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Abstract

This paper reports on the global potential for carbon sequestration in forest plantations, and the reduction of carbon emissions from deforestation, in response to six carbon price scenarios from 2000 to 2100. These carbon price scenarios cover a range typically seen in global integrated assessment models. The world forest sector was disaggregated into ten regions, four largely temperate, developed regions: the European Union, Oceania, Russia, and the United States; and six developing, mostly tropical, regions: Africa, Central America, China, India, Rest of Asia, and South America. Three mitigation options -- long- and short-rotation forestry, and the reduction of deforestation -- were analyzed using a global dynamic partial equilibrium model (GCOMAP). Key findings of this work are that cumulative carbon gain ranges from 50.9 to 113.2 Gt C by 2100, higher carbon prices early lead to earlier carbon gain and vice versa, and avoided deforestation accounts for 51 to 78% of modeled carbon gains by 2100. The estimated present value of cumulative welfare change in the sector ranges from a decline of $158 billion to a gain of $81 billion by 2100. The decline is associated with a decrease in deforestation.

Key words: GCOMAP, GHG mitigation, global forests, partial equilibrium model

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1 Introduction

Forests play an important role in the global carbon cycle. An estimated 1,146 Gt C are stored within the 4.17 billion hectares of tropical, temperate and boreal forest areas. A third of this carbon is stored in forest vegetation, and the rest in forest soils (Watson et al. 2000). Another 634 Gt C is stored in tropical savannas and temperate grasslands. Watson et al. (2000) estimate a net terrestrial carbon uptake of 0.7± 1.0 Gt C/year. Carbon dioxide annual average emissions from land use change, mostly from deforestation, are estimated to be 1.6 ±0.8 Gt C/year for 1989-95. Other estimates suggest a range between 1.2 to 1.9 Gt C/year for the early 1990s (Foley and Ramankutty, 2004).

The IPCC Second Assessment Report (SAR) noted that the technical potential for carbon sequestration through forestry activities over a 50-year period ranged from 55-76 Gt C, without considering carbon price incentives (Brown et al. 1996). A more recent assessment of the technical potential for afforestation and reforestation options for storing carbon suggests a total potential in the range of 197-584 Mt C/year in 2010, and a potential for reducing emissions from deforestation of 1788 Mt C by 2010 (Watson and the Core Writing Team, 2001). This potential is about one-sixth of the net annual anthropogenic emissions, estimated at 6.3 ± 0.6 Gt C /year between 1989-1998 by Watson and the Core Writing Team (2001), and at 6.6 Gt C/year for 2001 by the US Department of Energy (2003).

The mitigation potential in forestry varies across countries, and over time. Significant factors that influence this potential include the availability and suitability of land for forestation, its carbon sequestration potential; current and future land use activities, including deforestation trends; and changes in the efficiency and use of forest products, including biomass dedicated for fuel.

A number of studies have analyzed mitigation activities in forestry and estimated the associated costs per t C in different countries (Watson et al. 2000). These studies use different assumptions and methodologies with respect to carbon pools and cost elements included in the estimation. Watson et al. (2000) report costs ranging from $0.1 to $15/t C.

Sathaye et al. (2001) summarized the potential and cost for seven tropical and subtropical countries -- Brazil, China, India, Indonesia, Mexico, the Philippines and Tanzania -- by applying a common bottom-up model, COMAP (Sathaye et al. 1995). They report a forest sector total carbon sequestration and emissions avoidance potential of about 3 Gt C by 2030 at a negative cost after accounting for the market value of the associated forest products.

Other models have addressed these questions using partial and general equilibrium frameworks. The Global Timber Model (GTM), a partial equilibrium model, has been used to examine the effects of carbon prices on afforestation and forest management options for 53 forest ecosystems in nine regions in an integrated framework of global demand and supply of timber (Sedjo and Sohngen, 2000; and Sohngen and Sedjo, this issue). The Mini Climate Assessment Model (MiniCam) is a long-run integrated assessment framework (Edmonds et al., 1996) that generates a commercial biomass price and a carbon price and passes these to another partial equilibrium model, AgLU, which generates a biomass crop supply and GHG emissions from land use. Competition for land occurs in the AgLU in generating the commercial biomass supply. These models have been used to assess the demand for agricultural products over time, by region, and competition between agricultural and forest lands for production of crops, biofuels, and tree planting. At an aggregate level, it ensures that demand for agricultural and forest products is met over the model time horizon to 2100. The Integrated Model to Assess the Global Environment (IMAGE 2.2) provides similar analysis using a heuristic, decision–rule approach to the allocation of global lands by region for agriculture, biofuels, and afforestation (Graveland et al., 2002). Manne and Richels (this issue) applied the general equilibrium model (MERGE) to evaluate the role of non-CO2 GHG and carbon sinks in mitigating global climate. A paper comparing the reference cases and results for the EMF 21 sequestration scenarios (below) of these models (Sohngen and Sedjo, this issue), including GCOMAP, is presented in this volume (van Vuuren et al., this issue).

In this paper, we use a dynamic partial equilibrium model (Generalized Comprehensive Mitigation Assessment Process, GCOMAP) built to simulate the response of the forestry sector to changes in future carbon prices. The general equilibrium models reported above mostly rely on a few global data sets. A major goal of GCOMAP is to make use of detailed country-specific activity, demand, and cost data available to the authors on mitigation options and land use change by region (see Appendix A, and Sathaye et al., (2001) for tropical country data). The model permits explicit analysis of the carbon benefits of reducing deforestation in tropical countries. However, it does not consider the impact of increasing carbon dioxide concentration (i.e., CO_2 fertilization) on changes in the carbon cycle, and its effect on biomass growth.

This paper seeks to: (1) report results in a format readily usable by climate change general equilibrium modelers, and (2) facilitate comparisons of land use change and carbon benefits across developed and developing regions by mitigation options over time. For example, the MERGE model incorporates GCOMAP model results to estimate the potential for carbon benefits from the forest sector given alternative carbon price paths.

The paper is organized as follows. Section 2 reports on the model structure and the approach adopted for the accounting of carbon and monetary flows, and for the determination of land area that is planted in response to an exogenous carbon price scenario. Section 3 discusses the data and sources, and Section 4 the reference case land use change and carbon price scenarios. Section 5 discusses the impacts of these scenarios on the increase in planted land area and its carbon consequences, and the sensitivity of results to changes in the reference case land use scenario. Finally, Section 6 concludes with observations about the key findings of this study.

2 Structure of the Model

The GCOMAP model establishes a reference case level of land use, absent carbon prices, for 2000 to 2100. It then simulates the response of forest land users (farmers) to changes in prices in forest land and products, and prices emerging in carbon markets. The objective is to estimate the land area that land users would plant above the reference case level, or prevent from being deforested, in response to carbon prices. The model then estimates the net changes in carbon stocks while meeting the annual demand for timber and non-timber products. Table 1 provides a list of the key features of the model. The ten world regions covered by the model and as utilized in the EMF 21 modeling process are listed in Table 2. More detailed description of the model structure, approaches, and data are presented in the model description paper (Sathaye et al., 2005), including regional land use and carbon stock data, equations for the carbon accounting and financial modules, and other details.

Table 1: GCOMAP Model Features

Feature	GCOMAP
Temporal coverage	2000 to 2100; changes tracked annually.
Land-use change scenarios	Reference scenario — Historical trends, modified government plans. Mitigation scenarios — Driven by land use response to six future carbon price scenarios
Timber and non-timber forest product output and prices	Use supply and demand elasticities to estimate timber price and quantity changes. Five timber and non-timber products. Separate domestic and international markets.
Discount rates	Rate of return (ROR) remains unchanged between reference and mitigation scenarios. Reference case ROR is derived from input costs, product price, and output levels.
Model mechanics	Region-specific for 10 regions. Perfect foresight; based on investment theory. Permits sensitivity and alternative scenario analyses. Software: Excel, Visual Basic.
Macro-economic implications	Estimates total outlays and changes in consumer and producer surpluses and net social pay-off (welfare)

Earlier studies have grouped forestry mitigation activities into three categories (Brown et al. 1996, and Watson et al. 2000). One category, carbon sequestration, includes activities that store carbon, for example through afforestation, reforestation and agroforestry. A second one, conservation, includes activities that avoid the release of emissions from carbon stock, such as forest conservation and protection, and a third category, substitution, which involves the substitution of carbon-intensive products and fossil fuels with sustainably harvested wood products and wood fuel. Activities and products in these categories may be interlinked.

Table 2: Mitigation options, regions , and carbon pools in GCOMAP

Mitigation Option	GCOMAP Reporting Regions	Carbon Pools (All Regions)
Forestation • Short rotation • Long rotation • Biofuels (not reported in this paper)	• China • India • Rest of Asia • Africa • South America • Central America • USA • EU (Incl. E Europe and Baltic States) • Russia • Oceania (Australia/NZ/Japan/PNG)	Above/below ground biomass Soil organic carbon Litter Post-harvest residues Products: - Domestic timber products - International timber products - Fuelwood products Biofuels (mill-waste) – used as a substitute for coal in power plants
Avoided deforestation	• Rest of Asia • Africa • South America • Central America (Minimal or no deforestation assumed for other regions)	

We analyze three mitigation options: 1) short-rotation forestry, i.e., new or replanted tree crops or forests managed on a rotation of growth and harvest between 6-60 years; varying by region and forest type; 2) long-rotation forestry, i.e., planting and management for rotations between 20-100 years; and 3) avoided deforestation, i.e., land use management that extends rotations and prevents deforestation. The first two options conform to the first IPCC category, carbon sequestration, and the third conforms to the conservation category. These options currently are practiced in many countries in a wide range of biophysical and socioeconomic conditions, and often co-exist on similar lands, especially in the tropics. (The model also is capable of analyzing biofuels mitigation, a substitution option, but that is not reported here.) Afforestation and reforestation are difficult to define and track separately, especially in the tropics, so they are combined into two forestation options analyzed for each of the ten regions. The option to avoid deforestation is analyzed for four developing regions where deforestation is significant – Africa, Central America, Rest of Asia, and South America. We did not analyze the forest management option in the model and hence vintages of carbon stocks were not tracked for managed or unmanaged forests.

The model is composed of three modules.[1] The carbon stock module tracks annual changes in carbon stocks in ten carbon pools (Table 2): above- and below-ground biomass, soils, litter, post-harvest residues, and wood products – domestic and international timber, non-timber products (fuelwood, resin, honey, and fruits), mill waste, and biofuels (though not reported in this analysis). Product decay and deforestation releases carbon and other greenhouse gas emissions and causes carbon stocks to decline. The same carbon stock dynamics apply to each parcel of forest or planted land in a region over the model time horizon. Vintages of future carbon stock are tracked on planted land. Data for each option represent the characteristics of a representative species for a given region.

The financial module tracks the annual monetary flows associated with the implementation of each of the three mitigation options. The costs of forestation activity include the value of inputs used during establishment (or during deforestation), usually in the first three years or so (e.g., opportunity cost of land, machinery, labor and materiel), as well as expenditures on periodic operations thereafter (e.g., thinning, harvest, and annual overheads like management, maintenance, and monitoring). Costs of deforestation include the cost of harvesting trees and transporting timber from the deforested site, and the opportunity cost, which is estimated as the value of economic activity on deforested land. The benefits from forestation include the revenues derived from the sale of domestic and international timber, non-timber products and fuelwood that have no associated carbon storage, and other mill-waste products. The benefits from deforestation include the above components, except non-timber products.

