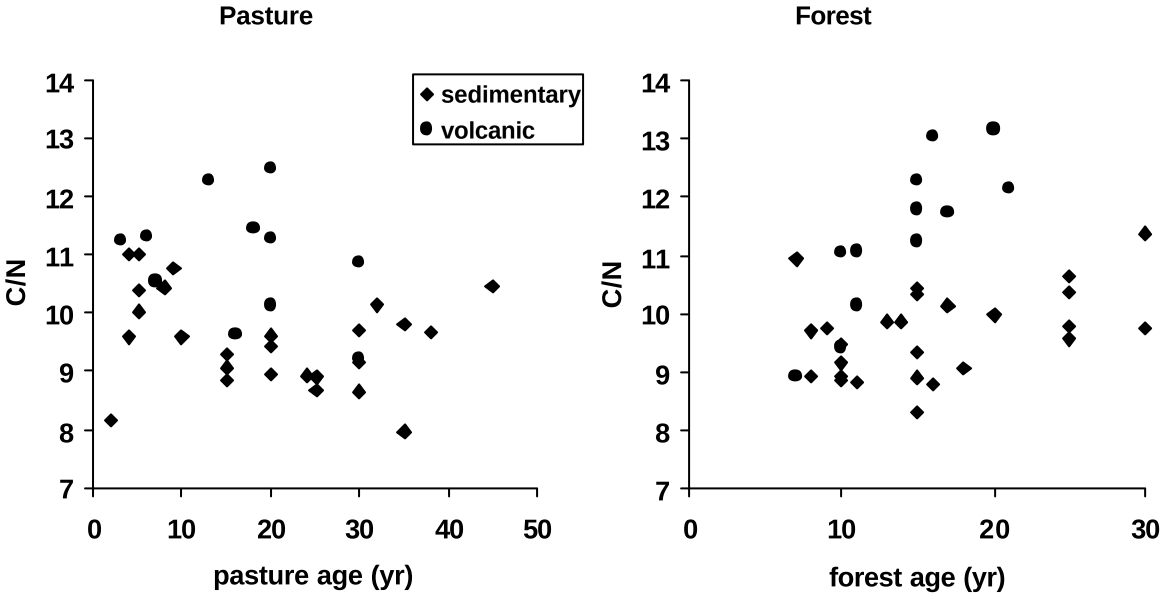

Figure 33. C/N ratio in pasture and forest plots as a function of vegetation age, Ecuador.

These results confirm our hypothesis, namely that pastures degrade with age, which is accompanied with a decrease in carbon content. Reforestation in these degraded pastures leads on average to an increase in carbon content, which is positive in terms of carbon sequestration and soil quality. It has to be taken into account, however, that the variability of the carbon differences within pasture age classes was large (Figure 15), limiting the predictability of the effect of forest growth on the basis of pasture age alone.

With respect to the observed carbon differences in dependence of pasture age in this study, a similar pattern has been reported by García-Oliva et al. (1994) in a study in Mexico. Soil organic matter from pastures of different ages after deforestation was compared with the soil organic matter of the original forest.

After 3 years, pastures had 31% more soil organic matter in the top 6 cm of soil due to an increase of soil organic matter originating from the decomposition of remnant forest roots. However, after 11 years the total soil organic matter level in pasture was 7% lower than in the original forest. In a study of a conversion from forest to maize in temperate France, Balesdent et al. (1998) conclude that the observed decrease in total soil organic matter could not be contributed to lower C-input through leaves and roots. Instead, the decrease was the result of the changed soil C turnover rate, which under cultivation was 8 times higher than under forest, leading to a decrease in the C/N ratio over time. The decrease in the C/N ratio was also observed in the pastures of our study (Figure 33), but is probably also the results of higher C/N ratios of forest litter compared to grass residues.

Our results indicate that for the interpretation of literature concerning the effects of forest to pasture conversions or vice versa on soil organic carbon, it is very important to take into account the vegetation age, as the long-term and short-term effects can be quite different.

Multiple regression analysis can explain site differences in soil carbon (t/ha) between pasture and forest in Ecuador for volcanic soils, using pasture age and altitude as explaining variables. As expected, differences increase with pasture age. The positive relation with altitude reflects the increasing absolute differences with increasing volcanic properties. Although a significant model was found for sedimentary soils, the percentage of variation explained was low.

The ^{13}C isotope analysis indicated that in Ecuador about 50% of soil organic carbon is stable. The observed differences in SOC between pasture and forest sites will in the timeframe considered have taken place in the labile carbon fraction. While the total carbon content (t/ha) is on average 7% higher in pastures than forests, this difference would be 14% if we assume that the changes in carbon levels take place in the labile fraction. The results of the ^{13}C isotope analysis also confirm the high turnover rates, as forest-derived carbon decreases rapidly in the first 20 years of pasture growth, while pasture-derived carbon decreases rapidly in forest regrowth after pasture abandonment.

In Argentina, soil carbon contents in the 0-25 cm layer could for each vegetation type independently be accurately predicted on the basis of biotic and abiotic variables, which explain over 87% of the variation. Aluminium content is an important variable in each of the models, indicating the importance of aluminium in stabilizing carbon in the soil. Negative association with the sand fraction for cypress and pine indicates the low carbon-stabilizing capacity of this texture class.

In Argentina the average amount of soil organic carbon in the 0-50 cm soil layer of cypress forests was about 29 t/ha higher than in pastures, while that of pine plantations was about 3 t/ha lower than in pastures. As in Ecuador, these differences are mainly due to differences in the 0-25 cm layer. The average SOC difference in the 0-50 cm layer between cypress and pasture is about four times the average difference between forests and pastures in Ecuador.

The paired site differences in soil organic carbon content in the 0-25 cm layer between cypress and pastures and between pine and pastures in Argentina were significant as indicated by the paired t-test. However, the differences from pasture in total carbon content in the 0-50 cm layer were only significant for cypress. For the 0-25 cm layer, differences in Cp were not significant, which was also observed in Ecuador. As in Ecuador, differences in total carbon between the land use types are thus mainly associated with the non-organo-metal carbon fraction (indicated by the significant differences in C minus Cp), which is carbon associated with clay and silt minerals and, in the case of volcanic soils, also associated with allophanes.

Contrary to Ecuador, no clear relation was found between carbon differences and vegetation age in Argentina. Only in the multiple regression model for soil organic carbon differences between pasture and cypress was a positive relation found between biomass (which is correlated with age) and the amount of carbon in cypress minus pasture. The range of ages of the selected cypress stands was much wider and included much older forests than the selected pine stands (Figure 11). The fact that most pine stands were rather young (< 30 years) might be one of the reasons that in pine stands the total amount of SOC in the 0-50 cm layer was very similar to pasture. Compared to tropical Ecuador, soil biological processes are slower due to the temperate climate, with humid but cool winters and hot and dry summers. The pine stands accumulate a high amount of litter compared to the cypress stands, with slow decomposition of the deposited needles.

As in Ecuador, the mineralisation rate might in Argentina be slower in forests than in pastures, and/or the C/N ratio of forest litter might be higher than the C/N ratio of vegetative material of pasture (Gobbi et al., 2002; Buamscha et al., 1998). This seems to be confirmed for pine stands, with a clearly increasing C/N ratio in the soil over time (Figure 34). For cypress this is less clear, probably as result of the higher variation in the relation between age and density and biomass.

With multiple regression analysis, site differences in soil carbon (t/ha) between pasture and forest could not as well be explained as for volcanic soils in Ecuador. The coefficient of variation was low, especially for pine. Except for biomass in the case of the models for cypress, the selected variables were all indicators for mineralogy.

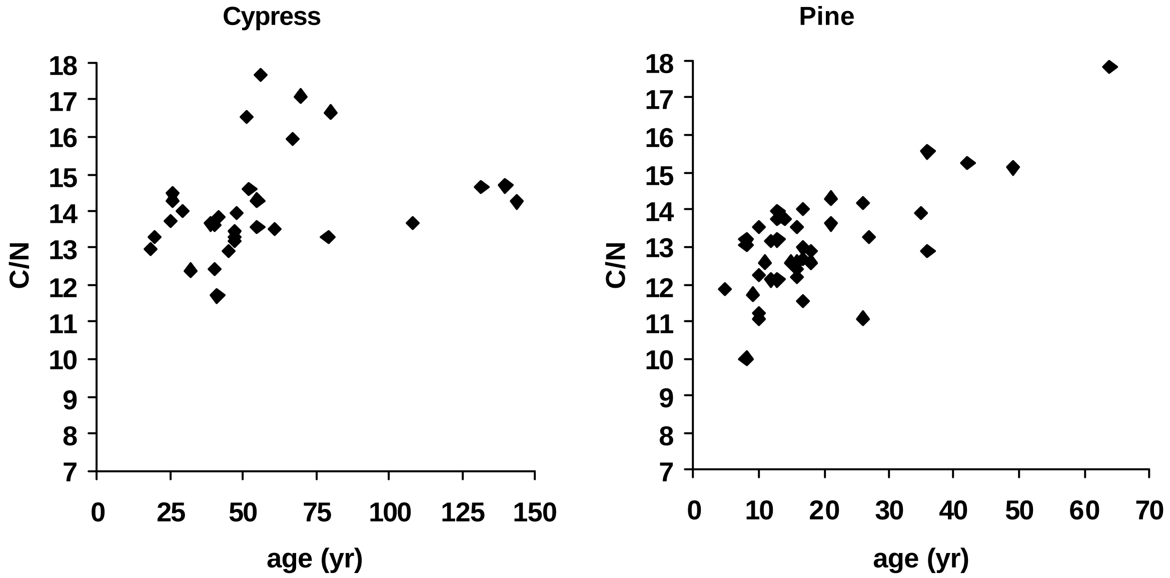

Figure 34. C/N ratio in cypress and pine plots as a function of vegetation age (ABH), Argentina.

4.3 Economic analysis

The economic results are based on data gathered during the fieldwork in Ecuador and Argentina in 2001. For both regions, typical land uses were defined and a comparison for medium sites was conducted. The estimated average costs per ha represent point estimates. Nevertheless, they might be interpreted as marginal costs, "if large scale sequestration was being undertaken using a host of projects" (Sedjo 1994). The way these results are influenced by changes in economic variables can be shown by a sensitivity analysis.

4.3.1 Sensitivity Analysis

Conducting 30-year projects at average sites in NW Ecuador leads to an average net storage of about 77 (secondary forest) to 88 (forest plantation) tCO_2/ha in a 100-year timeframe. Soil organic carbon contributes approximately 15% of the average net storage, and results in an overall average net storage of about 92 to 101 tCO_2/ha. The minimum prices for CO_2 sequestration in the most suitable area (zone 2) range from $4–6 per tCO_2. If these prices were actually paid, the landowners would receive income flows of about $390/ha (secondary forest) (average: $130/(ha yr)) to $580/ha (forest plantation) (average: $190/(ha yr)) within the first 3 years.

30-year plantation projects at medium sites in the study area in NW Patagonia sequester about 64 tCO_2/ha at a 100-year time horizon. The required minimum compensation is $10 per t CO_2, resulting in a payment of approximately $640/ha within 11 years (average: $60/(ha yr)).

100-year projects at medium sites in NW Ecuador store approximately 355/380 tCO_2/ha (secondary forest/forest plantation) on average, of which 15% is fixed in the soil. Minimum prices of $2.3 per tCO_2 (for both alternatives) would generate payments of about $870/ha within 22 years (secondary forest) (average: $40/(ha yr)) and $810/ha within 13 years (forest plantation) (average: $60/(ha yr)).
100-year plantation projects in medium sites in NW Patagonia sequester about 180 tCO_2/ha. The minimum financial incentive for switching from pasture to forestry is about $5/$tCO_{2,}$ and results in a payment of about $895/ha within 16 years) (average: $55/(ha yr)). The minimum price of sequestration in sites with a medium SI is twice as high as for suitable medium sites in NW Ecuador, about $10 per tCO_2 for 30-year projects and $5 per t CO_2 for 100-year projects.