The land use change module tracks the annual changes in land use in the forestry sector for each of the three mitigation options. Based on the price elasticity values for land supply and demand, the model computes the price of land and the area to be planted or not deforested annually in response to a carbon price. The module ensures that the

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[1] Equations that describe the carbon stored in each pool, monetary costs and benefits, and the amount of land area planted in response to a carbon price scenario are described in Sathaye, Makundi, Dale, Chan, and Andrasko (2005).

cumulative planted land area does not exceed the estimated maximum available area suitable for that option in a region.

2.1 Approach

Each mitigation option is analyzed separately for each region in the model. The analysis begins with the specification of a land use change scenario for the reference case. Using input data on biophysical characteristics of the region -- biomass yield, carbon content of the biomass and soils, product shares, etc., -- the first module computes the annual changes in carbon stock over the model time horizon. It tracks both the accumulation of carbon and its release due to the decay of vegetation and products separately on lands planted each year. Simultaneously, using input data on fixed and variable costs, and product prices, the second module computes the financial viability of the forestry option. While the model is capable of computing several financial parameters, we are mainly interested in the estimate of the rate of return. Since the carbon dynamics are the same on land planted each year, as are costs and product prices, the rate of return remains unchanged on lands planted in subsequent years.

The third module of the model then estimates the changes in land use that result from a carbon price scenario. The rate of return is maintained the same as in the reference case scenario, which decides the additional land area to be planted in the mitigation case each year. The first module is then rerun to compute the annual changes in carbon stock brought about by the change in mitigation land use. Finally, the model computes the difference in carbon stocks in the mitigation and reference cases and reports the carbon and land area gain for each decade between 2000 and 2100. This module also estimates the change in social welfare in the forestry sector.

Various land uses (short, and long rotation forestry, agriculture, human habitats, etc.) coexist in competition with one another in each region. Our estimated historical rates of return for forestation options reflect the prevailing returns at which land markets are in equilibrium. In the reference case, we project future planting using the historical planting rate, and assume that the current equilibrium conditions will hold over the model time horizon.

2.1.1 Rates of Return

Two approaches to discounting -- prescriptive and descriptive-- may be used in climate change modeling (IPCC, 1996). The former approach leads to lower, and the latter to higher, rates of discount. The descriptive approach is based on the private or social rates of discount that, savers and investors actually apply in their daily decisions. Private rates of discount typically range between 10% and 25%, and social rates of discount between 4% and 12% (Markandya and Halsnaes, 2001). The rates are lower for developed countries and higher for developing ones. We estimate private rates of discount from data on cost and revenue profiles in forestry land use activities, and use these in our analysis of the three mitigation options. Cost and revenue profiles are derived from data shown in Appendix A1.

The estimated rates of return (ROR) for land use activities may also depend on the capital markets from which a land user may borrow funds for investment in forestry projects. The estimation of changes in capital markets between the reference and mitigation cases and their influence on interest rates is outside the scope of a partial equilibrium framework. Instead, we assume a conservative rule that the land user would demand at least the same rate of return in a mitigation case as the ROR in the reference case — or the user would have no monetary incentive to plant additional land area or reduce the area being deforested.

Within a region, the model may compute different rates of return for short- and long-rotation forestation options, each of which satisfies demand for different wood products. The differences among land users in their access to financing, timing of revenue streams, biophysical conditions of their lands, etc., results in the coexistence of both options in each region. The model allows both forestry options to persist in the future, consistent with historical and current land use trends. Forestry options also co-exist with other land uses, with comparable implicit effective rates of return after taking into account specific factors like taxes, subsidies and risk. A carbon price allows the land-owner to increase the land under forestry by enabling him/her to plant on higher marginal cost lands. The higher costs of this incremental planting are offset by the carbon price subsidy such that the rate of return from the new areas is maintained at its reference case value.

The rates of return vary across regions but are held constant over time. For short rotation forestry, the rates range from 6% to 12% for the three OECD regions and Russia, between 12% and 19% for Africa and Latin America, and between 26% and 30% for the Asian countries. These rates are derived from sources specific to these regions, and are higher than societal discount rates[2]. The rates for long-rotation forestry are uniformly lower, between 3% to 7% for the three OECD regions and Russia, from 6% to 11% for Africa and Latin America, and from 9% to 13% for the Asian countries. The higher rates of return in Asia also correspond to significantly higher planting rates in those countries (Figure 2). In each region, the rates of return for long rotation are lower than those for short rotation due to the temporal distribution of costs and revenues, with costs occurring in the beginning in both options but revenues coming in much later for long rotation. The price differential (with long rotation species generally having higher product prices), is not sufficient to defray the temporal effect.

2.1.2 Timber Market: Supply and Demand

The model represents international (timber products) and domestic markets (three types of products -- timber, fuelwood, and non-timber products) with separate demand curves and product prices by region, using International Tropical Timber Organization (ITTO) and other data (see Appendix A, Table A1). There is no single global timber clearing price, but rather a separate demand curve for each product in each region. Demand is exogenous, and supply of products meets it by region.

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[2] These rates of return are higher than the societal discount rates that are used in national and global models of climate change. LBNL's review of 23 forestry projects in the tropics shows societal discount rates to range from 1% to 12%, with the median value at 10% and the average at 7% (Dale, 2003). Other studies have used a 10% rate for short-rotation forestry and arrived at a high positive net present value of benefits. For example, Xu *et al* (2001) using a discount rate of 10% report NPV estimates for China of $540 - $740 and $410 - $610 per hectare for short- and long-rotation forestry respectively. Likewise, Masera et al. (2001) reported NPV of $497 and $5780 per ha for short- and long-rotation respectively, using a 10% real discount rate.

Consistent with historical data, this analysis assumes that real timber price remains unchanged in the reference case, mostly due to technological improvements and substitution effects. Future timber demand increases over time as population and economies continue to expand, but timber supply continues to increase to meet this demand. Data from the last 40 years suggest that real prices of forest products have remained static over this period (FAO, 2000; FAO, 1992; FAO 1985), with the exception of tropical logs, whose real prices have been slowly increasing. Prices for wood-based panels, paper, and paperboard had been declining since the early 1960s, but have remained constant since the 1980s (FAO, 1992). This may be because substitution of other materials for wood products and technological improvements have reduced the quantity of wood demanded per unit of GDP over time.

In the past 50 years, production of industrial roundwood has grown at about 1 percent per year, with the share of plantations rising from negligible to the current 25% of global industrial roundwood and 5% of wood fuel production (FAO, 2000). This shift to a managed, faster growing, higher timber density source of wood and fiber represents part of the technological change that has kept real product prices unchanged, and is assumed to persist in the reference case analyzed in GCOMAP, which allows recent rates of forestation observed in each region to be maintained in the reference case. Productivity change is computed within the model, and is defined broadly to include not only productivity improvements, but also changes in species mix and distribution of timber production within a region. Other authors have used a narrower definition, for example, in the AgLU model, Sands and Leimbach, (2003) simulate increases in crop yields in a range of 0.0% to 1.5% per year. ().

2.1.3 Social Welfare Change in the Forest Sector

While we use the land user's perspective in estimating the increased land area that will be planted, it is also useful to estimate the implied increase in social welfare as estimated by the increase in consumer and producer surplus (Varian, 1992). This welfare gain (net social payoff) is an estimate for the forestry sector only. In order to be comprehensive, one ought to use a general equilibrium approach and adjust the welfare gain in this sector by the change in net social payoff (NSP) in all the other related sectors whose demand and supply may have been affected by this sector, especially the carbon credit buyers. Since this is outside the scope of our paper, we estimate only the regional and global welfare gain for the forestry sector. The assumption of constant marginal utility for money among timber producers and consumers applies to the estimate of the social welfare gain. However, this is partly mitigated by the use of region-specific implicit discount rates.

3 Data and Sources

Data on land use change, biomass stocks and growth, carbon pools, forestation and deforestation activity, emission factors, and costs and benefits of forestation and avoiding deforestation were gathered for each region. The data and sources are shown in the Appendix Table A1. By their very nature, data from various sources may use similar but not identical definitions. For the tropical countries, country-specific data were gathered over a period of years by the F7 network on tropical forestry. Definitions of various activities and data differences were reconciled by network researchers through workshops and meetings beginning in the early 1990s (Sathaye and Makundi, 1992; Makundi et al, 1995; Sathaye et al, 1995).

Data on land use change, (forestation and deforestation) for the tropical and temperate/boreal countries were gathered largely from the FAO 2002 Forest Resource Assessment (FAO, 2003a) and FAO 1990 FRA - Tropical Countries (FAO, 1993). The regional data on forestland cover, biomass volume, planting and deforestation rates, and industrial roundwood production were based on FAO and ITTO statistics. The FAO and ITTO data collection and publishing process involves some standardization, thus enhancing comparability across regions.

The afforestation and reforestation costs/benefits data as well as carbon sequestration data for the tropical countries are drawn from earlier studies for the COMAP model (summarized in Sathaye et al., 2001), and supplemented with country- or region-specific sources (RSMD, 2001; Potter and Lee, 1998; Sist et al., 1997; Kaimowitz, 1996; Nambiar et al., 1998; Nair, 2000; Nambiar et al., 1999; Barraclough and Ghimire, 2000; and Pandey, 1983). When data were not available for other countries in a region, these sources then were applied to represent tropical regions in geographic proximity. . The yield data were adjusted to ensure that all biomes are appropriately covered. Country-specific labor costs are used where available or adjusted by wage index for a given region, as detailed in Table A1 in the Appendix. Domestic prices of timber and non-timber products were scaled using regional average values weighted by volume for these parameters. The regionalization approach provides coverage of tropical countries in Asia, Africa, and Latin America.

Some of the data for the industrialized regions were obtained from common international sources (FAO, 1992; FAO 2001, FAO, 2002). However, the bulk of the data were gathered from sources unique to each region (see Appendix 1) (Moulton et al., 1995; Moulton et al., 1996; EPA, 2002; Cairns et al., 1995; Parks and Hardie, 1997; King, 1993; Peterson, 1993; Izrael and Avdjushin, 1997; ECE/FAO, 1992; Hutjes et al., 2001; Nilsson et al., 1992; Kirshbaum et al., 2000; Lyons, 1997; Petrov, 2001). Country-specific data were scaled to regional values using ratios of regional averages to country-specific values for the industrialized regions -- the EU countries, Russia, and Oceania. These were supplemented with additional country-specific data for the US. Although Canada has a large forested area, it is not included in this analysis since we do not analyze the forest management option, and we assume that there is no net deforestation in non-tropical regions. Further more, we do not analyze Canada’s forestation potential since there is negligible area under industrial plantations, a key element in initializing the forestation module in the model.

Data on price elasticity of timber demand and supply were obtained from the literature; these are relatively sparse and dated and were applied to each region. This lack of differentiation by region, and constancy over time, of the elasticities is conceptually sub-optimal, but the few data available seem inadequate to justify a range of values by region. A very elastic demand for exported timber, -33.3 was used (Makundi, 1990), while price elasticity of -1.0 was used for domestic timber demand (McKillop, 1967; Robinson, 1974; Adams, 1985). The supply of timber was assumed to be much more inelastic, +0.5 (Adams, et al, 1986; Adams and Haynes, 1980). In this analysis we used the US forestland supply price elasticity, 0.25, and applied it to all regions over the 100-year horizon, since few studies of such elasticities exist. This value is also the average price elasticity of forestland reported in Sohngen and Mendelsohn (2002) for eight of the ten regions in GCOMAP.[3] Cost and price data were adjusted to 2000 US dollars.

The supply of woodfuel was determined as a residual from the harvested biomass after extracting timber and an estimate of a proportion of onsite post-harvest wood waste. This estimate varies across regions depending on the level of woodfuel use in the country, with developing regions having a much higher proportion than the developed regions. As mentioned above, the proportion of firewood from industrial plantations is about 5%, but in some regions e.g., Africa and Asia, some plantations are dedicated for firewood. The demand for woodfuel and mill-waste for fuel in the reference case is modeled as a residual in the combined multiple-product demand function (international timber, domestic timber and woodfuel).

4 Scenarios

We analyze the incremental effect of six carbon price mitigation scenarios on changes in land use and carbon gain between 2000 and 2100 in comparison to a single reference scenario. The reference scenario has no carbon market and hence there is no price for carbon. The six mitigation scenarios were developed for use in the EMF-21 forest and agriculture sequestration analyses, and have different initial carbon prices and follow varying carbon price paths. The six carbon price scenarios are illustrated in Figure 1. Scenario 1 has the lowest initial carbon price of $5/t C rising at 5% per year. Scenario 2 has a higher initial price of $10 /t C, but rises at 5% per year, while Scenario 3 also starts at $10/t C but has a lower growth rate of 3% per year and reaches the second-lowest price in 2100 of $143 per t C. Scenario 4 starts at a higher initial price of $20 /t C, and rises at 3% per year. Scenario 5 represents a different trend where the carbon price is held

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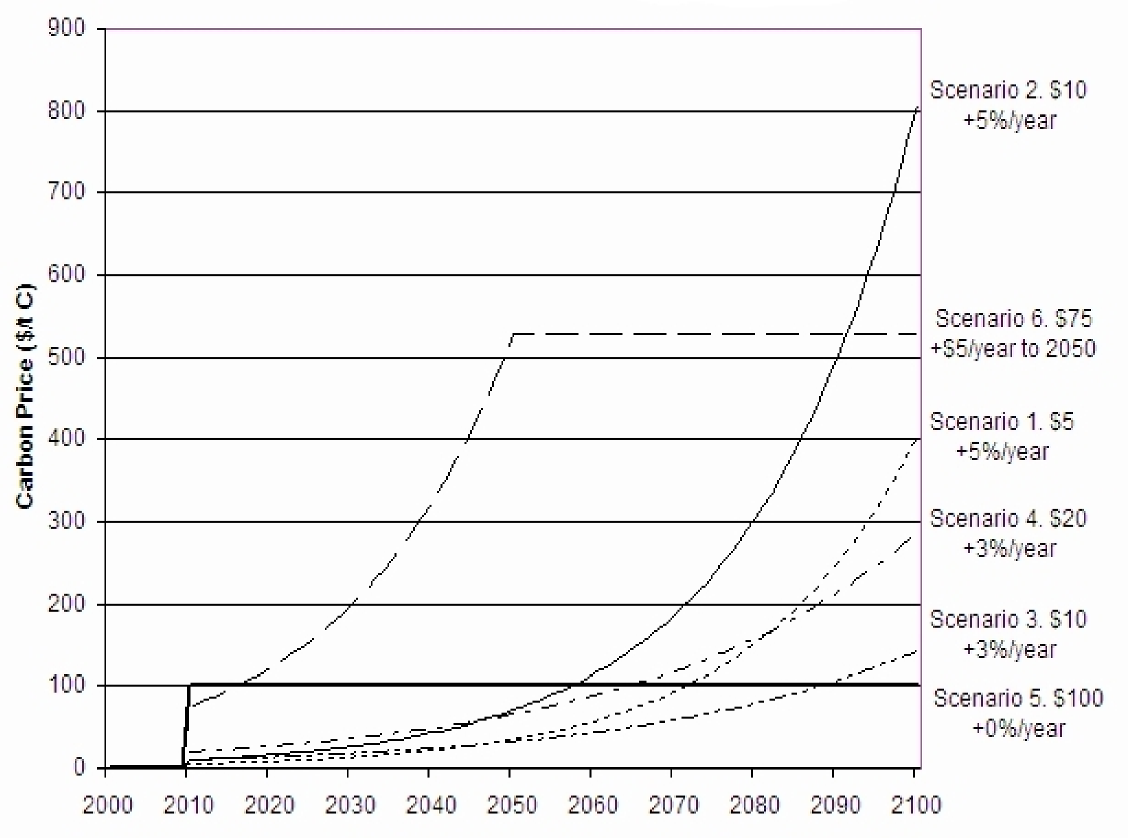
[3] Sohngen and Mendelsohn (2002) report elasticities for North America, Former Soviet Union, and China that are lower than the average we use; and higher elasticities for Western Europe, India, and Oceania. The relatively high elasticity of 1 reported for India and Oceania was considered uncharacteristically high and was excluded from the average.

constant at $100/tC through 2100. In Scenario 6, the carbon price starts at $75/tC, rises at 5% per year until 2050, and is then held constant to 2100. Because of their unusual price paths, the timing of carbon gains, and the relative contributions of forestation and avoided deforestation in these two scenarios, is quite different from that for the first four scenarios. All scenarios are below or at $100/tC by 2050, except for Scenario 6, but they range from $100 to over $800/tC in 2100.

Figure 1: Carbon Price Mitigation Scenarios

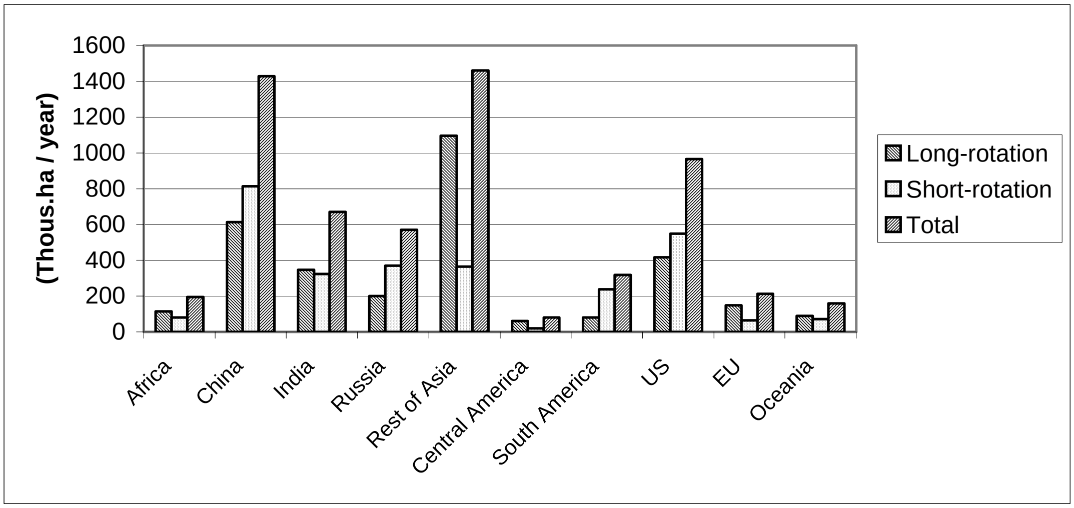


4.1 Reference Scenario – Land Use Change

The amount of carbon sequestered through forestation and that released through deforestation depend critically on future reference case scenarios of land use change. Below, we describe the historical land use change patterns, and our estimated availability of lands that may be suitable for tree planting in each region.

Forestation: The reference case for short- and long-rotation forestry assumes that historical forest planting rates in each of the ten regions continue out to 2100. The historical data range from 1975 to 2000, and are largely based on FAO statistics on land area planted. In the case of the US, EU, and Oceania, however, the data are derived from national statistics (see Table A1). For some regions, like US and China, we collected data by sub-regions, nine for the US and four for China and used these to estimate aggregate totals or weighted average values for the relevant model parameters. By using historical planting rates that vary by region, we reflect differential regional infrastructure, response to economic incentives, and institutional settings. As noted in Section 3 above, the price of land increases at a supply price elasticity of 0.25. The unit cost of planting, however, remains constant due to productivity improvements over the period of analysis in the reference case.

Figure 2: Average annual planting rate per region using available data from varying periods during 1975-2000



The above land data show that the average total land area planted annually amounted to about 6.1 Mha/year, of which about 3.3 Mha/year was used for long-rotation planting. Figure 2 shows the land area planted annually under short- and long-rotation plantations, based on available historical data (for varying years during the period 1975 to 2000). The assumption that historical planting rates continue through 2100 in the reference case importantly drives the availability of land suitable for planting in mitigation scenarios. In some regions and time periods this assumption limits the quantity of planting that occurs. Other reasonable assumptions of afforestation, both lower and higher than historical rates, may be used and these would impact the mitigation potential and timing for afforestation. We report on the results of a sensitivity analysis, which tests the model's response to alternative forestation assumptions, in Section 5.4.

The maximum amount of land area that could be planted is quite large in each region (Table 3). Regions such as Africa, South America, and Rest of Asia have vast amounts of marginally utilized land and/or wastelands that could be available for tree planting. In other regions like the US, EU, and perhaps Russia, croplands could become suitable areas for tree planting as increased agricultural productivity reduces land requirements for farming, releasing some lands currently under agriculture for forestry.

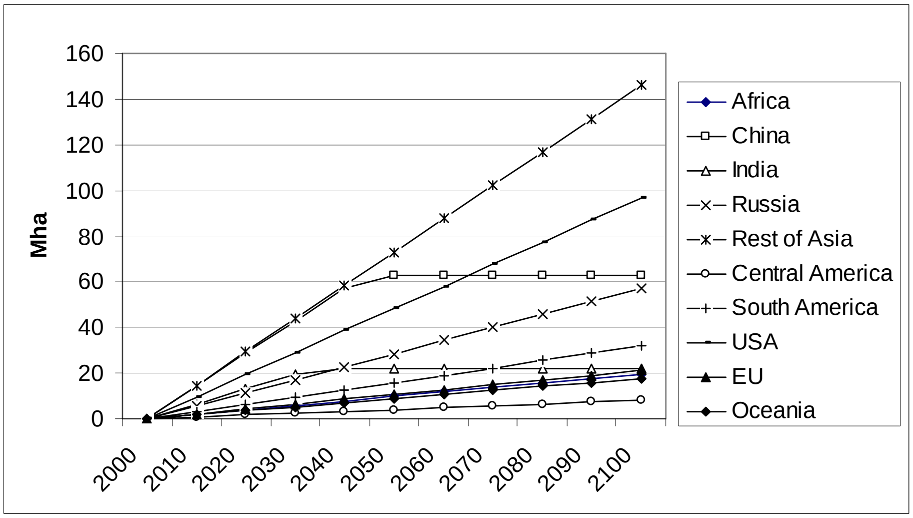
Finally, in China and India notably, but to some extent in Russia, the total land area is large but only a small fraction is suitable for planting. Table 3 shows the land area (including previously deforested land) that is deemed suitable for planting in each region. The comments column explains the approach and references used to estimate the land types and areas suitable for short-and long-rotation plantations.

A consequence of the limited area of land suitable for planting in each region, and of current high rates of planting, is that the amount of land area suitable for planting is exhausted in the reference case by 2030 and 2050 in India and China respectively (Figure 3). As will be shown below, mitigation planting accelerates the planting rate and exhausts the land area sooner than in the reference case.