Tables 18 and 19 show the results of a sensitivity analysis for Ecuador and Argentina, respectively. The impact of changes in product prices and interest rates is evaluated and certification costs are estimated, assuming costs calculated in Dollars per ton CO_2 or Dollars per hectare and year.[21]

Table 18. Sensitivity analysis in NW Ecuador (zone 2)[22]

Sensitivity Analysis NW Ecuador (zone 2)				
	Minimum price of CO2 sequestration (p_{CER} in $/tCO2)			
	30 years project in zone 2		**100 years project in zone 2**	
	SF 30 managed	**PL 2x15 years**	**SF 100 managed**	**PL 5x20 years**
Timber price ($/m3)				
15$/m3=75%	5.6	9	2.6	3.3
20 $/m3=100%	**4.2**	**5.8**	**2.3**	**2.3**
25 $/m3=125%	2.7	2.6	2	1.3
Meat price ($/kg)				
0.7	1.3	3.2	1.2	1.3
0.9	**4.2**	**5.8**	**2.3**	**2.3**
1.1	7.1	8.5	3.4	3.3
Milk price ($/l)				
0.18	2.8	4.6	1.8	1.8
0.24	**4.2**	**5.8**	**2.3**	**2.3**
0.3	5.6	7.1	2.8	2.8
Interest rate				
5%	4.4	4.4	2.9	1.5
7%	**4.2**	**5.8**	**2.3**	**2.3**
9%	3.7	6.7	1.9	2.7
Certification costs ($/tCO2)				
0	**4.2**	**5.8**	**2.3**	**2.3**
0.5	4.7	6.3	2.8	2.8
1	5.2	6.8	3.3	3.3
Certification costs ($/ha*a)				
0	**4.2**	**5.8**	**2.3**	**2.3**
0.5	4.3	5.9	2.4	2.3
1	4.4	6	2.4	2.3
Payment procedure				
according to annual fixation	**4.2**	**5.8**	**2.3**	**2.3**
10 years	5.3	7.5	2.1	2.5
30 years	8.9	12.8	3.6	3.4
100 years	25.8	37.3	11.6	11.8

---

[21] Both payment regimes can be included in equation *(5)*: the $/ha-approach is entered in the numerator as an additional annual cost per hectare in the NPV_F. The same holds for the $/$tCO_2$ approach, where the calculation is based on the amount of CER units generated by the respective forestry alternative.

[22] Bold types show basic results.

Also, we compare different CER payment regimes. In the case of Ecuador we assume: a) payment is according to net increment of CO_2 storage until average net storage is reached, b) average payment per year is within the first ten years, c) within 30 years, d) within 100 years. For Argentina we consider: a) payment according to net increment of CO_2 storage until average net storage is reached, b) average payment within the first 3 years, c) average payment per year according to rotation length.

Table 19. Sensitivity analysis for NW Patagonia[23]

Sensitivity Analysis NW Patagonia						
	Minimum price of CO2 sequestration (p_{CER} in $/tCO2)					
	Pine plantation (1 rotation)			**Pine plantation (various rotations)**		
	SI11 (48 years)	**SI15 (32 years)**	**SI19 (23 years)**	**SI11 (2x48)**	**SI15 (3x32)**	**SI19 (4x23)**
Timber price (% of 2001 prices)						
75%	16.2	15.5	12.8	10.9	7.8	5.3
100%	**14.3**	**9.9**	**1.2**	**9.6**	**5.0**	**0.5**
125%	12.5	4.2	-10.5	8.3	2.1	-4.3
Meat price ($/kg)						
0.65	14.3	9.9	1.2	9.6	5.0	0.5
0.85	**14.3**	**9.9**	**1.2**	**9.6**	**5.0**	**0.5**
1.05	16.6	12.4	3.8	11.1	7.4	2.6
Interest rate						
5%	10.0	3.5	-7.5	6.7	1.8	-3.5
7%	**14.3**	**9.9**	**1.2**	**9.6**	**5.0**	**0.5**
9%	19.0	15.8	9.2	13.0	8.0	3.7
Certification costs ($/tCO2)						
0	14.3	9.9	1.2	9.6	5.0	0.5
0.5	**14.8**	**10.4**	**1.7**	**10.1**	**5.5**	**1.0**
1.0	15.3	10.9	2.2	10.6	6.0	1.5
Certification costs ($/ha*a)						
0	14.3	9.9	1.2	9.6	5.0	0.5
0.5	**14.5**	**10.1**	**1.4**	**9.7**	**5.1**	**0.6**
1.0	14.7	10.3	1.6	9.8	5.2	0.7
Payment procedure						
annual net fixation	**14.3**	**9.9**	**1.2**	**9.6**	**5.0**	**0.5**
3 years	7.2	6.5	0.9	n.a.	n.a.	n.a.
according to rotation length	20.6	13.3	1.4	22.5	14.9	1.7

---

[23] Bold types show the basic results. “Timber price” consists of prices for different wood qualities (used for boards, posts, wood pulp, charcoal). For 100-year projects, no 3-year payment was calculated.

As expected according to equation *(9),* the minimum compensation declines with rising timber prices and increases with increasing prices of pasture products (meat, milk). The interest rate level also has a significant impact on the minimum CER prices: in the case of plantations, the compensation rises with higher interest rates, mainly because revenues only occur after each rotation and thus are affected more heavily by discounting than annual revenue flows. The percentage price variation in NW Patagonia is higher than in NW Ecuador, even resulting in a negative price for the best sites (SI 19). This means that, at a real interest rate of 5%, a pine plantation in the Patagonian study area is economically feasible even without CER revenues.

In Ecuador the required compensation for CO_2 sequestration in secondary forests declines with higher interest rates due to the overwhelming effect of increasing the (fixed capital) opportunity costs of cattle ranching. This characteristic of the pasture alternative is also taken into consideration when comparing it with plantations; however, there it is dominated by the discounting effect described above, resulting in rising minimum prices.

The impact of certification costs depends on the payment regime. Assuming a payment per ha and year does not have a great influence on the minimum prices. If the costs are supposed to be calculated per tCO_2, the compensation varies according to the level of costs assumed.[24]

Tables 18 and 19 also show the importance of the CER payment procedure. The earlier the payment takes place, the lower the compensation requirement. This relationship is based on the landowner's positive time preference reflected by discounting future revenues.

---

[24] Jotzo and Michaelowa (2001) assume implementation and transaction costs of about $0.5/$tCO_2$ for CDM projects, including reporting and verification requirements.

A further aspect has to be taken into consideration: until now, no final decision has been taken about the definition of storage permanence. IPCC (2000) argues that permanence does not mean that a specific atom of carbon will “remain in the forest forever”. The difference between carbon in trees and carbon in the atmosphere is that atmospheric carbon is “subject to removal through natural processes that transfer it to sinks such as oceans and the biosphere, whereas carbon in trees is assumed to remain fixed”. Thus, if a carbon atom is stored by an afforestation project, the time necessary to have an equivalent effect on the atmosphere as a reduced emission of a carbon atom might be shorter than 100 years. Fearnside et al. (2000) suggest a 46 year timeframe based on the results of the “Revised Bern Model”. Because of the uncertainty concerning the final decision on the permanence criterion, all results in the present study were recalculated, applying the so-called “equivalence-adjusted average storage approach” (Moura Costa, 2000c), that uses a 46 year timeframe instead of 100 years in equation *(12)*. This approach approximately doubles the accounted average net storage and leads to a reduction of about half of the minimum price per ton of CO_2 sequestered in both study areas.

4.3.2 Regional comparative analysis

In the following section the results of the evaluation are used for an exemplary calculation of the CO_2 fixation potential in both study areas.
The overall area of zone 2 in NW Ecuador is about 420,000 ha, of which about 40% is used for extensive pasture. We assume that 20,000 ha (approximately 12% of pasture expanse) could be used for 30 (or 100) year forestry projects without leakage effects.[25]

---

[25] According to UNFCCC, leakage is defined as the net change of anthropogenic emissions by greenhouse gas sources occurring outside the project boundary, and which is measurable and attributable to the CDM project activity.

The study area in Argentina has about 1.15 million ha, of which about 445,000 ha are used for pasture (Laclau et al., 2002b). Again, we assume that 20,000 ha could be used for forestry alternatives (33 and 96 years) without leakage effects. Comparison of the results in Table 20 shows that - under the assumptions made - the ecological potential of CO_2 sequestration in NW Ecuador is higher than in NW Patagonia. When establishing 30-year projects on the same surface area (20,000 ha), about 50% more CO_2 can be fixed in the NW Ecuadorian study area (including SOC, excluding roots). For 100-year projects, the picture is even clearer, because the amount fixed is about 100 % higher in the case of Ecuador. Even neglecting soil organic carbon in both cases would not significantly change this result.[26] On the other hand, it has to be taken into account that only about 4% of the overall pasture area in the Patagonian study area was included in the example given above. If we assume that much wider areas of grassland could be used for forestry alternatives without leakage effects, the overall ecological potential to sequester carbon in NW Patagonia increases.

---

[26] In Argentina it proved possible to estimate root biomass, resulting in a root carbon fixation of about 15% of total carbon for ponderosa pine. In Ecuador root biomass was neglected. Assuming a root to shoot ratio of about 0.10 for lowland moist forest (Brown, 1997) would lead to a further 10% increase of average carbon fixation in the Ecuadorian case.

Table 20. Comparison of Sequestration Potential (20,000 ha)

		Net Av. Storage	Total storage	Min. Payment	Total Costs
		(tCO2/ha)	(tCO2)	($/tCO2)	($)
30- year projects	**ECUADOR (Zone 2)**				
	Secondary Forest (30 years)	92	1,840,000	4.2	7,728,000
	Forest Plantation (2x15 years)	100	2,000,000	5.8	11,600,000
	ARGENTINA (NW-Patagonia)				
	Forest Plantation (1x32 years)	64	1,280,000	9.9 (5.0)	12.670.000 (6.336.000)
100- year projects	**ECUADOR (Zone 2)**				
	Secondary Forest (100 years)	377	7,540,000	2,3	17,342,000
	Forest Plantation (5x20 years)	356	7,120,000	2.3	16,376,000
	ARGENTINA (NW-Patagonia)				
	Forest Plantation (3x32 years)	179	3,580,000	5.0 (2.5)	17,900,000 (8,950,000)

When estimating the economic potential, it has to be taken into account that the calculations for Argentina are based on the Dollar-Peso-Parity that was in force until the end of 2001. The devaluation of the Peso results in lower minimum prices of CO_2 sequestration when calculated in Dollars. This is taken into account in Table 20, and allows the situation to be compared before and after abandoning the currency board.[27]

Before devaluation, costs per ton of CO_2 in NW Patagonia reached about two times the value of the costs in the Ecuadorian zone 2. Total costs for 100-year projects are at about the same level in all the alternatives considered. The 30-year projects of managed secondary forest in NW Ecuador require the lowest compensation, while the minimum costs of forest plantations in both study areas are at about the same level. Of course, in the case of Patagonia this financial compensation leads to only half the amount of CO_2 sequestered.

---

[27] In brackets: costs calculated assuming an exchange rate of 2 Pesos/$ in the longer run, which reflects a 50% devaluation of the Peso.

After the assumed 50 % devaluation, minimum payments per tCO_2 are approximately the same for both countries. This means that equal financial compensation has to be paid to landowners to make them switch from pasture to forestry. In such a situation, potential CER demanders from Annex 1 countries will take additional factors like political stability, land tenure, monitoring costs, and forest fire risk into account.