Table 3: Maximum land area suitable for tree planting

Regions	**Short-rotation forestation**	**Long-rotation forestation**	**Comments**
	(Mha)	(Mha)	
Africa	80.0	120.0	50% of the deforested land (4 Mha/yr 1970-2020), the rest from grasslands, woodlands, and abandoned agricultural lands. (FAO 2000, FAO, 1993, Barraclough and Ghimire, 2000)
China	35.9	27.1	Based on China's short, medium, and long-term expansion plans for timber and non-timber forests by 117 Mha by 2050. (MOF, 2000)
India	10.2	11.5	National Forest Action Plan to increase India’s forest area by 33% by 2020 (FSI, 1999)
Russia	37.5	20.2	50% of the 115 Mha of the Unforested land under FFS, part of which is currently used for Reforestation (NEAP, 1995 In National Implementation of Agenda 21)
Rest of Asia	50.0	150.0	Degraded forestland and wasteland. (FAO, 2001 (FRA 2000), FAO, 1993 (TFRA 1990), CIFOR, 2000)
Central America	6.5	15.0	Degraded forestland and wasteland. (FAO, 2001 (FRA 2000), FAO, 1993 (TFRA 1990), Cairns et al., 1995, Kaimowitz, 1996)
South America	50.0	150.0	Degraded forests, deforested lands and cerrados. (FAO, 1993; 2001 (FRA, 2000; TFRA, 1990), Fearnside, 2001; Cairns et al., 1995.)
United States	50.1	65.9	Dry and wet soil pastureland and cropland and non-grazing forest from 10 US regions. (US Forest Service, 2001; Moulton et al., 1990; 1996, Lubowski et al., 2001)
European Union	40.0	50.0	Abandoned crop and pasturelands and sparse woodlands. (ECE/FAO, 1990, FAO 2000 (GFPOS) FAO, 2001 (FRA 2000), Nilsson et al., 1992)
Oceania	28.0	42.0	Australia wastelands and cropland, NZ FAO 2050 scenario, and Japan sparsely wooded lands, and PNG degraded and deforested land. (ECE/FAO, 1990, FAO, 1993 (TFRA 1990), UNFCCC National Communications, Kirschbaum 2000)
TOTAL	388.3	651.7	

Figure 3: Reference Case Land Area Planted (Cumulative) Short- and Long-Rotation



<u>Deforestation:</u> The rate and spatial distribution of deforestation remains uncertain. The FAO estimated that global tropical deforestation in Africa, Central and South America, and in the Rest of Asia region exceeded 17 Mha annually in the 1980s (FAO, 2001), and was 12.2 million ha annually in the 1990's (FAO, 2003a). Deforestation reportedly has been virtually halted in two of the study regions, India and China (Ravindranath et al., 2001, and Xu et al., 2001, respectively). More recent analysis by Houghton (2003) has revised downward to 700 Mt C/year the previous estimate of 1400 Mt C/year carbon flux from tropical deforestation. Deforestation is assumed to be net zero for developed regions.

In the past two decades, Central and South America, and Rest of Asia showed a decline in the annual rate of deforestation (FAO, 2001). Annual remote sensing data in the last few years from Brazil, however, indicate that the decline shown for South America may have reversed. Africa's rate of deforestation is still rising in step with its rural population's continued dependence on agriculture and primary resources.

Table 4 shows the annual percent change in deforestation rates for 1990 and 2000, and our projection of the deforestation trend to 2100 for each of the four tropical regions. The deforestation rate during the last decade increased in Africa at 0.026% per year, while it declined in the other three study regions. Consistent with IPCC scenarios, we project the rate in Africa to rise through 2020 before beginning to decline largely due to the depletion of its forests and a high rural-urban migration rate (Nakicenovic, 2000). Meanwhile deforestation continues to decline in the other regions due to economic development, urbanization, and increased agricultural productivity, which reduce the pressure on forest land. Figure 4 shows the projected quantity of deforested land for each of the four tropical regions. The implications of the deforestation rate projection over time are significant for avoided deforestation as a mitigation option in several scenarios, and for the timeframe of any such mitigation. We test the sensitivity of carbon gains to land use change due to deforestation and report this in Section 5.4.

Table 4: Historical and Projected Deforestation Rates Used in GCOMAP

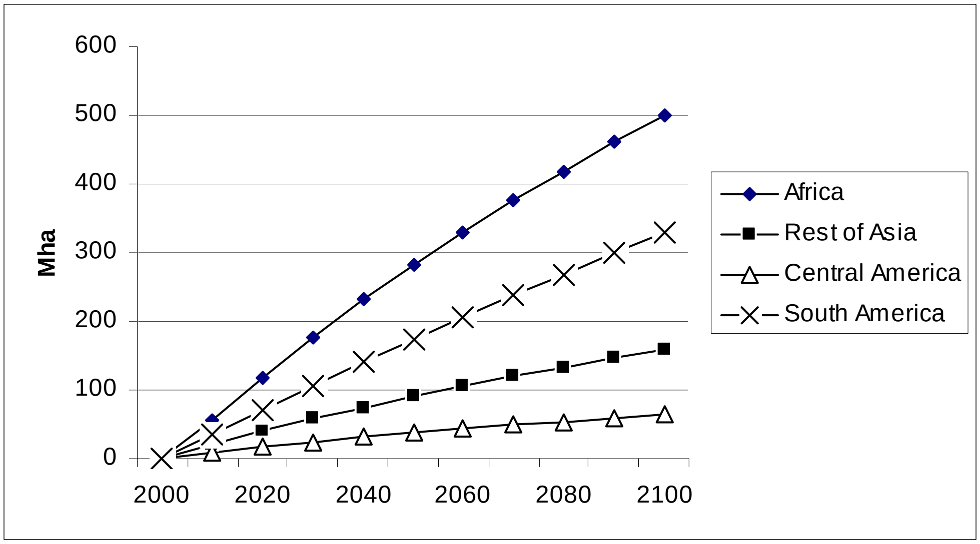
Region	**Deforestation Rates**$^{(a)}$ **(%/year)**				
	2000 [b]	**2020**	**2040**	**2050**	**2100**
Africa	0.80(+0.026)	1.29(-0.026)	0.78(-0.013)	0.65(-0.006)	0.26
Rest of Asia	1.03(-0.005)	0.82(-0.008)	0.60(-0.008)	0.52(-0.008)	0.12
Central America	1.19(-0.011)	0.97(-0.011)	0.75(-0.011)	0.65(-0.011)	0.37
South America	0.40(-0.013)	0.26(-0.001)	0.21(-0.001)	0.20(-0.001)	0.13

Notes:

(a) The values are percent of the land area deforested in the year shown. For example, Africa will loose 0.8 percent of its forests in 2000, while South America will loose 0.4 percent.

(b) The value in parenthesis is the rate at which the deforestation rate is changing each year, with a (+) sign indicating the rate is increasing. The initial rate of change is estimated from the land use change between 1990 and 2000. For example, Africa is loosing 0.8% of its existing forest in year 2000, and this rate is increasing by 0.026% per year, as such by 2020 it will loose 1.29% of the then existing forest. The decline in deforestation rates are region-specific, with the rates estimated to cause a smooth decline ensuring that by the end of the period the rate will still be adequate to support necessary forest conversion to settlements, development and communications infrastructure.

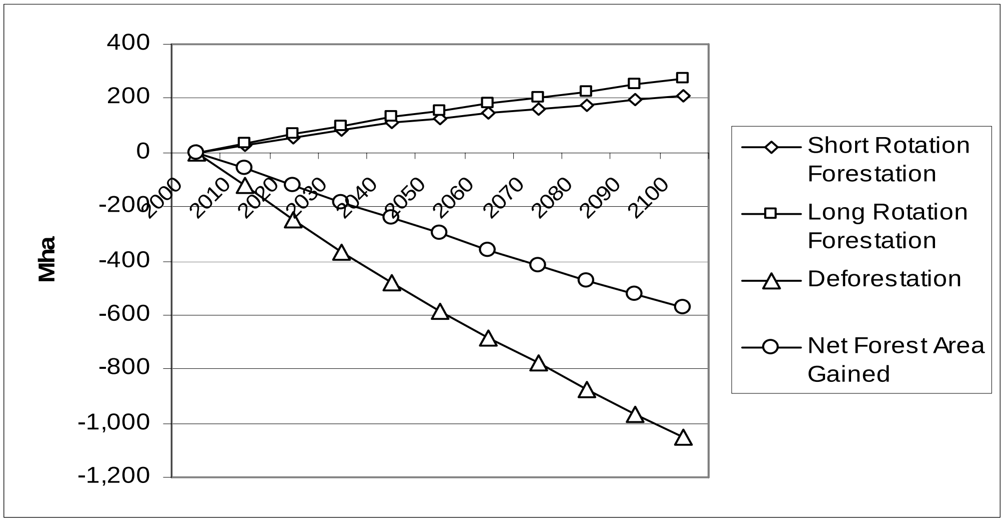
Figure 4: Reference Case: Land Area Deforested by Region (Cumulative to year reported)



Assumptions of global forest area change over the next century vary significantly across several studies, by model structure, and factors driving land use e.g., population changes, changes in diet and demand for calories in response to changes in GDP over time, and substitution of biomass fuels for fossil fuels. Like other sectoral models, we do not explicitly model these assumptions. Instead we simply and transparently assume that recent historical deforestation rates increase (in the case of Africa), or decline over the near- and long-term time horizons, by region. The carbon consequences of our reference scenario are reported in Section 5.1 and shown in Figure 7 in comparison to those reported for IPCC scenarios.

The changes in forest cover reported in the IPCC scenarios may be compared with the combined forestation and deforestation land use change in our reference case (Nakicenovic, 2000). Similar to some of the IPCC non-marker scenarios, world forest land in our reference case declines continually starting in 2000 with a cumulative loss of 570 Mha by 2100 (Figure 5). Forest cover increases in Asia and decreases in the Africa and Latin America regions continually up to 2100. In all other model regions, forest cover increases between 2000 and 2100.

Figure 5: Reference Case: Land Use Change by Activity for All Regions (Cumulative to year reported)



5 Results

We analyze six mitigation carbon price scenarios using the GCOMAP model, and compare land use change and carbon sequestration between each scenario and the common reference scenario. For each scenario, we estimate the increase in land use and carbon stock over time for ten global regions for the short- and long-term forestation options. We also estimate the effect of the avoided deforestation option for four tropical regions (Africa, Asia, Central and South America), which when compared to a reference scenario slows the rate of deforestation in each region.

5.1 Reference Case

The decline in forest land area by 570 Mha between 2000 and 2100 in the reference case is caused by continued deforestation, which results in a net loss of forest land in each of the four tropical regions. This loss is partly offset by an increase in forest land in the six other model regions of the world. Break down of regional land use and carbon stock data are presented in the model description report (Sathaye et al., 2005).

Figure 6 shows the changes in carbon stock in the reference case. Carbon stock declines initially until 2030 and then increases up to 2100. The decline in the earlier years is caused by the higher deforestation rates in the earlier decades. In the latter decades, deforestation rates decline and carbon stocks from forestation, particularly from long-rotation planting, increase enough to offset the loss in carbon stock due to deforestation. The net result is that despite the large loss in forest land area, carbon stock is slightly higher in 2100 than in 2000. Two regions, Rest of Asia and the US, account for the bulk of the increase in carbon stock in the reference case. Rest of Asia contributes 34 Gt C stock and the US 15 Gt C stock in 2100 out of a total stock of 82 Gt C in short- and long-rotation forestry. Because the net carbon gain is small compared to either the forestation or the deforestation carbon gain, small changes in reference case assumptions about land use change for either of the two types of activities have a significant impact on the net carbon gained estimated by the model. In order to explore this issue further, we analyze the sensitivity of the model results to changes in the reference case land use scenario in Section 5.4.