5 General discussion and conclusions

The research objectives as described in section 2.1.2 were twofold: to assess the carbon sequestration potential of forests in the study areas in Ecuador and Argentina, and to assess the economic potential of carbon sequestration as a source of income for landowners. The intention of the project was to address these research objectives by means of four specific project results, as defined in section 2.1.3.

The first expected project result was the construction of statistical models for the estimation of total biomass of tree plantations and secondary forests in the research areas, based on the climate and soil characteristics and vegetation age. These models were necessary for the economic analysis, in which information was needed on carbon accumulation over time, in dependence of soil, climate and management characteristics. The point biomass estimations at each site were used to investigate the relations between tree biomass and soil organic matter. The biomass estimations for each site were, in the case of Ecuador, based on non-destructive forest inventories combined with data from the literature. The data from the 34 secondary forest sites allowed a statistically significant model of biomass as a function of age to be constructed. When stratifying the study area into two climate zones, a slightly higher maximum biomass was modelled for the more humid zone than for the drier zone, but no significant influence of soil characteristics on secondary forest growth was found. Much of the variation in biomass is probably related to management and species composition. The biomass model for plantations in Ecuador was not based on the site results, as only 6 sites in Ecuador had forest plantations. For this reason, the plantation biomass model used for the economic analysis was a growth model of laurel based on secondary data that describes growth in dependence of age, site index and planting density. In Argentina, destructive sampling methods allowed specie-specific biomass estimations using allometric regression models for pine and cypress to be made. With these site-specific estimations, a significant multiple regression model was constructed that describes pine biomass as a function of age and precipitation. For cypress only a clear relation with age was found. Although the pine model explained a high percentage of variation in biomass, for the economic analysis growth models for pine were preferred that are based on a larger dataset and that furthermore describe the biomass of pine in dependence of age and site index, including management operations such as pruning and thinning. For cypress such models were not available. For this reason, carbon sequestration in cypress forests was not included in the economic analysis.

The second expected result was the construction of statistical models that describe the carbon sequestration potential in soils of forests growing in former pastures as a function of water availability, forest productivity, landscape position, land use history and soil characteristics. As in the case of the biomass estimations, models were necessary to translate the site results to regionally valid relations between soil carbon dynamics and its determining variables for use in the economic analysis. For both Ecuador as well as Argentina, it was shown that soil organic carbon levels for each land use type are strongly related to soil characteristics such as mineralogy and texture. Between 45% and 97% of the variation in carbon content for each land use type in Ecuador could be explained on the basis of soil characteristics alone. The differences between forests and pastures, indicative for the soil carbon sequestration potential of forests, depend on soil characteristics as well, but are above all determined by vegetation age. In the case of Ecuador, the loss or increase of soil organic carbon after conversion of pasture to forests is strongly related to the age of the reference pasture. Compared to young pastures, forest growth on average leads to a loss of carbon, while compared to old pastures forest growth leads to an increase in soil carbon. This is probably the result of the higher turnover rate in pastures. As pasture age was the dominant variable, this information was used in the economic analysis, assuming that the carbon sequestration activities take place in old pastures (as required by the definitions in the Marrakesh agreement), thereby taking advantage of the carbon sequestration in the soil. The additional benefit of carbon storage in soils is that the carbon can be maintained in the system in subsequent forest rotations, provided that good management is applied. Vegetation age plays an important role in Argentina as well, but due to the temperate climate processes are much slower. The natural pastures are old. Of more significance is the age of the forest system. During the normal (short) rotation length of pine plantations, no increase in soil organic carbon can be expected on the basis of the results. Therefore no carbon sequestration in the soils of pine plantations was included in the economic analysis. The cypress forests did show an increase in soil organic carbon as compared to the pastures, probably because of their higher average age than pine plantations and maybe also because of the specific carbon cycling processes under cypress.

The models for carbon sequestration in biomass and soil were used in the analysis of the economic potential of carbon sequestration, which was the third expected result of the project. In the economic analysis, the C-sequestration potential was evaluated from the landowners' point of view, by determining the minimum compensation needed for them to switch from pasture to forestry alternatives. These calculated minimum prices for the sequestration of $CO_{2,}$ reflecting the average (opportunity) costs per ton of CO_2 in the different zones (1-4) in NW Ecuador, and for different pasture qualities in NW Patagonia.
The ecological and economic results allow us to evaluate the state of forestry projects in Ecuador and Argentina in the context of the Kyoto protocol, which was defined as the fourth expected outcome of the project. The feasibility of

a carbon sequestration project within the international CER market generated by the protocol depends very much on its cost[28]. After the withdrawal of the United States from the Kyoto Process, the future CER market can be characterised by low demand and low prices (Jotzo and Michaelowa, 2001). In the Bonn agreement, the maximum amount of CO_2 emissions that can be mitigated by Annex B countries through afforestation and reforestation activities (sink projects) under CDM to achieve the reductions for the first commitment period (2008-2012) is limited to 1% of the Annex B base year emissions, i.e. 183 million t CO_2 in each year of the commitment period (including the United States). However, demand for mitigation within CDM could be relatively small, because the United States does not intend to ratify the protocol, and carbon sequestered in domestic sinks will be credited to Annex B countries. Furthermore, emission quota surpluses (hot air) are potentially available at the emission rights market from Russia and other former Soviet Union States (FSU) in transition. The allowable emissions reduction of 1% of base year emissions within sink projects under CDM for OECD countries except the United States is 67 Mt CO_2/yr, which is relatively small in comparison with the potential supply (Jotzo and Michaelowa, 2001). In this situation even an emission right price of zero is possible, substantially reducing the incentive to invest in CDM projects (Löschel and Zhong Xiang, 2002). On the other hand, the FSU states have little interest in selling their emission rights without receiving anything in return. Assuming strategic behaviour, the FSU states will use their bargaining power and restrict the emission rights supply in order to maximise their revenues (Buchner et al., 2000). This scenario would lead to emission right prices higher than zero. On the supply side, CDM projects compete with these emission rights for the demand from

---

[28] The case of Argentina demonstrates that the exchange rate also plays an important role, and therefore the country's political stability.

Annex B countries. In such a competitive situation, the cost of carbon sequestration will play a determining role in incentives to invest in CDM projects.

The results of this study showed that costs are very variable within the Ecuadorian and Argentinean study areas, and also vary between Ecuador and Argentina. The costs are mainly determined by opportunity costs in the case of Ecuador, and site suitability for pine plantations in the case of Argentina. Within Ecuador, zone 2 offers relatively low prices for both plantation forests and secondary forests as well as the availability of areas for reforestation. For a 30-year project, costs are between $4-6 per tCO_2 in this zone, while costs are between $15 and $16 per tCO_2 in zones 3 and 4. Costs in Argentina for a 30-year project are low at the most suitable sites for pine plantations: $1.2 per tCO_2 as opposed to $9.9 per tCO_2 at medium sites and $14.3 tCO_2 at the least suitable sites. A 100-year project reduces costs by about 50%, resulting in a cost of $2.3 per tCO_2 in zone 2 in Ecuador, and $0.5 per tCO_2 at the best site index in Argentina. In terms of costs, zones 3 and 4 are not competitive compared to zone 2 within Ecuador, while sites with indices 11 and 15 are not competitive in comparison with sites with index 19 within Argentina. When comparing Argentina and Ecuador, only projects in Argentina on sites with index 19 have lower costs than in zone 2 in Ecuador. As explained in section 4.3.2, the recent devaluation of the peso in Argentina is changing this situation, as it has reduced costs considerably in that country. Whether the costs calculated for Ecuador and Argentina would be competitive on international markets remains to be seen, as the CER market is not well established yet. An example of a payment for CERs within the CDM energy sector is the Dutch Cerupt programme, which offers a price of up to $5 per tCO_2. This price would cover the costs in zone 2 in Ecuador and at SI 19 in Argentina for 30-year and 100-year projects, and in the case of Argentina also at SI 15 in a 100-year project.

It has to be taken into consideration that the calculated costs are the compensation payments needed for a forestry system to generate the same net benefits as the pasture system. At such a price level, the welfare of landowners does not increase when switching from pasture to forest. However, CDM projects (Art. 12 of the Kyoto Protocol) should comply with social and ecological criteria and support sustainable development (Smith et al., 2000). In order to increase welfare, CER prices would have to be higher than the calculated opportunity costs. As the sensitivity analysis indicated, it is also much more attractive for landowners to be paid during the initial years of the project. Although compared to 30-year projects the costs are about half those of 100-year projects, such a time horizon normally presents problems for landowners who are reluctant to make commitments for such a long time period, involving several generations. The 30-year projects and their calculated costs are therefore more realistic from the landowners' point of view.

In the case of Ecuador, many landowners have small or medium-sized properties. In case of a 30-year project, the cost of carbon sequestration is slightly lower in a secondary forest than in a plantation forest. Secondary forests offer an interesting alternative for these landowners, because this type of forest system does not require the high initial investments needed to establish a plantation forest. Secondary forests therefore allow the local population to participate in carbon projects (provided scale problems are solved, see below) - one of the criteria for CDM projects - while large-scale plantations risk displacing local populations and causing the loss of labour opportunities. If more wood were to be extracted from managed secondary forests, this might also help in reducing the pressure on the remaining primary forests (ECO/GTZ, 2000). Compared to plantations, secondary forests have an additional advantage in ecological terms because of their high biodiversity. In Ecuador a laurel plantation was evaluated, a species native to the area. However, large scale monoculture plantations present economic and ecological risks (diseases, low biodiversity, effects on soils). Therefore, the use of a variety of species should be considered. Various native species in the study region in Ecuador are promising in this respect (Alder, 1999). The same potential risks facing plantation forests apply to Patagonia. The indigenous cypress forests seem to represent an interesting alternative to the exotic pine plantations, although their carbon sequestration costs could not be evaluated due to the lack of forest management models.

An important requirement with respect to CDM sink projects is their additionality. The economic analysis showed that without payment for CERs, forestry projects are not competitive in comparison with pastures in Ecuador. Plantation forests in the study area are being managed by a small number of companies, most of which are also involved in wood extraction from native forests. Plantations are often in an experimental phase. Abandonment of pastures, leading to old secondary forests, is also not very common in the study area, as the "cleaning" of old secondary forests represents major costs. Complete abandonment of pastures is normally the result of particular circumstances, such as cash flow problems, or legal problems with land tenure. In Argentina as well, plantation forests are not very attractive under the current circumstances, as indicated by the payment needed for CERs to be profitable. The current low level of economic attractiveness of forestry projects in both countries makes it likely that carbon sequestration projects would be additional in most cases. The sensitivity analysis in Chapter 4 gives an impression of how additionality could be affected by changing conditions. The analysis for Ecuador indicates that within the considered ranges in timber prices, meat prices and milk prices as well as interest rates, forestry projects would only be competitive with a payment for CERs, indicating their likely additionality under possible future changes within the limits considered. For Argentina, the establishment of pine plantations might be stimulated even without payment for CERs at the most suitable sites if the timber price were to rise by 25% or the interest rate to fall from 7% to 5%. In all other situations, payment for CERs would still be necessary under the range of conditions considered.

Risks connected to carbon sequestration activities are related to several factors. In the case of Ecuador, land property rights are not always well defined. This undermines the legal basis of contracts for carbon projects, which can lead to non-compliance. A related risk is the frequent occurrence of land invasions. Legalisation of land tenure is therefore an important requirement for projects in Ecuador. In Argentina, the most important risk is the destruction of plantations by fire. In the economic analysis, therefore, the costs of fire prevention have been included. Fire prevention consists of the removal of cut branches, the maintenance of corridors, the availability of fire-fighting equipment, and permanent fire observation posts during the fire season. However, a residual fire risk always remains, and this risk should be included as a safety margin in cost estimations for large projects. As indicated above, the risk of non-compliance can also be reduced by implementing 30-year instead of 100-year projects. Furthermore, in the case of plantations, diversification also helps in reducing risks.

Land ownership in Patagonia is characterised by large properties, in most cases thousands of ha. In Ecuador, on the other hand, most properties are small (i.e. less than 10 ha) to medium (10-100 ha) in size. The Ecuadorian land structure is a limitation in terms of scale, as transaction costs represent a much higher proportion of total costs in projects with a small number of CERs. This limits the access of small and medium landowners to the carbon market. Institutional support will thus be necessary, directed at summing the supply of CERs of individual land owners to reach a volume interesting to investors. Such an accumulated supply could be achieved and commercialised by means of a trust fund.

The project results will help the GTZ projects in Ecuador and Argentina (PPF-RN and PRODESAR) in designing carbon sequestration projects. Such projects require a base-line definition that deals with issues such as the current land use situation, increase of carbon stocks obtained by the project, the economic feasibility, and social and ecological impacts. All this information can be derived from the outcomes presented in this report. Furthermore, the results will assist in the selection of the best locations for sink projects. In Ecuador, old pastures (> 20 yr) should be selected when aiming at the largest increases of soil organic matter during forest growth. Information on soil organic carbon changes is often not included or is treated as a black box in the preparation of sink projects, or during their monitoring and certification. The current study shows that important changes can take place that should be included in the estimations of project additionality and used to benefit the project design. The advantage of accumulated carbon in the forest soil is that, through good management, this carbon can be maintained during subsequent rotations. In the economic analysis of Ecuador it was shown that for this reason, soil organic carbon contributes quite significantly towards reducing the costs of a sequestration project (about 15%). The rather large variation in costs also permits the selection of sites within the study areas where the lowest opportunity costs are generated by CO_2 sequestration.

The methodology developed in this project can be directly applied to other areas. The data used in the approach are, however, to a certain extent specific to the study area, such as forest growth rates, soil characteristics and opportunity costs. This means that for new assessments some of the currently used data will have to be updated. Soil sampling in the project was very intensive, as the soil organic carbon dynamics were a major research theme in the project. For practical purposes, in follow-up work carbon analysis could be limited to composite samples only, which reduces the number of carbon analyses eightfold, representing an important reduction in costs. Necessary analyses can be executed in standard soil laboratories in Ecuador (e.g. at the national institute for agricultural research, INIAP) and Argentina (e.g. at INTA).

The project results can also be used by the PPF-RN and PRODESAR projects to define the role carbon sequestration projects can have in forest management, forest policies, sustainable development, local economies, soil conservation and the combating of desertification. Forestry projects for carbon sequestration have additional benefits, such as protecting biodiversity (especially in the case of secondary forests), protecting and improving soils (as demonstrated in Ecuador), and increasing welfare if sufficiently high prices are obtained for CERs. Additionally, in Argentina approximately 30% of the country's electricity is generated by hydroelectric power plants, the water basins of which being within the influence of the study area. Soil protection and regulation of the regional water balance through forestry is therefore of importance for the energy sector.

The project outcome is directly relevant to the Ministry of Environment of Ecuador and the Secretary of Agriculture and Fisheries of Argentina, and more specifically for their Climate Change Offices. Direct contacts exist between these governmental organisations and PPF-RN and INTA/PRODESAR, and the project results are directly communicated. The results indicate the possibilities and limitations of sink projects, and furthermore give estimates for the potential regional supply of CERs as well as indicate what prices have to be negotiated in order to obtain higher income for land owners. Although the COP 7 agreement in Marrakesh has further defined rules for sink projects, a final definition of the rules remains to be established in subsequent COPs. For this reason, Annex 1 countries are hesitant to invest already in sink projects, causing a low actual level of demand. Many land owners in Ecuador and Argentina consider it a serious limitation that no CDM projects in primary forest are considered in the Kyoto protocol. There is a need for financing conservation, especially in Ecuador, where the deforestation rate is the highest in Latin America (FAO, 2001). Reducing deforestation rates would contribute to a reduction in CO_2 emissions and would help protect biodiversity. At the moment, a payment for avoiding deforestation can only be obtained at the voluntary carbon markets, where organisations that want to voluntarily compensate for greenhouse gas emissions resulting from their operations can invest in afforestation, reforestation or conservation projects. The project results can also be used in the voluntary market, for example in the negotiation process between the demand and supply sides.

NGOs in Ecuador and Argentina can further use the project results when assessing the possibilities of sink projects. In Ecuador the results are being used in a joint activity of various NGOs, supported by GTZ, designed to develop an institutional setting for the implementation of payments for ecosystems services, including carbon sequestration. The objective is to create a trust fund that channels supply and demand, thus resolving problems of scale for small land owners and offering a more attractive portfolio for investors or donors. The trust fund aims at the Kyoto market as well as voluntary markets.

6 Recommendations

6.1 For the Development Cooperation projects

The development cooperation projects PPF-RN and PRODESAR should actively include the theme of payment for ecosystems in their working programs, specifically carbon sequestration projects. The results of our study have identified the economic and ecological conditions under which there is scope to improve landowners’ income through carbon sequestration in forest systems. The development cooperation projects should focus their activities on the areas with economic potential, while also taking into account ecological and social aspects. In Ecuador, forest can improve the soil quality of degraded tropical pasture areas and therefore these degraded soils are the most appropriate for reforestation. Managed secondary forests have advantages over plantations because of their higher biodiversity and low level of investment, which facilitates the participation of a variety of landowners. In Argentina, payment for CERs can make forestry projects that are otherwise not profitable economically interesting in a region where currently few alternatives exist and deforestation has caused large-scale erosion.

The development projects should aim at maximizing the participation of the local population and avoiding displacement due to large-scale external projects; this is especially a risk in Ecuador. Activities in buffer zones around remaining natural forest are especially promising in Ecuador, as these could reduce the current high degree of pressure on these forests. Technical assistance should be given to landowners willing to embark on reforestation. Support is necessary for forest management plans, exploitation techniques and marketing. In the case of Ecuador, a further priority is the legalisation of land ownership, as this is a prerequisite for the establishment of carbon contracts.

Carbon sequestration projects covering small areas are not viable because of high transaction costs. The development cooperation projects should therefore create the institutional setting that supports landowners at the supply-side in obtaining access to markets by accumulating sufficiently large volumes of CERs, and offering an attractive portfolio with low transaction costs. This could for example be achieved through the establishment of one or more trust funds. Such trust funds should be part of an institutional set-up that includes a certification and monitoring scheme, legal arrangements concerning land tenure and national forest laws, national registration of projects, and commercialisation. A proactive attitude is necessary to participate in a competitive market.

6.2 For local organisations

The project results help local organisations define their strategy towards carbon sequestration projects. Organisations that work at the local level in the areas of forestry, conservation and development should support landowners by giving them well-founded and balanced information about the possibilities, limitations and possible risks of carbon sequestration projects and the Clean Development Mechanism. At the moment, expectations in the field are sometimes unrealistically high, giving rise to speculation and abuse. The organisations can also help landowners with technical assistance and support them in their efforts to organise themselves and access markets.

At the national level, the Ministry of Environment of Ecuador, the Secretary of Agriculture, Fishery and Forestry of Argentina and the Climate Change Offices of both countries deal with carbon sequestration projects and the Clean Development Mechanism. The project results can be used in international negotiations, giving background information on “minimum price levels” . These governmental organisations also have to play a leading role in establishing guidelines for socially and ecologically appropriate projects, as well as to maintain a national register of projects and ensure projects respect national laws concerning forest management and property rights. In Ecuador, new forest and biodiversity laws are being developed in which systems of payments for ecosystem services are planned. Decisions taken on issues related to ecosystem services should be the result of consensus, uniting all the main representatives of civil society, and should protect vulnerable groups and ecosystems.

6.3 For GTZ Headquarters and BMZ

The themes of carbon sequestration and payment for ecosystem services in general offer a new challenge for development cooperation. Externalities of land use activities have in the past often not been valued economically. The benefits of forest systems for society at large, such as the mitigation of carbon emissions and soil and water protection, should result in economic benefits for the people that produce ecosystem services through appropriate management. Carbon sequestration projects can - under certain conditions – contribute to sustainable development by increasing the welfare of the rural population and by protecting natural resources, provided that social and ecological criteria are respected. The GTZ should therefore clearly define these criteria. Especially relevant in this respect are the Forestry Division and the Climate Protection Programme. The Forestry Division should develop guidelines for forest management aimed at carbon sequestration and other ecosystem services, and translate these guidelines into technical assistance. The Climate Protection Programme should explore all possibilities for sink projects within the Clean Development Mechanism and actively pursue the implementation of these projects in priority areas, according to the general criteria to be set by the GTZ and in relation to existing GTZ projects.

Investments in carbon sequestration projects within CDM are an interesting option for the German Government, German private companies and NGOs. They contribute to a better global climate, and at the same time address development cooperation objectives such as poverty alleviation and the sustainable use of natural resources. BMZ should play an active role in this new field of action.

7 Literature

Alder, D., Montenegro, F., 1999. A yield model for *Cordia alliodora* plantations in Ecuador. *International Forestry Review* **1,** 242-250.

Alder, D., 1999. Growth and yield of some plantation species of the lowland tropics in Ecuador. Articulo presentado en Conferencias sobre las Investigaciones y Experiencias de 20 Años de la Fundacion Forestal Juan Manuel Durini, Quito.

Amelung, W., Zech, W., Zhang, X., Follett, R.F., Tiessen, H., Knox, E., Flach, K.W., 1998. Carbon, nitrogen, and sulfur pools in particle-size fractions as influenced by climate. *Soil Science Society of America Journal* **62,** 172-181.

Andenmatten, E., Letourneau, F., 1997. Tablas de volumen de rodal para *Pseudostsuga menziesii* (Mirb.) Franco y *Pinus ponderosa* (Dougl.) Laws de aplicación en la región Andino-Patagónica de las Provincias de Chubut y Río Negro, Argentina. IUFRO Conference, Valdivia, Chile Septiembre 1997.

Balesdent, J., Besnard, E., Arrouays, D., Chenu, C., 1998. The dynamics of carbon in particle-size fractions of soil in a forest-cultivation sequence. *Plant and Soil* **201**, 49-57.

Banco Central del Ecuador, 2002. (http://www.bce.fin.ec).

Benítez, P., Olschewski, R., de Koning, F., López, M., 2001. Análisis costo-beneficio de usos del suelo y fijación de carbono en sistemas forestales de Ecuador Noroccidental. Report TWF-30s of the Tropical Ecology Support Programme (TÖB) of the Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ), Eschborn, Germany, 82 pp.

Böhringer, C., 2001. Climate Politics From Kyoto to Bonn: From Little to Nothing?!?, Zentrum für Europäische Wirtschaftsforschung (ZEW).

Brown, S., 1997. Estimating biomass and biomass change of tropical forests. A primer. FAO Forestry Paper, 134. Rome, FAO.

Buamscha, G., Gobbi, M., Mazzarino, M.J., Laos, F., 1998. Indicators of nitrogen conservation in *Austrocedrus chilensis* forests along a moisture gradient in Argentina. *Forest Ecology and Management* **112**, 253-261.

Buchner, B., Carraro, C., Cersosimo, I., 2002. On the Consequences of the U.S. Withdrawal from the Kyoto/Bonn Protocol. *Climate Policy* (in press).

Cairns, M.A., Brown, S., Helmer, E.H., Baumgardner, G.A., 1997. Root biomass allocation in the world´s upland forests. *Oecologia* **111,** 1-11.

Cañadas, 1983.El mapa bioclimático y ecológico del Ecuador. Banco Central del Ecuador, Quito, Ecuador. 210 pp.

Central Bank of Argentina, 2002. (http://www.bcra.gov.ar/pdfs/estadistica/ pre2001.xlw)

CEPAL, 2002. Anuario estadístico de América Latina y el Caribe 2001. Santiago de Chile, Comisión Económica para América Latina**:** http://www.cepal.org/publicaciones/Estadisticas/1/LCG2151PB/c2_III.pdf, pp. 424-431.