Figure 6: Reference Case: Carbon Stock Change (Cumulative to Year Reported)

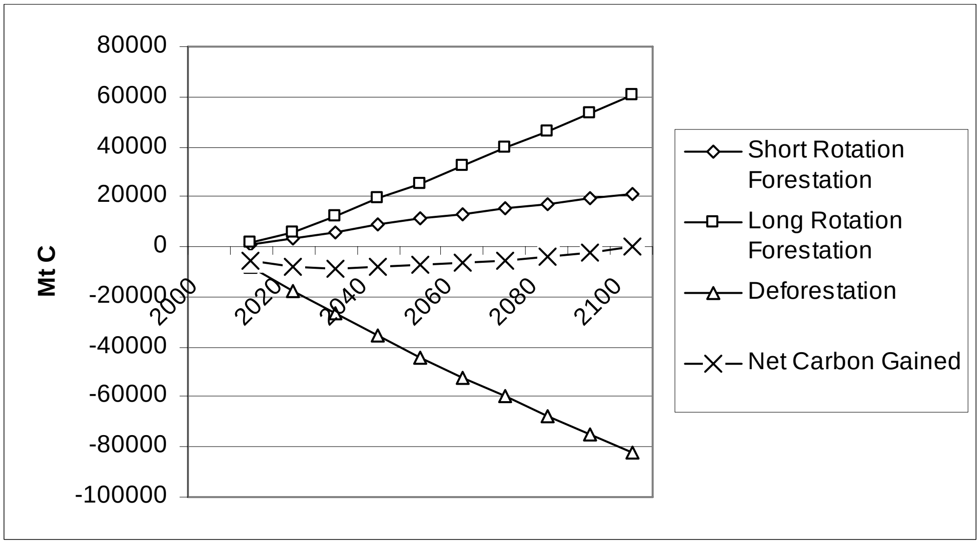
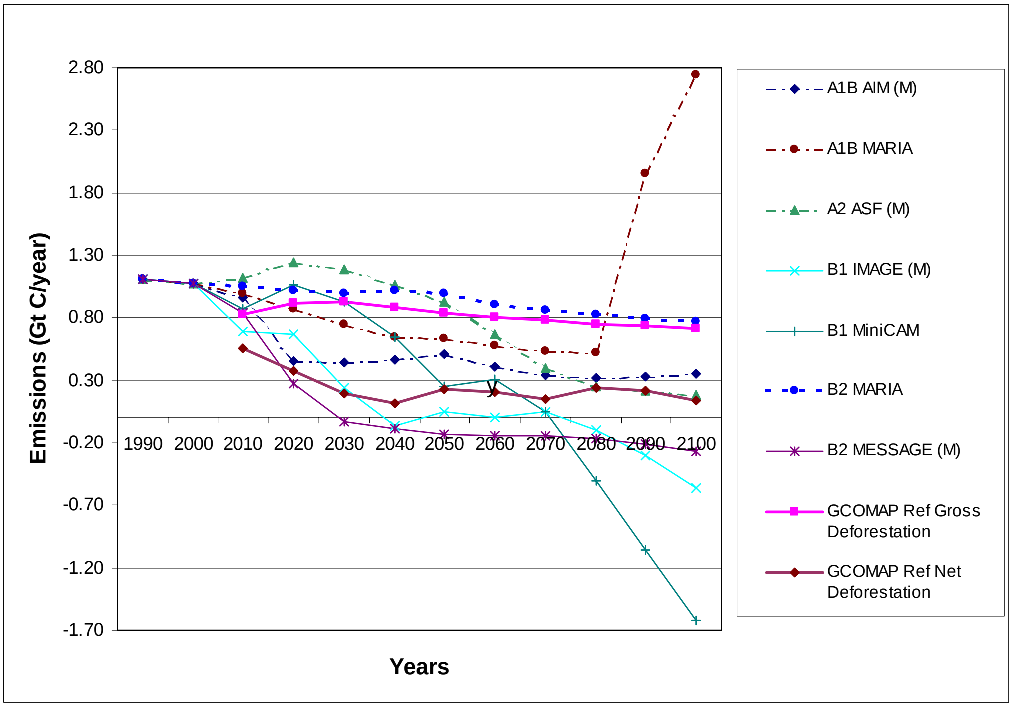


Figure 7. Carbon Emissions from Deforestation: GCOMAP Reference Case (Gross and Net) and IPCC SRES Scenarios (Africa, Asia, Latin America and the Middle East)



Our results are within the range of results reported for the IPCC scenarios by Nakicenovic (2000). Figure 7 shows that in the IPCC scenarios, emissions from deforestation have a wide range by 2100, from about 2.8 Gt C/year in the A1B Maria scenario to –1.7 Gt C/year in the B1 MiniCAM scenario. While the IPCC made an effort to produce comparable results, some inconsistencies in accounting for gross and net deforestation remained, and these may account for the wide variation in the 2100 emissions even within the same scenario family (see for example the difference between B2 MARIA and B2 MESSAGE scenarios. We also show GCOMAP emissions from gross and net deforestation in Figure 7. Net deforestation figures are calculated by subtracting the sequestration due to forestation from the emissions due to gross deforestation. Our gross deforestation scenario shows a small peak in 2030 due to the increase in deforestation in Africa. It is similar in magnitude and path to the B2 MARIA scenario, and our net deforestation scenario is similar in path but lower in magnitude to the A1B AIM marker scenario.

5.2 Mitigation Cases

Table 5 shows the results for carbon sequestration and emissions avoided across the six carbon price scenarios for 2050 and 2100. Scenarios that explicitly model the effect of reference case drivers like population and economic growth on changes in forested and deforested areas are feasible, but we have not attempted these as yet. Two sensitivity analyses on reference case deforestation and forestation rates, however, are reported below.

The land area and carbon benefits gained in the price scenarios are consistent with the trends in carbon prices. Scenario 1 ($5 initial carbon price in 2010, rising at 5%/year to 2100) and Scenario 3 ($10 initial carbon price in 2010, rising at 3%/year to 2100) have the lowest amount of land area and carbon benefits gained by 2050. This result is consistent with the lowest prices ($35 and $33, respectively) reached by 2050 among the six scenarios.

Generally, the higher the carbon price, the higher the land area planted and the carbon benefits gained by that date. However, the model uses perfect foresight, where land users "know" today the price path of C in future periods and use that knowledge to make land use decisions. Thus the model tends to report lower C change for a date in scenarios where prices continue to rise after that date (compared to constant prices). For example, Scenarios 1 and 3 have similar 2050 carbon prices of $35 and $33 respectively, but the increase in forest area through forestation relative to the reference case is disproportionately higher in Scenario 1. The land user in the model anticipates the higher prices beyond 2050 in Scenario 1, and hence increases the planting rate for long rotation forestry before 2050. Since forest growth takes time, this anticipatory behavior results in carbon benefits later in the century, but they reach a higher level relative to Scenario 3 by 2100. Similarly in Scenario 5 ($100 + 0%/year) a high carbon price early results in a large carbon gain relative to Scenario 4 ($20 + 3%/year) by 2050, but by 2100, both scenarios have the same carbon gains.

Table 5: Land area and carbon benefits gained [a] across scenarios, relative to reference case

Scenario [b]	**Carbon Price ($/t C)**		**Land Area Gained (Mha)**		**Carbon Benefits Gained (Mt C)**	
2010 C Price + Annual Increase	**2050**	**2100**	**2050**	**2100**	**2050**	**2100**
1. $5 + 5%	35	404	190	662	13,570	70,145
Forestation			68	163	5,554	33,162
Avoided deforestation			122	499	8,034	37,105
2. $10 + 5%	70	807	327	880	24,917	96,496
Forestation			108	231	10,123	47,849
Avoided deforestation			219	649	14,796	48,835
3. $10 + 3%	33	143	212	555	15,628	50,905
Forestation			52	77	4,934	16,358
Avoided deforestation			160	478	10,694	34,547
4. $20 + 3%	65	286	363	819	28,582	79,559
Forestation			75	135	8,917	28,575
Avoided deforestation			288	684	19,665	50,985
5. $100 + 0%	100	100	537	866	47,252	78,970
Forestation			83	56	13,587	17,245
Avoided deforestation			454	810	33,665	61,725
6. $75 + $5	275	275	664	1081	63,300	113,208
Forestation			192	146	25,675	38,422
Avoided deforestation			501	959	37,625	74,786

Notes:

a) Gained amount refers to the cumulative difference between a mitigation scenario and the reference case scenario by 2050 and 2100

b) All carbon prices are zero until 2009, and begin with the stated value in 2010.

The carbon price reaches $807 by 2100 in Scenario 2 ($10+5%/year), which leads to continued high rates of planting throughout the 100-year period, and the large carbon gain of 96.5 Gt C by 2100. Because the carbon price rises quickly in Scenario 6 ($75+$5/year to 2050 and constant thereafter) to $275 and stays at this relatively high level until 2100, this scenario results in the largest carbon gain of 113.2 Gt C by 2100.

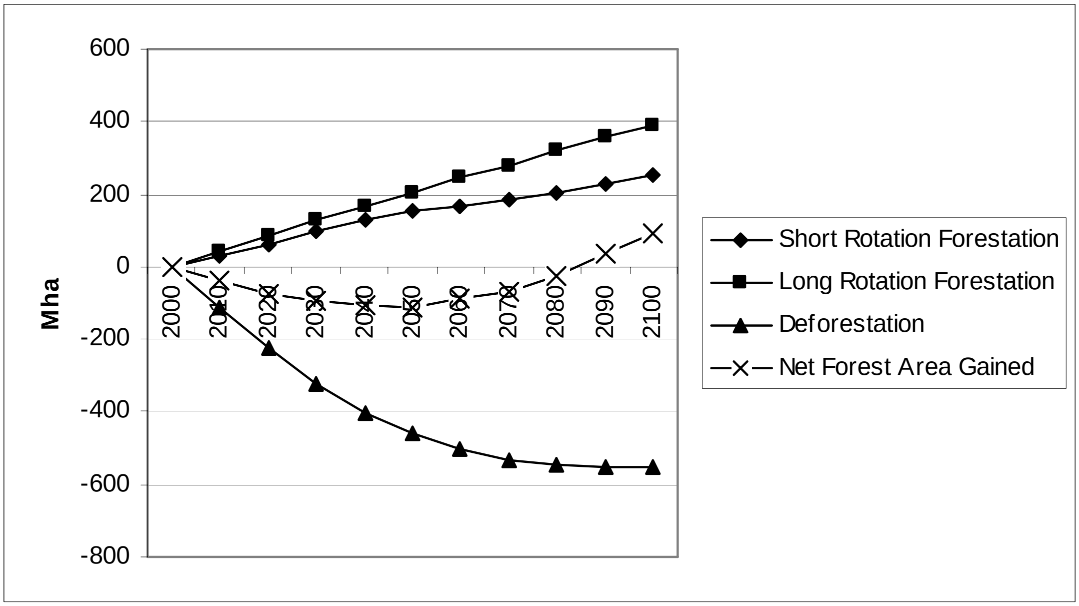
In Scenarios 5 and 6, the land area gained (relative to the reference scenario) declines after 2050. The high initial price results in a large increase in land area planted relative to the reference case up to 2050, but this declines in subsequent years as the land cap limit is approached in many regions.

Table 5 also shows the contribution of forestation and avoided deforestation to the total amount of carbon benefits and forest land area. Avoided deforestation -- although not widely reported as a mitigation option in other analyses-- contributes substantially, and accounts for more than half of the carbon benefits gained in each scenario by 2050. By 2100, the percentage of carbon benefits gained from avoided deforestation is lower or the same in the first four scenarios, but it increases in Scenarios 5 and 6. In Scenario 2 ($10+5%/year), for instance, it declines to 51%, but in Scenario 5 it increases to 78% by 2100. A slowly increasing or constant price (as in Scenarios 3 and 5, respectively) provides less incentive for increased planting in the later decades. Hence much of the carbon benefits gain from forestation occurs prior to 2050 under these price paths. Gains from avoided deforestation, however, continue past 2050.

In the reference scenario, short- and long-rotation forestry increase the area of forested land over the timeframe analyzed, but are overshadowed by deforestation practices that remove forest cover from land (Figure 5). The mitigation scenarios reverse this process by planting more land in trees and reducing the rate of deforestation. In each mitigation scenario, global forest area declines in the earlier decades, but the decline is halted and net forest area begins to increase before 2100. The decade in which the decline is halted is earlier for higher carbon price scenarios than for lower price ones. This transition is realized by 2090 for Scenario 1, for example (Figure 8).

The regional distribution of carbon gains varies across scenarios. The total amount of land available for planting is limited in each region. For instance in India and China, due to the high planting rates in the reference case, the land cap is reached in 2040 and 2050 respectively. The mitigation scenario accelerates the date by which the cap is reached depending on the magnitude, and rate of increase, of the carbon price. A similar cap is reached for long-rotation planting in Russia in the reference case by 2100. Elsewhere land availability is not a constraint to tree planting.

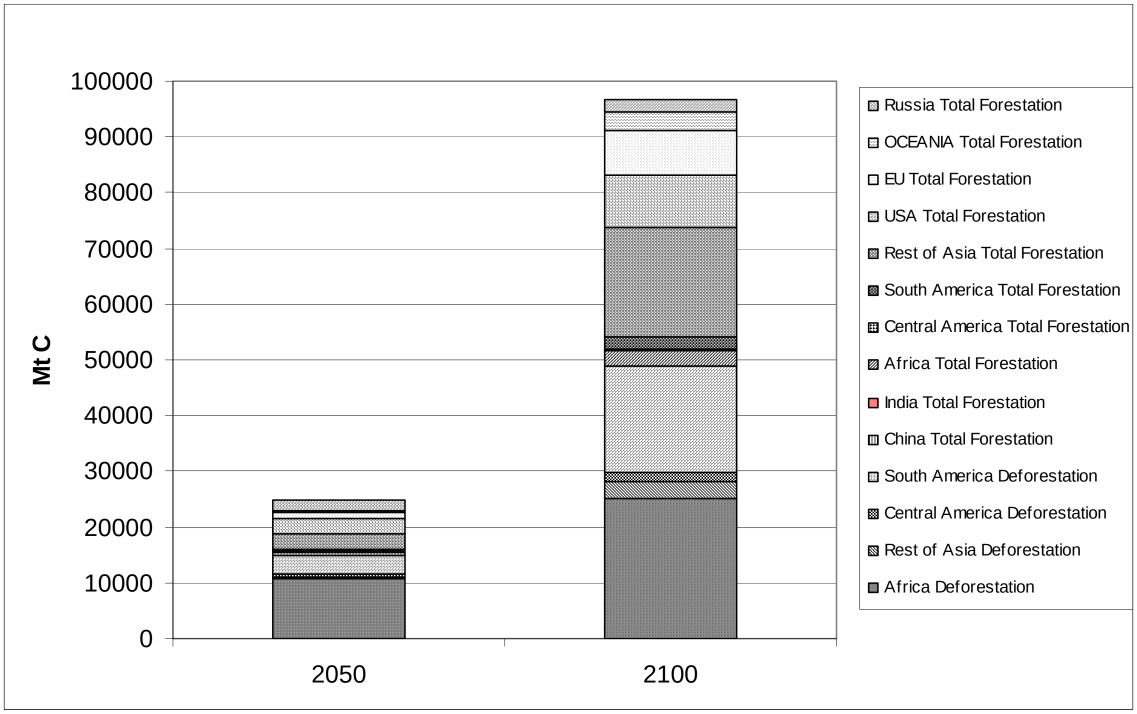
Figure 8: Scenario 1 ($5 + 5% /year) -- Land Use Change by Activity for All Regions (Cumulative to year reported)



The contribution to carbon gain varies by region over time (Figure 9). Rest of Asia, US and Russia account for the more significant carbon gains through forestation in 2050, and the first two along with the EU are the largest contributors to carbon gains in 2100. While the different rates of return and carbon dynamics have some influence, the high rates of planting in the reference case and the large availability of suitable land areas (no cap) are the main reasons for these results.

Figure 9 also shows the carbon gain from avoided deforestation by model regions. Africa and South America are the predominant contributors to this carbon gain. Africa contributes more emissions avoided earlier than the other regions. Two factors play a role. One is the absolute magnitude of deforestation in the reference case, which is high in both Africa and South America. The second factor is the opportunity cost of avoiding deforestation, which is lowest among the four regions in Africa.

Figure 9: Scenario 2 ($10+5%/year): Regional Contribution to Carbon Gain in 2050 and 2100



5.2.1 *Reducing Deforestation*

Reducing emissions due to deforestation has the potential to be an important mitigation option particularly in Africa, South and Central America and the Rest of Asia region. Population growth, extraction of timber, road network expansion, shifting cultivation for subsistence agriculture, higher agricultural prices, national debt and other macroeconomic factors, and weak forest management and protection institutions, are major contributors to deforestation (Angelsen and Kaimowitz, 1999; Bhattarai and Hammig, 2001). The contribution of these factors to deforestation varies across the regions. Timber extraction is more dominant in the Rest of Asia region, subsistence agriculture in Africa, and road building, cattle ranching and land speculation in the Americas.

Reducing deforestation would thus require that deforesters be compensated for the loss of revenue or welfare derived from these activities. It also may require that a complex web of social, economic, institutional, and land tenure barriers or conditions be assessed and addressed in any practices or policies to slow deforestation. Land in the model on which deforestation is avoided due to the imposition of a price incentive is assumed to be mature forest with the average biomass and carbon density of the dominant merchantable timber species or forest type reported in timber trade from the region. These lands continue under the reference case assumptions of timber growth and land use and land use change, except in the event that they are deforested in the future.

The results show that slowing deforestation in Rest of Asia would require higher compensation than in the other regions, since export-quality timber commands a much higher price than other products.. The global carbon price at which deforestation theoretically could be halted in Africa is lower than for other regions, due to Africa's lower opportunity cost. Since export-quality timber commands a much higher price than other products, slowing deforestation in Rest of Asia would require higher compensation than in the other regions. The global carbon price at which deforestation theoretically could be halted in Africa is lower than for other regions, due to Africa's low opportunity costs and low rate of export of wood products into international markets. The price is higher in the other tropical regions. Based on region-specific data and GCOMAP analysis, we estimate a global carbon price of $39/t C in Africa, $127/t C in Central America, $147/t C in South America, and $281/t C in the Rest of the Asia region would be sufficient to theoretically halt deforestation.[4]

Depending on the carbon price, deforestation is virtually halted in each of the four regions by 2100. A carbon price path that begins low and rises slowly means that deforestation is not halted until later in this century, and vice versa. Since the revenue derived per ha from deforestation is low in Africa, a $100 per t C price (Scenario 5) is sufficient to halt deforestation in that region, while significantly reducing it in other regions. In the highest carbon price scenario (Scenario 2), deforestation is halted by 2040 in Africa, 2060 in Central America, 2070 in South America, and by 2080 in Rest of Asia.

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[4] The corresponding net revenue amounts to $4836 $21,590, $30,723 and $41,026 per ha respectively for Africa, Central America, South America, and Rest of Asia.

Slowing deforestation is a feasible, though difficult public policy and climate mitigation strategy. Altering land use patterns and incentives requires a strong government commitment and clear policies, strict enforcement, and incentives for adoption of alternative land management practices. India, for example, passed a Forest Conservation Act in 1980, which has been reasonably well-enforced, thus slowing deforestation to a negligible fraction of its historical rate (Ravindranath et al., 1994). Elsewhere, a carbon price is likely to provide the monetary incentive to slow or even halt deforestation, but it will need to be accompanied by: (1) mechanisms to translate this price incentive into effective monetary stimuli, and (2) well-enforced policies and measures that encourage institutional change in order to provide strong disincentives to deforesters.

5.3 Welfare Gain:

The GCOMAP model also allows the computation of the gross change in welfare in the forestry sector in each region due to the higher carbon price. This would be offset by the loss in welfare in other sectors in these regions. Forestation leads to an increase and avoided deforestation to a loss in social welfare. The magnitude of the change in social welfare depends on the carbon price trajectory and level, and the proportion of carbon benefit that is derived from forestation compared to that from avoided deforestation. The largest increases in social welfare per tonne of carbon are achieved in Scenarios 1 and 2 (US $ 0.9 and 0.8/t C respectively), which have a lower proportion of carbon gains from avoided deforestation. The lowest value is for Scenario 5 ($ -2.0/t C) in which avoided deforestation accounts for 78% of the carbon benefit gains. The carbon gain per dollar of subsidy is proportional to the total carbon benefits gained. Higher carbon benefits require a higher subsidy to achieve those gains ranging from $4.0 per t C for Scenario 3 (51 Gt C gain by 2100) to a high of $20.4 per t C for Scenario 6 (113 Gt C gain by 2100). The estimated present value of cumulative welfare change ranges from a decline of $158 billion in Scenario 5 to a gain of $81 billion in Scenario 1 by 2100. The decline is associated with a decrease in deforestation.

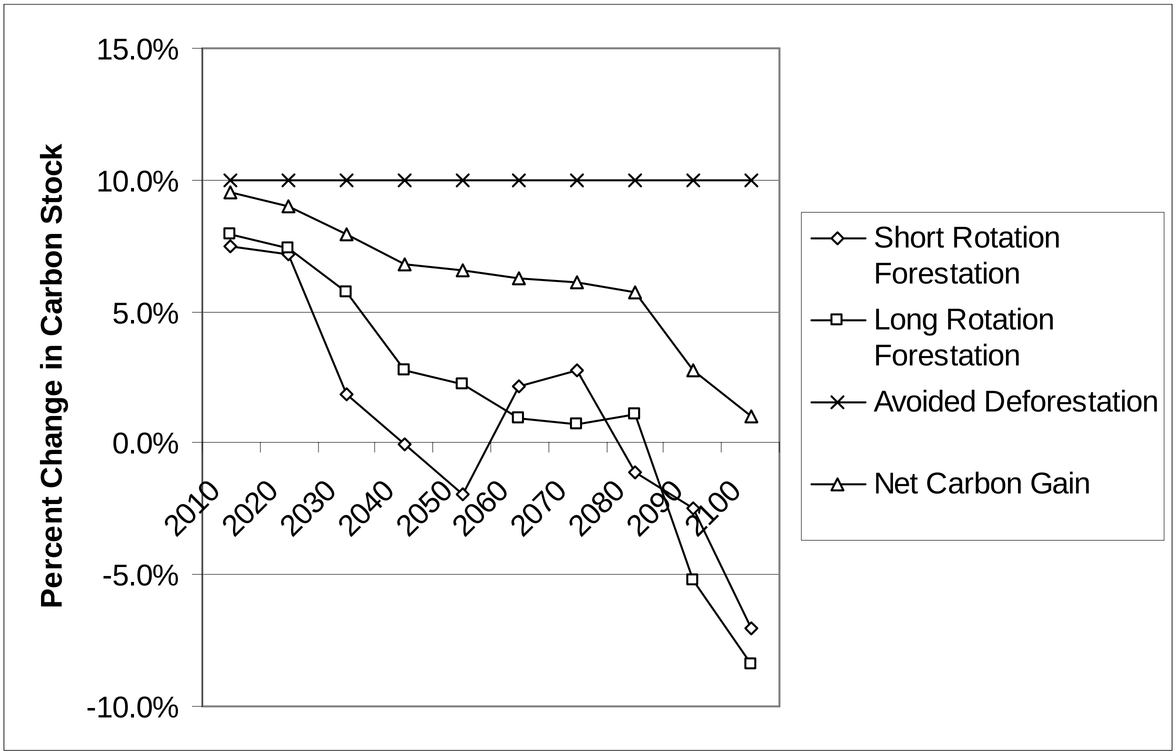
5.4 Sensitivity Analysis

We tested the sensitivity of the results of the GCOMAP model to changes in the reference case land use scenario, which forms the basis for the estimation of mitigation carbon benefits. We change the reference case land use by 10% uniformly between 2000 and 2100, and estimate the resulting change in the carbon gain for one of the carbon price scenarios (Scenario 2).