Chomitz, K.M., Brenes, E., Constantino, L., 1999. Financing environmental services: the Costa Rican experience and its implications. *The Science of the Total Environment* **240**, 157-169.

Cline, W. R., 1993. Give Greenhouse Abatement a Fair Chance. *Finance and Development* **30**, 3-5.

Clirsen/Patra, 1998. Zonificación Económica Ecológica de Esmeraldas. Ministerio de Ambiente, Quito. Ecuador.

Colmet Dâage, F., Lanciotti, M.L., Marcolin, A.A., 1995. Importancia Forestal de los Suelos Volcánicos de la Patagonia Norte y Central. Ed. INTA-SAGyP, 27pp.

Conservation International, 2001. The Chocó-Manabí conservation corridor, profile of an Ecuadorian ecosystem (In Spanish). Quito, Ecuador.

De Jong, B.H.J. et al., 2000. An Economic Analysis of the potential for carbon sequestration by forests: evidence from Southern Mexico. Ecological Economics **33**: 313-327. Del Valle, H.F., Elissalde, N.O., Gagliardini, D.A., Milovich, J., 1997. Status of desertification in the Patagonian region: assessment and mapping from satelite imagery. *Arid Soil Research and Rehabilitation* **12,** 95-122.

Desjardins, T., Andreux, F., Volkoff, B., Cerri, C.C., 1994. Organic carbon and 13C contents in soils and soil size-fractions, and their changes due to deforestation and pasture installation in eastern Amazonia. *Geoderma* **61,** 103-118.

Detwiller, R.P., 1986. Land use change and the global carbon cycle: the role of tropical soils. *Biogeochemistry* **2**, 67:93.

De Urquiza et al., 2002. Secuestro de carbono en suelos bajo uso ganadero y forestal en el noroeste de la Patagonia. Report #. of the Tropical Ecology Support Program (TÖB) of the Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ), Eschborn, Germany. (www.gtz.de/toeb)

Dezzotti, A., Sancholuz, L., 1991. Los bosque de *Austrocedrus chilensis* en Argentina: ubicación, estructura y crecimiento. *Bosque* **12 (2)**, 43-52.

Economist Intelligence Unit, 2000. Country Forecast Ecuador, London. (http://www.eiu.com)

ECO/GTZ, 2000. The significance of Secondary Forest Management for Development Policy Report FTWF-18e of the Tropical Ecology Support Programme (TÖB) of the Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ), Eschborn, Germany, 98 pp.

Etchevehere, P.H. 1972. Los Suelos de la Región Andino – Patagónica. En: Dimitri M.J. 1972: La Región de los Bosques Andino-Patagónicos, Sinopsis General. Col. Científica INTA. Buenos Aires, T.X: 83-95.

FAO, 2001. The global forest resources assessment 2000 summary report.

Fearnside, P.M., 1999. Environmental services as a strategy for sustainable development in rural Amazonia. *Ecological Economics* **20**, 53-70.

Fearnside, P.M., Barbosa, R.I., 1998. Soil carbon changes from conversion of forest to pasture in Brazilian Amazonia. *Forest Ecology and Management* **198**, 147-16.

Fearnside, P. M., Lashof, D.A., Moura Costa, P., 2000. Accounting for Time in Mitigating Global Warming through Land-Use Change and Forestry. *Mitigation and Adaptation Strategies for Global Change* **5**, 239-270.

Fehse, J., Aguirre, N., Paladines, Ch., Hofstede, R., Sevink, J., 1999. La productividad de cuatro bosques secundarios en la Sierra del Ecuador. Proyecto ECOPAR. Quito-Ecuador, 41 pp.

Feigl, B.J., Melillo, J., Cerri, C.C., 1995. Changes in the origin and quality of soil organic matter after pasture introduction in Rondonia (Brazil). *Plant and Soil* **175**, 21-29.

Feller, C., Beare, M.H., 1997. Physical control of soil organic matter dynamics in the tropics. *Geoderma* **79**, 69-116.

Flint Hughes, R., Boone Kauffman, J., Jaramillo, V.J., 2001. Ecosystem-scale impacts of deforestation and land use in a humid tropical region of Mexico. *Ecological Applications* **10(2)**, 515-527.

García-Oliva, F., Casar, I., Morales, P., Maass, J.M., 1994. Forest to pasture conversion influences on soil organic carbon dynamics in a tropical deciduous forest. *Oecologia* **99**, 392-396.

Gentry, A.H., 1986. Endemism in tropical versus temperate plant communities In Prnace, G. (Ed.) Biological diversification in the tropics. New York, Columbia University Press.

Gobbi, M.E:, Mazzarino, M.J., Roselli, L., Satti, P., Moyano, S., Schlichter, T., 2002 (submitted). Native vegetation vs exotic plantations in Northwestern Patagonia: effects of *Pinus ponderosa* on soil quality. Submitted to Ecological Applications.

GTZ, 2000. Portafolio Ecuador. Cooperacion Récnica Alema, Ecuador. Quito, 38 pp.

Guggenberger, G., Zech, W., 1999. Soil organic matter composition under primary forest, pasture, and secondary forest succession, Region Huetar Norte, Costa Rica. *Forest Ecology and Management* **124,** 93-104.

INEC, 1995. Encuesta de superficie y producción agropecuaria por muestreo de áreas. Instituto Ecuatoriano de Estadísticas y Censos, Quito.

INEFAN, 1996. Lista de especies comerciales del Ecuador con sus diametros minimos de corta. Instituto Ecuadtoriano Forestal y de Areas Naturales y Vida Silvestre (INEFAN), Anexo 2 N-2.6, Resolución N:047, Conocoto, Ecuador.

IPCC, 1996. Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories. Reference Manual (Volume 3), p. 5.17, Box 5, Intergovernmental Panel on Climate Change**:** http://www.ipcc-nggip.iges.or.jp/public/gl/invs6d.htm.

IPCC, 2000. Land Use, Land Use Change and Forestry - Special Report of the Intergovernmental Panel on Climate Change -, Chapter 2.3.6. Timing Issues**:** http://www.grida.no/climate/ipcc/land_use/index.htm.

IPCC, 2000. Land use, Land-use change, and Forestry. A special report of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University, USA. 377 pp.

Jotzo, F., Michaelowa, A., 2001. Estimating the CDM Market under the Bonn Agreement. Hamburg, Hamburg Institute of International Economics (HWWA)**:** HWWA Discussion Papaer 145, pp. 47.

Kotto-Same, J., Woomer, P.L., Appolinaire, M., Louis, Z., 1997. Carbon dynamics in slash-and-burn agriculture and land use alternatives of the humid forest zone in Cameroon. *Agriculture, Ecosystems and Environment* **65**, 245-256.

Koutika, L.S., Andreux, F., Hassink, J., Chone, T., Cerri, C.C., 1999. Characterization of organic matter in topsoils under rain forest and pasture in the eastern Brazilian Amazon basin. *Biology and Fertility of Soils* **29,** 309-313.

Koutika, L.S., Chone, T., Andreux, F., Cerri, C.C., 2000. Carbon decomposition of the topsoils and soil fractions under forest and pasture in the western Brazilian Amazon basin, Rondonia *Biology and Fertility of Soils* **30,** 284-287.

Laclau, P. 1997. Los Ecosistemas Forestales y el Hombre en el Sur de Chile y Argentina. Boletín Técnico Nº 34. Fundación Vida Silvestre Argentina. 147 pgs.

Laclau, P., Pozo, L.M., Huerta, G., Mazzuchelli, M., Andenmatten, E., Letourneau, F., 1999. Rentabilidad de la Forestación con coníferas en Patagonia.

Laclau, P., et al., 2002a. Secuestro de carbono en biomasa de plantaciones de pinos y cipresales nativos en el Noroeste de la Patagonia. Report #. of the Tropical Ecology Support Program (TÖB) of Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ), Eschborn, Germany. (www.gtz.de/toeb)

Laclau, P., Olschewski, R., Schlichter, T, de Koning, F., 2002b. Rentabilidad comparada del uso forestal y ganadero del suelo en el noroeste de la Patagonia. Report #. of the Tropical Ecology Support Program (TÖB) of the Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ), Eschborn, Germany. (www.gtz.de/toeb).

Laclau, P., 2002. Root biomass and carbon storage of Ponderosa pine in a northwest Patagonia plantation. Forest Ecology and Management xxx-xxx.

Lanciotti, M.L., Marcolin, A.A., López, C.R., González, A.C., 1995. El area forestal de la Patagonia Andina Central y Norte; productividad elevada y sostenida. INTA, SAGyP, Bariloche, Argentina. 37 pp.

León, R.J.C., Aguiar, M.R., 1985. El deterioro por uso pasturil en estepas herbáceas patagónicas. *Phytocoenologia* **13(2)**, 181-196.

Lind, R. C., 1995. Intergenerational equity, discounting, and the role of cost-benefit analysis in evaluating global climate policy. Energy Policy **23(4/5)**, 379-389.

Loguercio, G.A., Rajchenberg, M., Rodríguez, N. y Pantaenius, P., 1999. Curso-Taller de Actualización en Silvicultura de los Bosques de Ciprés de la Cordillera. CIEFAP – GTZ. El Bolsón, 13 y 14 de Mayo de 1999, 104 pp.

López, M., de Koning, F., Veldkamp E., 2002. Estimation of carbon in biomass of secondary forests and plantation forests in Northwestern Ecuador. Report TWF-31s of the Tropical Ecology Support Program (TÖB) of the Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ), Eschborn, Germany. (In Spanish). (www.gtz.de/toeb)

Löschel, A., Zhong Xiang, Z., 2002. The economic and environmental implications of the US repudiation of the Kyoto Protocol and the subsequent deals in Bonn and Marrakesh. Mannheim, Centre for European Economic Research (ZEW) Discussion Paper No. 02-28**:** 35 pp.

MAG/ORSTOM, 1980. Soil Maps. Ministry of Agriculture of Ecuador (MAG) and the Office de la Recherche Scientifique et Technique Outre Mer (ORSTOM). Quito, Ecuador.

Mizota, C., van Reeuwijk, L.P., 1989. Clay mineralogy and chemistry of soils formed in volcanic material in diverse climatic regions. Soil Monograph 2, International Soil Reference and Information Centre, Wageningen, The Netherlands, 185 pp.

Moraes, J.F.L. de, Volkoff, B., Cerri, C.C., Bernoux, M., 1996. Soil properties under Amazon forest and changes due to pasture installation in Rondonia, Brazil. *Geoderma* **70**, 63-81.

Moura Costa, P., 2000a. Carbon Accounting versus Project Financing. Oxford, Ecosecurities, unpublished manuscript**:** www.forest-trends.org/keytrends.

Moura Costa, P., 2000b. Carbon Accounting Methods, Ecosecurities, Ltd.**:** www.forest-trends.org/keytrends.

Moura Costa, P., 2000c. Project Duration and Accounting Methods. Oxford, Ecosecurities, unpublished manuscript**:** 8 pp.

Myers, 1988. Threatened biotas: hot-spots in tropical forests. *The Environmentalist* **8,** 187-208.

Myers, N., Mittermeier, R.A., Mittermeier, C.G., Da Fonseca, G.A.B. Kent, J., 2000. Biodiversity hotspots for conservation priorities. *Nature* **403**, 853 - 858.

Neill, C., Melillo, J.M., Steudler, P.A., Cerri, C.C., de Moraes, J.F.L., Piccolo, M.C., Brito, M., 1997. Soil carbon and nitrogen stocks following forest clearing for pasture in the southwestern Brazilian Amazon. *Ecological Applications* **7(4)**, 1216-1225.

Nordhaus, W. D., 1999. Discounting and Public Policies that Affect the Distant Future. In: Portney, P.R. and J.P. Weyant (Eds.): Discounting and Intergenerational Equity. Washington D.C., Resources for the Future.

Palm, C. A., et al., 2000. Carbon Sequestration and Trace Gas Emissions in Slash-and-burn and Alternative Land-uses in the Humid Tropics. Nairobi, ASB Climate Change Working Group.

Portney, P. R., Weyant, J.P. (Eds.), 1999. Discounting and Intergenerational Equity. Washington D.C., Resources for the Future.

Post, W.M., Kwon, K.C., 2000. Soil carbon sequestration and land-use change: process and potential. *Global Change Biology* **6,** 317-327.

Powers, J., 2001. Geographic variation in soil organic carbon dynamics following land-use change in Costa Rica. PhD thesis, Duke University, USA, 283 pp.

Powers, J.S., Schlesinger, W.H., 2002. Relationships among soil carbon distributions and biophysical factors at nested spatial scales in rain forests of northeastern Costa Rica. *Geoderma* **109,** 165-190.

Price, C., 1994. Time profiles and pricing of CO2 externalities. *Scandinavian Forest Economics* **35**, 320-336.

Richards, K. R., 1997. The time value of carbon in bottom-up studies. *Critical Reviews in Environmental Science and Technology* **27**: 279-S292.

Rhoades, C.C., Eckert, G.E., Coleman, D.C., 2000. Soil carbon differences among forest, agriculture, and secondary vegetation in lower montane Ecuador. *Ecological Applications* **10(2)**, 497-505.

Schelling, T. C., 1995. Intergenerational Discounting. *Energy Policy* **23(4/5)**, 395-401.

Schlichter, T., Laclau, P., 1998. Ecotono estepa-bosque y plantaciones forestales en la Patagonia norte. *Ecología Austral* **8**, 285-296

Schlichter, T., Gyenge, J., Fernández, M.E., Dalla Salda G., Laclau, P., 1999. Sistemas Silvopastoriles.

Sedjo, R. A., 1999. Potential for Carbon Forest Plantations in Marginal Timber Forests: The Case of Patagonia, Argentina. Washington, Resources for the Future**:** Discussion Paper 99-27, pp. 20.

Sedjo, R. A., Joe Wisniewski, Al Sample and John D. Kinsman, 1994. Managing Carbon via Forestry: Assessment of some Economic Studies. RFF-Discussion Paper.

Shoji, S., Nanzyo, M., Dahlgren R., 1993. Volcanic ash soils: genesis, properties and utilization. Developments in Soil Science. Elsevier, Amsterdam, The Netherlands.

Sierra, R., Stallings, J., 1998. The dynamics and social organization of tropical deforestation in Northwest Ecuador, 1983-1995. *Human ecology* **26**, 135-161.

Smith, J., Mulongoy, K., Persson, R., Sayer, J., 2000. Harnessing carbon markets for tropical forest conservation: towards a more realistic assessment. *Environmental Conservation* **27(3)**, 300-311

Somlo, R., Bran, D., 1994. Las regiones ecológicas de la Patagonia: superficies departamentales. Comunicación Técnica Nº 25. INTA, Estación Experimental Agropecuaria Bariloche, 16 pp.

Soriano, A., Movia, C.P., 1986. Erosión y desertización en Patagonia. *Interciencia* **11,** 77-83.

Stavins, R. N., 1999. The cost of carbon sequestration: A revealed preference approach. The American Economic Review **89(4)**, 994-1009.

Steininger, M.K., 2000. Secondary forest structure and biomass following short and extended land-use in central and southern Amazonia. *Journal of Tropical Ecology* **16**, 689-708.

Torn, M.S., Trumbore, S.E., Chadwick, O.A., Vitousek, P.M., Hendricks, D.M., 1997. Mineral control of soil organic carbon storage and turnover. *Nature* **389**, 170-173.

Townsend, A.R., Vitousek, P.M., Trumbore, S.E., 1995. Soil organic matter dynamics along gradients in temperature and land use on the island of Hawaii. *Ecology* 76: 721-733.

UNFCCC, 1998. Kyoto Protocol to the United Nations Framework Convention on Climate Change. FCCC/CP/1997/7/Add.1**:** http://unfccc.int/resource/docs/cop3/07a01.pdf.

UNFCCC, 2001. The Marrakesh Accords and the Marrakesh Declaration, http://unfccc.int/cop7/documents/accords_draft.pdf.

van Kooten, G. C., Krcmar-Nozic, E., Stennes, B., van Gorkom, R., 1999. Economics of fossil fuel substitution and wood products when trees are planted to sequester carbon on agricultural land in Western Canada. *Canadian Journal of Forest Research* **29**, 1669-1678.

Veldkamp, E., 1994. Organic carbon turnover in three tropical soils under pasture after deforestation. *Soil Science Society of America Journal* **58**, 175-180.

Veldkamp, E., 2001. Changes in soil carbon stocks following forest conversion to pasture in the tropics. In: Holland (Editor), Notes from underground: soil processes and global change. NATO ASI Series. Spinger-Verlag, Berlin.

World Bank, 2002. Country data. http://www.worldbank.org.

Appendix 1

The chart below lists the most frequently encountered tree species in secondary forests in Ecuador. The percentage indicates the amount of trees of a certain species as a percentage of the total amount of trees measured.

Common name	**Scientific name**	**Family**	**Percentage**
Laurel	*Cordia alliodra*	Boraginaceae	18.0
Guabo	*Inga Coruscana*	Fabacea	10.0
Chilca	*Vernonia baccharoides*	Compositae	6.3
Cordoncillo	*Piper aduncum L.*	Piperaceae	5.8
Arrayán	*Eugenia sp.*	Myrtaceae	3.2
Colca	*Miconia Sp.*	Melastomataceae	3.0
Canalon	*Zuarcia sp.*	Bignoniaceae	2.4
Guarumo	*Cecropia sp,*	Moraceae	2.2
Mambla	*Erytrina poeppigiana*	Fabaceae	2.2
Caucho	*Castilla elástica*	Moraceae	2.2
Espino	*Acacia sp.*	Acaceae	1.6
Helecho arboreo	*Cyathea Sp.*	Cyatheaceae	1.4
Tangare	*Carapa guianensis*	Meliaceae	1.4
Sapan	*Trema sp.*	Ulmaceae	1.4
Fernan Sanchez	*Triplaris guayaquilensis*	Poligonaceae	1.3
Nailli		Palmae	1.3
Cuasmo			1.2
Quitasol	*Cordia hebeclada*	Boraginaceae	1.2
Sapote	*Matisia Sp.*	Bombacaceae	1.2
Jigua	*Ocotea sp,*	Laureaceae	1.0
Guayacán	*Tabebuia spp.*	Bignoniaceae	1.0
		sub-total	70
Others			30

Appendix 2. Site characteristics, Ecuador

nr	name	altitude (masl)	clay (%)	sand (%)	silt (%)	altitude (masl)	type*	clay (%)	sand (%)	silt (%)	precip. ** (mm/yr)	soil type *** (sub-order)	geomorphology
		pasture				forest							
1	Arenales	21	26	13	60	17	sf	32	6	62	2938	tropepts	sedimentary
2	Sto. Domingo	48	16	18	66	48	sf	21	26	52	2869	tropepts	sedimentary
3	San Lorenzo	29	28	13	60	18	sf	21	13	66	2625	aquents	sedimentary
4	Mindo Lindo	1649	0	76	24	1650	sf	0	80	19	3459	andepts	volcanic
5	Mindo	1410	2	77	21	1390	sf	1	75	24	3485	andepts	volcanic
6	Mayronga	96	25	22	53	118	pf	29	11	60	2000	tropepts	sedimentary
7	Pedro Vicente	600	0	51	49	600	pf	2	44	55	4860	andepts	volcanic
8	Nuevo Mundo	850	0	62	38	850	sf	1	68	31	4038	andepts	volcanic
9	Maquipucuna	1251	6	57	37	1249	sf	5	53	42	2310	andepts	volcanic
10	Río Castillo	198	1	45	54	194	pf	4	53	43	2798	andepts	volcanic
11	Golondrinas	204	3	50	48	204	pf	2	48	50	3030	andepts	volcanic
12	San Mateo	20	23	26	51		sf	35	11	53	1170	orthents	sedimentary
13	Río Esmeraldas	15	38	2	60	25	sf	31	14	55	978	tropepts	sedimentary
14	Malimpia	140	23	25	52	170	sf	30	22	48	2383	fluvents	sedimentary
15	Río Blanco	166	0	88	11	140	sf	0	89	11	3150	fluvents	volcanic
16	Chontaduro	56	46	6	48	56	sf	45	5	50	1823	tropepts	sedimentary
17	Las Minas	147	60	3	38	147	sf	55	4	41	1327	tropepts	sedimentary
18	Guadalito	132	43	14	43	88	sf	35	17	48	3157	tropepts	sedimentary
19	La Chiquita	67	17	20	64	45	sf	35	16	49	2808	tropepts	sedimentary
20	La Unión	170	0	68	32	170	sf	3	61	36	3080	andepts	volcanic

Appendix 2 (cont.)

nr	name	altitude (masl)	clay (%)	sand (%)	silt (%)	altitude (masl)	type*	clay (%)	sand (%)	silt (%)	precip. ** (mm/yr)	soil type *** (sub-order)	geomorphology
		pasture				forest							
21	Puerto Quito	281	0	50	50	247	sf	6	46	48	3402	andepts	volcanic
22	Salima	54	22	33	44	66	sf	32	17	51	1401	orthents	sedimentary
23	Tazones	46	29	23	48	38	sf	28	26	46	1762	tropepts	sedimentary
24	Muisne	17	37	8	55	51	sf	21	34	45	2496	fluvents	sedimentary
25	Sua	46	33	22	46	46	sf	43	11	46	1734	tropepts	sedimentary
26	Guacharaco	136	28	31	41	140	sf	20	29	51	2421	udalfs	sedimentary
27	Chaupara	137	61	6	34	137	sf	46	6	48	1931	fluvents	sedimentary
28	San Andrés	116	30	16	54	116	sf	32	28	40	2370	udolls	sedimentary
29	Cube	221	28	16	56	221	sf	32	12	56	2021	udolls	sedimentary
30	Quinge	76	38	9	52	50	sf	38	9	53	2561	tropepts	sedimentary
31	Mache	88	28	18	54	130	sf	31	15	54	2023	tropepts	sedimentary
32	Chaflu	147	36	12	52	127	sf	38	8	55	1705	udolls	sedimentary
33	Las Peñas	53	36	27	36	58	sf	36	20	44	2509	tropepts	sedimentary
34	Patere	27	28	17	56	27	sf	21	36	43	2683	tropepts	sedimentary
35	Lagarto	32	40	21	39	32	sf	38	17	45	2356	tropepts	sedimentary
36	La Concordia	163	18	26	56	163	pf	22	26	51	3114	andepts	volcanic
37	Pitzara	294	5	41	54	294	pf	3	45	52	3467	andepts	volcanic
38	San Francisco	68	20	42	39	67	sf	22	22	57	3730	fluvents	sedimentary
39	Molinito	32	8	76	17	21	sf	9	88	4	2474	psaments	sedimentary
40	Alto Tambo	675	3	23	73	693	sf	4	36	61	5738	andepts	volcanic