A 10% increase in deforestation rate applied to the reference case for each of the four regions, and over the time horizon of the model, caused a 10% decline in carbon gain by 2050 and 2100, and a 10% reduction caused a 10% increase in carbon gain in both years. This sensitivity run demonstrates inverse perfect correlation between deforestation rate and carbon gain. Other deforestation rate assumptions would be useful to evaluate (such as the range represented in the IPCC SRES scenarios), as would alternate land availability caps, but have not been analyzed here.

Whereas, a 10% increase in forestation in the reference case applied to each model region causes a 2% increase in carbon gain by 2050, but an 8.8% *decrease* in carbon gain by 2100 (Figure 10). The lower increase in carbon gain by 2050 is due to the higher marginal cost of land, and the cap on land area causes the reversal. For instance, in Africa, where the land cap is not reached in the model, 10% more forestation increases the carbon gain by 5.1% by 2100. However, in China and India, carbon gain turns negative by 2040 and 2030 respectively, which contributes to a sharp decline in the forestation carbon gain in those years in Figure 10. For short-rotation forestation, carbon gain turns positive in 2060 and 2070, since trees planted in earlier years accumulate carbon during those years only to lose carbon with harvests in subsequent periods. For long- and short-rotation forestation, there is a second sharp decline in 2070-2080 period as land caps are reached in other regions. The combined effect of these responses is that the net carbon gain declines from 9.5% in 2010 to about 1% in 2100. In summary, planting 10% higher land area and deforesting 10% more in the reference case would result in progressively less carbon gain over the model time horizon relative to the core scenario run. The carbon gains reported in the model are more sensitive to changes in the deforestation rate than in the forestation rate.

Figure 10: Scenario 2 ($10+5%/year) Sensitivity Analysis: Change in carbon stock for a 10% increase in reference case forestation and deforested area



6 Conclusions

This paper describes a dynamic partial equilibrium global forest-sector model (GCOMAP) incorporating a reference case based on bottom-up data for the tropics from the COMAP model, region-specific data from several sources for the temperate countries, and FAO data on regional forestation and deforestation rates. The model estimates the additional land area that will be forested, and/or the additional deforestation that will be avoided, in response to potential future carbon prices. It tracks changes in carbon stocks in vegetation, soils and products over time.

By 2100, for six carbon price scenarios, the model estimates a global gain in carbon benefits between 50.9 Gt C and 113.2 Gt C. The time profile of carbon gains follows the carbon price trajectory; higher prices earlier lead to more carbon gain sooner, and vice versa. Reduced deforestation emerges as a dominant mitigation option. It accounts for 51% to 78% of carbon benefits gained by 2100. The percentage contribution generally increases from Scenarios 1, 2 and 3, which have low initial carbon price and/or a slowly rising one, to Scenarios 5 and 6 with higher initial prices.

Several analytic and policy implications of this analysis emerge. First, avoiding deforestation could be a significant, near-term option in Africa in particular. The ability of policymakers, local communities, and NGOs to assess existing land use practices and socioeconomic conditions, and to develop practical alternatives acceptable to land users, could determine whether this option is feasible.

Second, the potential for avoided deforestation is heavily dependent on levels of projected forest land use change, estimates of which remain uncertain, and on assumptions of future trends of land use and forest loss, which vary across analyses. Detailed assessment of the complex assumptions within the IPCC SRES scenarios of land use change over time, by region, and of potential alternatives to them, is needed to improve estimates in a range of models of the potential for reducing deforestation and of land availability for forestation. A range of simple sensitivity analyses may offer a first step forward.

Third, our estimates of land availability are crucial to the estimates of carbon gains for the forestation options. Thus our ability to estimate land allocation and costs, and identify the conditions when land is biophysically, economically, and institutionally available, drives the potential realization of forestation options. Land use competition among the forest, agriculture and grazing sectors is needed to improve land availability assumptions. A better determination of the availability of wastelands in the tropics (estimated in GCOMAP, but not in some other sectoral and CGE models) would strengthen estimates of the quantity and cost of what appear to be very large-scale forestation mitigation options in tropical regions.

Fourth, the use of biofuel timber products as a substitute for fossil fuels offers a way to greatly expand the potential for carbon mitigation from forestry. Thus, a land use cap, would not put an absolute limit on a region's forestry mitigation potential, but would only place a limit on the annual magnitude of avoidance of carbon emissions from fossil fuel combustion.

Fifth, improved, regionally disaggregated data are needed on the price elasticity of forest land, and the elasticities of timber demand and supply. Only scant and dated data are available, but the elasticities assumed are central to the analyses presented here and in other models.

Sixth, even the modest carbon prices of Scenario 3 ($10 initially, rising at 3%/year) could generate as much as 50.9 Gt C by 2100, the majority from avoided deforestation. If economic incentives of this level could be introduced over the period of this analysis, and we can identify the conditions where such options are feasible, a substantial reduction of carbon emissions or increased sequestration could be produced. Additional analysis is needed of the socioeconomic and biophysical conditions under which specific, introduced economic incentives are likely to be efficient and implemented successfully, as well as the necessary infrastructural and technology transfer or training requirements.

Finally, mitigation activities to reduce emissions or increase sequestration in the land use sector will need to address the timing (i.e., the start and duration) as well as magnitude of economic incentives, since delays in incentives tend to delay land use change decisions.

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APPENDIX A

Table A1. Input data for Africa and Central America

(Cost and price data are in 2000 US $, converted from local currency using market exchange rates)

	Notes	Africa		Central America	
Variable Name		***SR****	***LR****	***SR***	***LR***
Initial Cost (Land cost + Establishment Cost) ($/ha)	a	871	1104	415	394
Recurrent Cost ($/ha/yr)	b	121	116	30	17
Monitoring Cost ($/ha/yr)	c	0	0	8	24
Harvesting and Transport Cost($/m^3)	d	38	38	60	80
Timber domestic market price($/m^3)	e	63	150	35	98
Timber international market price ($/m^3)	f	128	242	65	175
% of timber exported	g	10.50%	26.50%	6.50%	12.30%
Max area dedicated to SR & LR afforestation (mi ha)	h	80	120	20	21.5
Area planted so far (mi ha)	i	3.3	4.8	0.3	1
Planting rate in base year (Kha/yr)	j	80	115	20.3	61
Base-year Vegetation C-stock (t C/ha)	k	56.8	38.8	30.2	42
Rotation Period (Yrs)	l	13	29	7	20
Mean annual increment (t biomass/ha/yr)	m	29.1	18.5	8.7	4.9
Deforestation rate (Kha/yr)	n	5264		958	

SR: Short-rotation, LR: Long-rotation.

Africa

a, b, d: From Makundi (2001) and adjusted by wage index for the region.

c: Monitoring is combined with recurrent cost.

e, f: Data for exports from United Nation Food and Agricultural Organization (FAO (2002)), and for domestic prices from FAO (2000).

g: Based on 2000 exports and domestic production data from (FAO, 2002).

h: Annual deforestation rate of 4 mi ha in the last 30 years is projected to persist up to 2020. We assume that 50% of the deforested land will be available for forestation. We also assume that at least another 100 mi ha of grassland and abandoned agricultural land will also be available for reforestation. : FRA2000.

i: FAO (2000), Global Forest Products Outlook Study (GFPOS).

j: Planting rate for 2000 FAO (2003a), Table 4 FAO (2001). We used annual planting rate for 2000 since historical forestation rates have been relatively low **k:** Data used in COMAP, analysis Makundi (2001).

l, m: Weighted average for existing plantation species in the region**,** FAO (2000).

n: FAO (2003b) Table 2, annual average for 1990 –2000

Central America

a, b, c: Fearnside (1995).Brazil data was adjusted by wage index for the region.

d: Mexico data Masera et: al (2001) was used for all of the region.

e, f: Tropical Timber Market Report, Jan 1 2003, Brazil Pine sawlog price From International Tropical Timber Organization (ITTO (2003)).

g:: From State of the World’s Forests, FAO (2003). The data is for 2000.

h: Includes degraded and deforested lands. From Forest Resource Assessment 2000 (FRA2000), FAO (2001).

i: FAO (1997), Chapter 3, Table 3-1. Assume 75% was for planting SR species.

j: From ITTO Annual Review Issues 1990 – 2000, Table 6-1, for annual planting rate.

k: Fearnside (1995) Table I. The value is for Brazil deforested areas

l, m: Masera (2001) Table IX estimate Mexico is applied for the region.

n: FAO (1993; 2001). Average for 1980-2000.

Table A1 (continued). Input data for China and India

(Cost and price data are in 2000 US $, converted from local currency using market exchange rates)

	Notes	**China**		**India**	
Variable Name		***SR****	***LR****	***SR***	***LR***
Initial Cost (Land cost + Establishment Cost) ($/ha)	a	245	245	340	778
Recurrent Cost ($/ha/yr)	b	12	3	19	19
Monitoring Cost ($/ha/yr)	c	12	3	2	2
Harvesting and Transport Cost($/m3)	d	60	40	49	40
Timber domestic market price($/m3)	e	150	200	123	421
Timber international market price ($/m3)	f	250	450	483	915
% of timber exported	g	5.00%	1%	0.50%	0.50%
Max area dedicated to SR & LR afforestation (mi ha)	h	35.9	27.1	10.2	11.6
Area planted so far (mi ha)	i	27.2	20.5	15.2	16.8
Planting rate in base year (Kha/yr)	j	814	614	307.4	346.6
Base-year Vegetation C-stock(t C/ha)	k	25	25	1	1
Rotation Period (Yrs)	l	15	42	14	34
Mean annual increment (t biomass/ha/yr)	m	9.9	6.5	18.9	9
Deforestation rate (Kha/yr)	n	NA	NA	NA	NA

* SR: Short-rotation, LR: Long-rotation

China

a, b, c: Weighted average for NE, SE & SW regions. From Xu et al,(2001).

d: Xu and Zhang (2002), estimate that 40% of the product price goes towards harvesting and transport

e, f: FAO (2002) Forest Products Year book, 2000 and Xu et al, (2001).

g: Average for 1996-2000, FAO (2002)

h: According to China's Long-term Nationwide Environmental Restoration Plan (PEER), China plans to raise the forest area to 26% of the land area which would involve adding 117 mi ha of forests by 2050, of which 63 mi ha will be for timber production. . Compiled from National Forest Resources Inventories (NFRI) I – IV, with the planting schedules adjusted for survival rate, minus the 11.5 mi ha of non-timber forests e.g. bamboos and orchards. From FAO (2001); CMOF (2000).

i: FAO (2000) – Global Forest Products Outlook Study.

j: Current stated planting rate adjusted for survival rate of 80% (Zang, 2001).

k: Original COMAP runs for wastelands.

l, m: Weighted average for individual spp, with LR/SR decided on the basis of rotation age.

n: Deforestation rate is assumed to be negligible.