*: sf = secondary forest, pf = plantation forest

**: precipitation interpolated from data from 20 weather stations

***: derived from Clirsen/Patra (1998)

soil texture data refer to the 0-25 cm soil layer

Appendix 3. Carbon contents, Ecuador

	pasture							forest							differences		
	% C (0-25)		% C (25-50)		C/N (0-25)	C/N (25-50)	C Mg/ha (0-50)	% C (0-25)		% C (25-50)		C/N (0-25)	C/N (25-50)	C Mg/ha (0-50)	C% 0-25	C% 0-25	C Mg/ha (0-50)
Site	**mean**	**cv**	**mean**	**cv**				**mean**	**cv**	**mean**	**cv**						
1	2.94	21	2.54	32	9.05	9.53	111.4	3.12	13	2.07	23	8.92	8.91	105.7	0.18	-0.47	-5.7
2	3.57	9	1.72	12	10.98	10.06	130.6	2.19	32	1.02	21	10.63	9.53	79.3	-1.38**	-0.7**	-51.3
3	2.16	13	1.05	18	10.77	10.55	92.2	2	15	0.77	33	9.78	8.37	79.8	-0.15	-0.28*	-12.4
4	2.42	27	2.19	10	12.54	11.61	114.2	3.86	30	2.39	17	13.17	12.1	155.8	1.44**	0.2	41.6
5	3.69	27	2.56	24	11.46	12.13	125.9	5.21	37	3.18	37	13.06	13.3	169	1.52*	0.62	43.1
6	2.65	31	1.15	14	9.27	8.1	107.4	2.14	29	0.85	23	9.76	7.87	84.5	-0.51	-0.3**	-22.9
7	4.99	35	2.43	27	12.26	12.01	131.4	4.65	10	2.54	12	12.13	11.22	127.1	-0.35	0.11	-4.3
8	3.09	17	1.82	11		10.54	121.4	3.65	26	1.86	24	12.28	10.61	136.8	0.56	0.04	15.3
9	3.08	43	1.59	58	11.25	10.85	136.3	3.96	22	1.46	57	11.79	11.04	158.6	0.89	-0.13	22.2
10	6.91	15	3.44	16	11.31	10.56	195.2	5.77	22	3.29	17	11.28	10.44	170.9	-1.14	-0.15	-24.3
11	5.18	11	3.33	17	10.14	10	134.3	6.02	16	3.23	16	11.71	11.17	145.7	0.84*	-0.1	11.5
12	2.04	7	0.95	14	8.89	7.63	91.5	2.31	5	1.16	5	8.93	8.52	106.4	0.27	0.21	14.9
13	1.92	9	0.89	4	8.68	8.14	82.7	2.02	12	0.85	24	9.08	7.88	84.4	0.09	-0.03	1.7
14	2.17	35	0.89	31	9.42	7.94	78	2.1	19	1.00	16	9.7	8.94	79	-0.06	0.11	1.1
15	2.34	5	0.59	18	10.86	13.21	87.2	2.48	17	0.75	30	11.07	12.44	97.1	0.14	0.17	9.9
16	2.15	21	0.99	25	7.96	6.93	88.1	2.31	14	0.98	13	8.31	7.53	92.3	0.17	-0.01	4.2
17	2.62	12	1.23	16	10.14	9.21	96.2	3.17	23	1.37	31	9.86	8.86	113.4	0.55	0.14	17.3
18	2.55	15	1.42	18	11.01	10.29	98.6	2.33	29	0.91	27	11.37	10.46	80.4	-0.22	-0.51**	-18.1
19	1.62	15	0.62	10	10.13	9.12	61.4	2.08	26	1.09	27	10.4	10.09	86.9	0.46*	0.47**	25.4
20	2.86	19	0.68	38	9.64	10.05	91.7	2.98	19	0.41	71	9.43	11.85	86.1	0.11	-0.27	-5.6

Appendix 3 (cont.).

	pasture							**forest**							**differences**		
	% C (0-25)		**% C (25-50)**		**C/N (0-25)**	**C/N (25-50)**	**C Mg/ha (0-50)**	**% C (0-25)**		**% C (25-50)**		**C/N (0-25)**	**C/N (25-50)**	**C Mg/ha (0-50)**	**C% 0-25**	**C% 25-50**	**C Mg/ha (0-50)**
Site	**mean**	**cv**	**mean**	**cv**				**mean**	**cv**	**mean**	**cv**						
21	4.9	15	2.86	19	10.53	9.97	130.8	4.14	8	2.18	17	10.15	10.24	106.4	-0.76	-0.68	-24.4
22	1.2	39	0.74	46	8.65	7.42	59.2	1.78	34	0.78	23	9.16	8.44	78.5	0.58	0.04	19.2
23	1.34	34	0.68	28	9.13	7.46	60.8	1.55	14	0.66	17	8.84	7.62	66.2	0.2	-0.02	5.4
24	1.46	11	0.62	18	9.6	7.91	63.8	1.8	27	0.71	36	9.76	7.83	77.2	0.34	0.09	13.4
25	2.62	8	1.08	20	10.43	8.95	86.7	4.18	50	0.81	21	10.46	7.92	118.2	1.57	-0.27*	31.5
26	1.75	48	1.33	45	8.83	9.17	91.4	2.55	20	0.86	22	9.48	8.24	101.5	0.8*	-0.47	10
27	2.82	11	1.61	35	9.58	9.05	83.3	3.59	47	1.46	30	10.34	8.76	94.6	0.76	-0.15	11.4
28	2.56	18	1.13	17	9.67	8.18	79.5	1.97	34	1.49	42	8.8	8.83	75.9	-0.59	0.36	-3.6
29	1.93	31	0.69	52	8.95	7.5	64.7	2.6	41	2.09	35	9.34	9.46	115.5	0.67	1.4**	50.9
30	3.11	29	1.16	39	10.42	9.59	110.1	2.29	34	1.25	25	9.71	8.48	91.4	-0.82	0.1	-18.7
31	2.1	44	0.71	42	8.16	7.25	72.6	2.06	30	0.99	35	8.95	8.06	79.8	-0.04	0.28	7.2
32	2.16	42	1.43	58	9.69	8.04	91.1	3.22	25	1.55	26	8.85	8.9	120.7	1.06*	0.12	29.5
33	1.85	17	1.06	24	9.89	9.55	85	2.54	17	1.1	28	10.16	9.98	106.4	0.69**	0.04	21.4
34	2.61	19	1.35	32	9.59	8.71	123.6	2.1	25	0.84	22	9.57	5.62	91.2	-0.51	-0.51**	-32.4
35	2.75	11	1.73	22	9.79	9.58	101.1	3.78	31	1.64	26	10	10.7	120.6	1.03*	-0.08	19.5
36	2.2	27	1.47	33	9.21	9.19	94.4	2.07	33	2.56	38	8.95	9.41	119.7	-0.13	1.09*	25.4
37	5.69	48	2.94	48	11.29	10.71	133.9	6.5	18	3.46	34	11.05	10.89	154.4	0.81	0.51	20.5
38	2.66	7	0.98	23	10.04	8.67	81.5	3.29	24	1.46	23	9.88	8.96	106.5	0.63*	0.48**	25
39	1.62	18	0.25	19	8.91		61.2	1.88	47	0.33	25	10.93		72.5	0.27	0.07	11.2
40	12.12	17	6.52	16	15.17	15.51	185.7	12.17	21	5.98	38	15.98	16.23	180.4	0.05	-0.53	-5.3

Appendix 4. Site characteristics, Argentina

nr	name	altit. (masl)	clay (%)	sand (%)	silt (%)	altit. (masl)	type*	clay (%)	sand (%)	silt (%)	altit. (masl)	type*	clay (%)	sand (%)	silt (%)	precip. ** (mm/yr)
		pasture				forest 1					forest 2					
1	Ea. Chacabuco	887	14	54	32	864	C	3	74	23	732	P	8	71	20	800
2	Lemu Cuyén	876	10	63	27	904	C	3	70	27	904	P	4	69	28	1200
3	Quechuquina	759	6	54	40	759	P	8	52	40						2450
4	Sta. Bárbara	921	6	64	30	975	C	5	62	33	921	P	5	68	26	1225
5	Puente Blanco	901	6	56	38	990	C	5	56	39	1079	P	5	55	40	1450
6	Ea. Chapelco	854	10	46	45	780	P1	5	54	41	780	P2	5	58	37	1000
7	Campo Forestal	416	13	36	51	390	C	12	32	56	363	P	34	26	40	975
8	Corfone - Junín	920	10	67	23	858	P1	3	74	24	840	P2	4	76	20	850
9	Lolog	1044	7	59	34	1021	C	5	66	29	1044	P	4	53	43	1700
10	Ea. Chacabuco	818	9	77	15	818	P1	7	79	15	836	P2	6	80	14	775
11	Santa Lucía	983	0	60	39	1008	C	1	63	36	983	P	4	58	38	1225
12	Collun Co	980	0	71	28	1060	C	5	69	26	979	P	2	72	26	1300
13	Cerro de los Pinos	770	17	55	28	1011	C	1	92	7	760	P	10	69	21	700
14	San Ramón	1021	5	63	32	1021	P1	5	57	38	1021	P2	8	53	39	675
15	El Arroyo	1000	7	68	26	1025	C	14	53	32	1029	P	6	77	17	1050
16	Mallin Ahogado	667	14	34	52	728	C	10	50	39	688	P	12	45	43	1500
17	Loma del Medio	305	13	32	55	305	C	6	48	47	322	P	10	34	56	1100
18	Cuesta del ternero	791	11	49	40	807	C	8	50	42	815	P	3	80	17	875
19	Ea. Mallin Cume	765	8	63	29	871	C	8	48	44	777	P	7	66	27	650
20	El Coihue	600	14	38	47	624	C	8	57	36	578	P	15	34	51	900

Appendix 4 (cont.).

nr	name	altit. (masl)	clay (%)	sand (%)	silt (%)	altit. (masl)	type*	clay (%)	sand (%)	silt (%)	altit. (masl)	type*	clay (%)	sand (%)	silt (%)	precip. ** (mm/yr)
		pasture				**forest 1**					**forest 2**					
21	El Maiten-Santos	728	27	49	24	728	C	9	49	42	802	P	18	43	39	650
22	Co. Otto	1295	4	75	21	1003	C	4	67	29	1295	P	7	63	30	1250
23	Filo Hua Hum (LC)	927	5	67	28	1072	C	4	59	38	992	P	4	73	23	1300
24	San Jorge	933	5	70	25	915	C	6	64	30	844	P	3	68	30	1075
25	Chacabuco-Caleufu	1036	8	59	33	1072	C1	6	63	31	1045	C2	10	65	25	1050
26	Paso Córdoba	936	6	75	19	887	C1	2	81	17	887	C2	3	80	17	1050
27	Rio Traful	783	4	75	21	966	C	3	70	26	788	P	4	72	25	1100
28	Fortín Chacabuco	929	3	81	16	983	C	6	81	13	929	P	2	78	20	1000
29	Challhuaco	949	12	54	34	949	C	12	58	30	950	P	6	67	28	1300
30	El Maitén-Bennetton	737	8	52	39	737	P1	8	55	37	737	P2	12	56	32	550
31	Brazo Huemul	798	6	65	29	810	C	5	56	39	800	P	1	76	23	1600
32	Pájaro Azul	790	6	69	26	850	C	6	58	36	790	P	2	67	31	1400
33	Arroyo del Medio	1022	11	58	31	1027	P1	10	62	28	1095	P2	10	62	28	1025
34	Cnia Suiza	825	10	63	27	825	P	4	76	20						1650
35	Isla Victoria	780	8	61	31	871	C	4	65	31	869	P	6	67	27	1700
37	Arroyo Verde	868	2	79	18	835	C	3	81	16	832	P	3	79	18	1225
38	Confluencia	734	9	67	25	759	C	2	80	18	739	P	6	70	24	950
39	Epuyén-Sanchez	448	4	40	56	443	C	6	68	26	448	P	9	65	26	1250
40	Pto Patriada-Epuyén	422	16	58	26	385	P	10	57	33						1700

*: P = pine forest, C = cypress forest

**: precipitation from maps

soil texture data refer to the 0-25 cm soil layer

Appendix 5. Carbon contents, Argentina

	pasture							forest								differences		
	% C (0-25)		% C (25-50)		C/N (0-25)	C/N (25-50)	C Mg/ha (0-50)	type	% C (0-25)		% C (25-50)		C/N (0-25)	C/N (25-50)	C Mg/ha (0-50)	C% 0-25	C% 25-50	C Mg/ha (0-50)
Site	**mean**	**cv**	**mean**	**cv**					**mean**	**cv**	**mean**	**cv**						
1	1.76	18	1.44	17	11.61	11.40	66.0	C	3.87	30	1.48	26	14.70		109.6	2.10***	0.05	43.6
								P	0.99	25	0.77	12	12.60	12.63	36.3	-0.78	-0.66	-29.7
2	1.60	16	1.19	14	12.48	12.05	54.4	C	2.16	56	1.12	36	13.59	11.12	64.7	0.56	-0.07	10.3
								P	1.75	34	1.29	16	13.52	11.04	59.1	0.15	0.10	4.8
3	5.29	14	2.87	11	13.34	13.02	141.0	P	3.78	23	2.78	19	15.13	13.85	114.2	-1.51**	-0.08	-26.9
4	3.00	34	1.84	22	11.64	11.44	102.1	C	3.06	27	2.01	24	12.97	12.75	107.0	0.06	0.17	4.9
								P	1.51	22	1.24	21	13.20	12.12	57.9	-1.49**	-0.60**	-44.2
5	3.52	26	2.31	12	12.24	11.80	98.9	C	5.10	28	2.60	40	17.66	14.08	130.8	1.59**	0.29	31.9
								P	4.17	10	3.07	13	15.27	13.14	122.9	0.65*	0.76***	24.0
6	6.70	14	3.08	13	11.63	11.12	235.6	P1	3.40	17	2.83	17	12.99	11.93	147.3	-3.30***	-0.25	-88.3
								P2	3.30	31	2.94	17	11.85	11.64	147.4	-3.40***	-0.14	-88.2
7	4.10	18	1.55	47	10.43	10.64	88.7	C	6.90	11	2.86	21	13.31	10.44	154.0	2.80***	1.31***	65.2
								P	5.31	19	2.52	39	13.93	12.10	124.4	1.22**	0.97**	35.6
8	1.42	16	1.03	23	11.80	11.54	65.4	P1	0.98	26	0.85	16	13.52	11.69	48.7	-0.44**	-0.18*	-16.7
								P2	0.99	47	0.65	31	13.07	11.79	43.9	-0.43**	-0.37**	-21.4
9	4.73	20	3.64	15	12.68	11.59	165.6	C	3.62	17	2.27	19	13.31	12.62	117.4	-1.11**	-1.37***	-48.2
								P	4.75	14	3.59	11	13.17	12.51	165.2	0.02	-0.04	-0.4
10	0.81	25	0.61	17	11.68	10.59	37.5	P1	0.67	15	0.54	11	12.11	11.16	31.7	-0.15*	-0.07	-5.8
								P2	0.59	24	0.46	19	11.09	10.14	27.6	-0.22**	-0.15**	-9.9
11	2.96	26	2.65	29	12.34	13.91	106.2	C	3.28	31	2.59	40	13.94	12.79	110.5	0.32	-0.06	4.3
								P	3.19	13	2.39	12	13.76	12.98	104.8	0.24	-0.26	-1.4
12	1.66	16	2.06	22	12.44	12.13	78.4	C	3.70	61	2.29	14	14.29	13.42	128.6	2.04**	0.22	50.2
								P	1.59	12	2.00	8	12.58	11.91	75.7	-0.07	-0.06	-2.7
13	1.06	10	0.94	30	10.61	10.34	45.8	C	1.35	50	0.71	22	13.54	10.70	46.9	0.29	-0.23*	1.0
								P	1.04	24	0.73	30	12.12	11.41	40.6	-0.02	-0.20	-5.2

Appendix 5 (cont.).

	pasture							forest								Differences		
	% C (0-25)		% C (25-50)		C/N (0-25)	C/N (25-50)	C Mg/ha (0-50)	type	% C (0-25)		% C (25-50)		C/N (0-25)	C/N (25-50)	C Mg/ha (0-50)	C% 0-25	C% 25-50	C Mg/ha (0-50)
Site	mean	cv	Mean	cv					mean	cv	mean	cv						
14	1.17	16	0.98	11	12.01	11.26	48.4	P1	1.59	15	1.19	10	13.27	11.86	62.9	0.43***	0.22**	14.4
								P2	1.87	24	1.29	17	14.19	12.35	71.5	0.71***	0.32**	23.0
15	1.66	14	1.32	6	12.37	11.96	71.1	C	3.88	21	2.28	11	14.00	12.62	146.2	2.21***	0.96***	75.0
								P	1.62	22	1.41	13	13.62	12.33	72.4	-0.04	0.09	1.3
16	7.12	10	5.41	5	10.59	10.69	239.8	C	6.17	25	3.75	30	14.61	13.41	189.7	-0.95	-1.67**	-50.1
								P	6.43	20	4.95	24	12.59	12.69	217.7	-0.70	-0.46	-22.1
17	6.64	28	3.73	36	13.19	11.88	195.7	C	4.92	22	2.39	21	16.68	13.32	137.7	-1.73**	-1.34**	-58.0
								P	5.03	14	2.99	17	12.18	11.65	151.4	-1.61**	-0.74	-44.3
18	4.13	15	3.02	14	13.30	12.14	131.6	C	5.54	16	3.55	22	12.91	11.77	166.5	1.41**	0.53	34.9
								P	1.68	12	1.63	12	11.09	10.74	61.4	-2.46***	-1.40***	-70.3
19	2.00	13	1.61	7	12.18	11.26	58.5	C	6.32	19	3.70	30	13.51	11.75	163.5	4.32***	2.09***	104.9
								P	2.08	14	2.00	21			65.8	0.07	0.39**	7.2
20	9.93	23	7.56	22	11.55	11.00	289.5	C	4.68	15	2.20	56	16.54	14.62	113.7	-5.25***	-5.36***	-175.8
								P	8.06	13	4.90	17	12.43	11.79	214.3	-1.87*	-2.66***	-75.2
21	3.26	48	2.73	53	12.94	12.84	106.8	C	5.23	20	2.17	8	15.91	12.63	130.5	1.98**	-0.55	23.7
								P	2.38	26	1.35	46	13.15	12.41	66.2	-0.87	-1.37**	-40.6
22	2.30	26	2.22	14	12.63	12.12	92.6	C	3.73	30	2.25	22	14.47	12.86	124.0	1.43**	0.03	31.4
								P	2.69	25	1.98	9	12.66	12.36	96.2	0.38	-0.24*	3.6
23	3.46	8	1.74	15	12.96	12.71	97.5	C	2.96	34	2.38	11	15.25	12.74	100.9	-0.50	0.65***	3.4
								P	3.16	18	2.41	16	13.73	11.97	105.2	-0.29	0.67***	7.7
24	2.27	21	1.43	15	13.04	11.70	71.9	C	3.26	30	2.42	28	13.73	12.78	110.1	0.99**	1.00**	38.2
								P	2.23	22	1.79	29	13.51	12.69	77.7	-0.04	0.36*	5.9
25	3.73	16	2.60	18	13.29	12.56	122.7	C1	3.18	23	2.30	37	13.31	12.34	106.2	-0.55	-0.30	-16.5
								C2	2.76	13	2.06	11	13.16	8.98	93.5	-0.96**	-0.54**	-29.2
26	1.19	28	1.02	20	11.92	11.93	49.7	C1	1.36	13	0.94	13	12.42	11.78	52.4	0.18	-0.08	2.6
								C2	1.35	20	1.00	19	12.38	11.31	53.3	0.17	-0.02	3.6

Appendix 5 (cont.).

	pasture							forest								differences		
	% C (0-25)		% C (25-50)		C/N (0-25)	C/N (25-50)	C Mg/ha (0-50)	type	% C (0-25)		% C (25-50)		C/N (0-25)	C/N (25-50)	C Mg/ha (0-50)	C% 0-25	C% 25-50	C Mg/ha (0-50)
Site	mean	cv	mean	cv					mean	cv	mean	cv						
27	0.91	14	0.62	15	12.03	10.91	37.4	C	1.37	48	1.10	37	14.31	12.97	60.4	0.47*	0.48**	23.0
								P	0.78	26	0.55	35	12.89	13.05	32.6	-0.13	-0.07	-4.8
28	1.10	14	1.02	8	11.84	11.42	48.9	C	2.37	39	1.46	30	14.62	12.04	86.6	1.27**	0.44	37.7
								P	1.29	12	0.98	8	12.60	11.09	51.7	0.19**	-0.05	2.8
29	2.79	25	1.86	16	13.06	12.82	104.7	C	4.87	67	3.12	74	13.66	13.44	179.8	2.08	1.26	75.1
								P	3.23	24	2.20	23	14.00	12.73	122.1	0.44	0.33	17.4
30	1.25	13	0.74	12	11.25	9.78	53.1	P1	0.95	16	0.55	14	12.88	10.60	40.2	-0.30**	-0.19***	-12.9
								P2	1.15	21	1.00	25	11.23	10.75	58.0	-0.09	0.26**	4.9
31	3.64	24	2.02	26	12.72	12.23	110.0	C	5.98	24	4.10	27	13.69	12.41	197.0	2.33***	2.08***	86.9
								P	1.66	28	1.52	29	14.29	13.34	62.7	-1.98***	-0.50*	-47.4
32	1.84	11	1.54	13	11.05	10.56	57.5	C	5.60	20	3.16	17	14.23	12.53	144.1	3.76***	1.62***	86.6
								P	2.09	15	1.76	9	12.23	11.28	65.4	0.24*	0.22**	7.9
33	1.28	11	1.02	15	11.64	11.34	55.1	P1	1.26	15	1.03	17	12.66	11.15	54.8	-0.02	0.02	-0.3
								P2	1.46	19	1.22	15	11.71	11.16	64.0	0.18	0.21**	8.9
34	6.48	42	5.50	36	14.40	14.36	250.6	P	1.34	39	1.09	27	13.96	12.86	50.8	-5.14***	-4.41***	-199.8
35	3.66	28	2.65	34	11.37	10.91	112.8	C	5.26	25	1.91	21	17.10	14.06	123.5	1.60**	-0.73*	10.7
								P	2.27	29	1.56	13	17.84	14.76	68.5	-1.38**	-1.08**	-44.4
37	1.50	17	1.06	40	11.37	11.73	54.9	C	2.37	36	0.96	20	13.42	11.61	70.7	0.87**	-0.11	15.8
								P	1.47	9	1.53	9	11.57	10.95	64.7	-0.03	0.47**	9.8
38	0.70	10	1.03	40	11.39	10.40	42.0	C	1.31	14	0.83	23	11.71	11.24	54.8	0.61***	-0.20	12.8
								P	0.67	13	0.57	16	10.02	10.77	31.3	-0.03	-0.46**	-10.7
39	8.14	15	5.39	13	10.26	9.79	286.7	C	5.51	35	3.48	36	13.80	12.79	190.5	-2.64**	-1.90**	-96.2
								P	3.68	14	3.26	12	12.58	11.79	146.8	-4.46***	-2.13***	-139.8
40	7.64	15	3.08	49	13.44	12.08	160.0	P	6.10	11	2.98	34	15.53	14.23	136.4	-1.54**	-0.09	-23.7

Deutsche Gesellschaft für
Technische Zusammenarbeit (GTZ) GmbH

Begleitprogramm Tropenökologie (TÖB)
Förderung der Tropenwaldforschung
Tropical Ecology Support Program
Postfach 5180
D-65726 Eschborn
Federal Republic of Germany

Fax: +49-(0)6196-79-6190
E-Mail: TOEB@gtz.de
Website: http://www.gtz.de/toeb

Bundesministerium
für wirtschaftliche
Zusammenarbeit
und Entwicklung

Im Auftrag des Bundesministeriums für
wirtschaftliche Zusammenarbeit und Entwicklung (BMZ)