India

a: Sum of Investment cost + Discounted value of costs in years 1 & 2 – Ravindranath et al (2001).

b: From COMAP: 500 Rupees/ha/yr @42Rupees/$, Source: Ravindranath, (2001).

c: From COMAP: 100 Rupees/ha/yr @42Rupees/$, Source: Ravindranath, (2001).

d: We estimate 40% of millsite domestic log price for SR & 10% of LR price mostly due to price differential while cost of operations, machinery and fuel is still as high as that of LR.

e: LR average for Teak, Sal & Shisan, girth 91-120 cm, SR average Sal, Eucalyptus and Populus, all f.o.b. at Agra, Chandagar and Ambala from RSMD (2001).

f: LR average for Teak, Sal and Shisan grade A (girth 151cm), SR Shorea Robusta all f.o.b. at Agra, Bareily & Shahampur: Source FRI 2000 Market Report, (2001).

g: Average RWE for 1996-2000. India exports 3% of Wood-based products and 1% of Pulp output.

h: National Action Plan proposes to increase Forest Cover by 33% (21.8 mi ha) over 20 yrs- FAO, (2001).

i: Sum of all areas under forest plantations up to 2000 (FAO, 2001).

j: Same target as NFAP of 1.09 mi ha/yr, adjusted by survival rate of 60% and existing LR: SR ratios.

k: Mostly, shrub and grass wastelands (Ravindranath, 2001).

l, m: Weighted average (by area) for all major plantation species in India – Source FSI (1999). n: NA – Not applicable. Net zero deforestation assumed.

Table A1. Input data for Rest of Asia and South America

(Cost and price data are in 2000 US $, converted from local currency using market exchange rates)

	Notes	**Rest of Asia**		**South America**	
Variable Name		**_SR*_**	**_LR*_**	***SR***	***LR***
Initial Cost (Land cost + Establishment Cost) ($/ha)	a	467	1034	716	716
Recurrent Cost ($/ha/yr)	b	13	27	34	30
Monitoring Cost ($/ha/yr)	c	39	40	28	24
Harvesting and Transport Cost($/m3)	d	64	64	0	0
Timber domestic market price($/m3)	e	80	161	6	15
Timber international market price ($/m3)	f	250	250	6	60
% of timber exported	g	15%	26.50%	28.10%	16.60%
Max area dedicated to SR & LR afforestation (mi ha)	h	50	150	150	150
Area planted so far (mi ha)	i	6.4	19.2	7.8	2.6
Planting rate in base year (Kha/yr)	j	365	1095	283.5	79.5
Base-year Vegetation C-stock(t C/ha)	k	74	74	30.2	30.2
Rotation Period (Yrs)	l	10	35	6	25
Mean annual increment (t biomass/ha/yr)	m	17.6	14.0	13	8.6
Deforestation rate (Kha/yr)	n	2235		3711	

* SR: Short-rotation, LR: Long-rotation

Rest of Asia

a, b, c, d: Data for Indonesia adjusted by Wage rate index for the region – Boer (2001).

e, f: FAO (2002), 2000 Indonesia f.o.b. prices.

g: FAO 2002 average export data 1996 - 2000

h: A portion of the vast degraded forests and grasslands, especially in Indonesia, Malaysia and other continental SE Asian countries e.g. Myanmar, Laos, Thailand, Cambodia etc – FAO (1993; 2001).

i: FAO, (2001), also from GFPOS FAO,(2000). **j:** Average from FAO,(2003) Table VI, State of Forests.

k: ITTO Table VI Annual Review Issues 1990-2000.

l, m: Weighted average for Indonesian plantation species with 75%LR. Assumes Indonesia biomass data is representative of the region.

n: FAO, (2001) Data is average for 1990-2000

South America

a, b, c: Data for Brazil adjusted by wage index for the region: Fearnside, (2001).

d: The price used is stumpage, as such we exclude harvesting and transport.

e, f: Tropical Timber Market Report, Jan 1 2003, Brazil Pine sawlog stumpage price. (ITTO (2003)).

g: FAO (2003) export data.

h: Mostly from deforested lands and cerrados. The Brazilian Amazon alone had 42.7 million ha deforested through 1991 from the original 500 mi ha of the Legal Amazon (Fearnside, 1997).

i, j: From FAO (1997) Chapter 3, Table 3.1. From ITTO Table 6-1, Annual Review, 1990 - 2000 annual planting rate. We assume 75% will be in short rotation. In 1995 95% of afforestation in Brazil was in SR (Fearnside, 1997)

k: From Fearnside (1995), Table 1.

l, m: Fearnside,(1995) Time between harvests is 6 years; 3 coppices, 24 year replanting cycle.

n: FAO (2001) Deforestation area is annual average for the period 1990-2000

Table A1. Input data for the EU and Oceania

(Cost and price data are in 2000 US $, converted from local currency using market exchange rates)

	Notes	EU		Oceania	
Variable Name		***SR****	***LR****	***SR***	***LR***
Initial Cost (Land cost +Establishment Cost)($/ha)	a	1068	1068	1598	1897
Recurrent Cost ($/ha/yr)	b	80	80	11	11
Monitoring Cost ($/ha/yr)	c	13	13	1	1
Harvesting and Transport Cost ($/m3)	d	42	42	7	7
Timber domestic market price ($/m3)	e	127	93	27	53
Timber international market price ($/m3)	f	160	110	53	86
% of timber exported	g	52%	52%	38%	38%
Max area dedicated to SR&LR afforestation (mi ha)	h	40	50	28	42
Area planted so far (mi ha)	i	3	6.1	71	106.4
Planting rate in base year (Kha/yr)	j	63.7	148.6	3	10.7
Base-year Vegetation C-stock (t C/ha)	k	59	8.8	64	64
Rotation Period (Yrs)	l	45	100	19	44
Mean annual increment (t biomass/ha/yr)	m	11.6	6.9	18.5	10.1

* SR: Short-rotation, LR: Long-rotation

EU

a, b, c: Based on EU agricultural subsidy data for land rental. FAO (2000). Recurrent cost source IMAGE.

d: We assumed the cost is the same as that used for the US.

e, f: Timber trade statistics, FAO (2002)

g: Roundwood equivalent (RWE) weighted average of Industrial roundwood, Sawnwood, Wood-based panels, Pulp, paper and Paperboard for year 2000 (FAO, 2002)

h: EU has woodlands estimated at 133 mi ha (ECE/FAO, 1992).

i: Land planted with Industrial forest plantations since 1930 – up to 1998. From: Appendix 3, GFPOS, 1999.

j: Average rate between 1981-1995. Source: FAO (2000)

k: For SR we used average standing biomass in EU forestlands and LR we assume will be on sparsely wooded lands pasturelands and abandoned croplands Source of data: ECE/FAO 1992.

l, m: Average for Populus spp, Eucalyptus, Salix, Picea and Abies for SR, and for LR for mixed and coniferous forests, with Rotation age at 100 though some of the species have much longer rotation age.

Oceania

a: Includes land rental and establishment cost. Estimates for industrial plantations in Australia and New Zealand (excluding fencing). Sources: Dixon et al (1991) and Lyons (1997a; 1997b).

b, c: Equivalent to costs for management plans, consultancy, etc for Southwest Australia industrial plantations. Monitoring is estimated at 10% of recurrent cost.

d: Costs for New England region (NSW) of Australia, 2002. Average for 100 km distance to the mill or port: Source: Lyons, (1997a,b).

e: Average for NZ on South and North island. Source: NZ Forest Industries (June 2002); MAF (2002).

f: Export price for Industrial Roundwood Wood for Australia.

g: Average Roundwood equivalent for 2000. FAO, (2002) (FP Yearbook.

h: Assume 20% of Australia sparse forest area, with the rest from croplands and grasslands. Papua New Guinea from deforested lands and 5 mi ha each from New Zealand and Japan.

i, j: FAO, (2000). Average planting rate 1970-1990.

k ,l, m: Vegetation Stock from ECE/FAO, (1992). MAI and Rotation average for spp in Australia &NZ.

Table A1. Input data for Russia and the US

(Cost and price data are in 2000 US $, converted from local currency using market exchange rates)

	Notes	Russia		USA	
Variable Name		***SR****	***LR****	***SR***	***LR***
Initial Cost (Land cost +Establishment Cost)($/ha)	a	123	123	1744	2277
Recurrent Cost ($/ha/yr)	b	1	1	30	29
Monitoring Cost ($/ha/yr)	c	1	1	13	13
Harvesting and Transport Cost ($/m3)	d	16	16	42	42
Timber domestic market price ($/m3)	e	49	20	127	93
Timber international market price ($/m3)	f	78	31	160	110
% of timber exported	g	27%	30%	16%	16%
Max area dedicated to SR&LR afforestation (mi ha)	h	37.5	20.2	50.1	65.9
Area planted so far (mi ha)	i	7.4	4	18.2	24.1
Planting rate in base year (Kha/yr)	j	371	200	417.3	548.6
Base-year Vegetation C-stock (t C/ha)	k	21	21	8.8	8.8
Rotation Period (Yrs)	l	60	100	45	100
Mean annual increment (t biomass/ha/yr)	M	2.7	3.6	6.3	8.1

* SR: Short-rotation, LR: Long-rotation

Russia:

a: Based on cost data from Khosika Project (KFE, 2000) and Petrov, (2001).

b, d: Data from Vologda Reforestation Project (VOLOGDA 1994) and Saratov Afforestation Project (RUSAFOR ,1994). .

c: Excludes project development monitoring cost - (KFE, 2000) and VOLOGDA (1994).

e, f: Source: Petrov (2001) for inland exports (c.i.f. Finland millgate) and other export timber from FAO (2002).

g: From FAO, (2002), data for 2000, with SR represented by non-coniferous industrial roundwood.

h: Current reforestation rate is 26% the unforested land (degraded from past activities) under Federal Forest Service (FFS) and the rest is left for natural regeneration) (NEAP, 1997). We assume this rate will rise to 50%.

i, l, m: Data from US Country Study Final Report, (Izrael and Avdjushin, (1997).

j: Used average rate for 1983-93 (NEAP 1997).

k: From Russian Forestry Handbook, (1995) and Israel and Avdjushin, (1997).

USA:

a: Present Value@7% of weighted average of land rental and establishment cost. Compiled from data for Cropland & Pasture on Wet soils and all non-grazing forestland from the major land use regions in US, i.e., North East, Appalachian, South East, Lake States, Corn Belt, Delta States, Northern Plains, Southern Plains Mountain and Pacific (Moulton and Richards, 1990). The Discount rate is equal to the cost of capital in forest investments in the US (Dale, 2003).

b: Assumed 10% of establishment cost**:** EPRI estimate of max $5/acre for certification and audits in Central and Western US mine land reclamation programs. file http://www.wws.princeton.edu/cgi-bin/byteserv.prl/~ota

d: Harvest and transport as per Weyerhauser operation in Appalachia. Source: Roskovensky (June 2000). Also from Kerstetter and Lyons, (2001).

e, f: Forest product prices Pacific North West (PNW) for export and Southern States for domestic prices. (Timber price Statistics).

g: Current export ratio for Industrial roundwood, Sawnwood, wood-based panels, pulp, paper and paperboard in RWE, weighted by volume using standard conversion factors. (FAO 2002)

h: Total available cropland, pastureland under wet and dry soils plus non-grazing forest lands. (Moulton and Richards, 1990)

i: Area planted between 1930-2000. (Moulton et al, 1996; FAO 2000).

j: Average planting rate 1975-1995. (Moulton, 1996).

k: Standing biomass of woodland for woodland, pastureland and cropland respectively (max 1.4, 0.3, 0.1), averaging 0.6 m3/ha/yr over the rotation), with a 1.2 Expansion factor, adjusted for wood density..

l, m: Weighted average from the main plantation species grown in the 10 regions listed in “a” above (Moulton and Richards, 1990)