Costs and Carbon Benefits of Global Forestation and Reduced Deforestation in Response to a Carbon Market[1]

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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 four carbon price scenarios from 2000 to 2100. 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). Four carbon price scenarios two starting in 2013 and the other two in 2015 with carbon prices ranging from \$20 to \$35 per t* CO_2 *were analyzed. Key findings of this work are that cumulative carbon gain ranges from 126.6 to 145.5 Gt C by 2100, higher carbon prices early lead to earlier carbon gain and vice versa, and avoided deforestation ranges between 52% and 48% of modeled carbon gains in the extreme scenarios by 2100.*

[1] This report is based on an earlier publication –Sathaye J. Makundi W., Dale L., Chan P. and Andrasko K. (2006). GHG Mitigation Potential, Costs and Benefits in Global Forests: A Dynamic Partial Equilibrium Approach. *The Energy Journal-Special Issue – Multigas Greenhouse Gas Mitigation.* LBNL – 55743

1. INTRODUCTION

Forests play an important role in the global carbon cycle. An estimated 1,036 Gt CO_2 is stored in living biomass within the 3.95 billion hectares of tropical, temperate and boreal forest areas (IPCC, 2007, Table 9.1). Carbon stored in forest vegetation (living biomass) accounts for a third of the stored carbon; the rest is stored in forest soils (Watson et al. 2000). Additional carbon is stored in tropical savannas and temperate grasslands. Carbon dioxide annual average emissions from deforestation are estimated to be 5.8 Gt CO_2/year for the 1990s (IPCC 2007). Another IPCC publication reports a terrestrial sink for the decade 1993-2003 at 3.3 Gt CO2/yr (IPCC 2007a). IPCC (2007) reports a wide range of estimates for the annual carbon flux during the 1990s. For land observations, global flux ranges from 4.0 Gt CO2/yr (FAO 2006a) to 8.49 Gt CO2/yr (Olivier et al. 2005). The high end of the range includes emissions from bog fires and from soils after land use change.

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 and regions. In its recent review of these studies, the IPCC the economic potential at costs up to US $100/tCO2-eq to range from 1.3-4.2 GtCo2-eq/yr (average of 2.7 GtCo2-eq./yr) in 2030 (IPCC 2007). About 60% or 1.6 GtCo2-eq./yr can be achieved at a cost under US $20/tCO2-eq. with large differences between regions. Global top-down models predict far higher mitigation potentials of 13.8 Gt CO2-eq/yr in 2030 at carbon prices less than $100/tCO2-eq. Regional studies may be more accurate since they tend to use more detailed data and a wider range of mitigation options, and better reflect regional circumstances and constraints.

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. A major goal of GCOMAP is to make use of detailed country-specific activity, demand, and cost data on mitigation options and land use change by region. 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.

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 four 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. Figure A illustrates the various components in GCOMAP. The ten world regions covered by the model and as utilized in the modeling process are listed in Table 2. More detailed description of the model structure, approaches, and data are presented in two papers (Sathaye et al., 2005 and Sathaye et al. 2006), 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, modified to account for delayed investment schedule due to real world barriers and market imperfections. 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)

Figure A: Schematic illustrating various components in GCOMAP (Source: Sathaye et al. 2008, Presentation to the World Bank, Washington D.C, May 27)

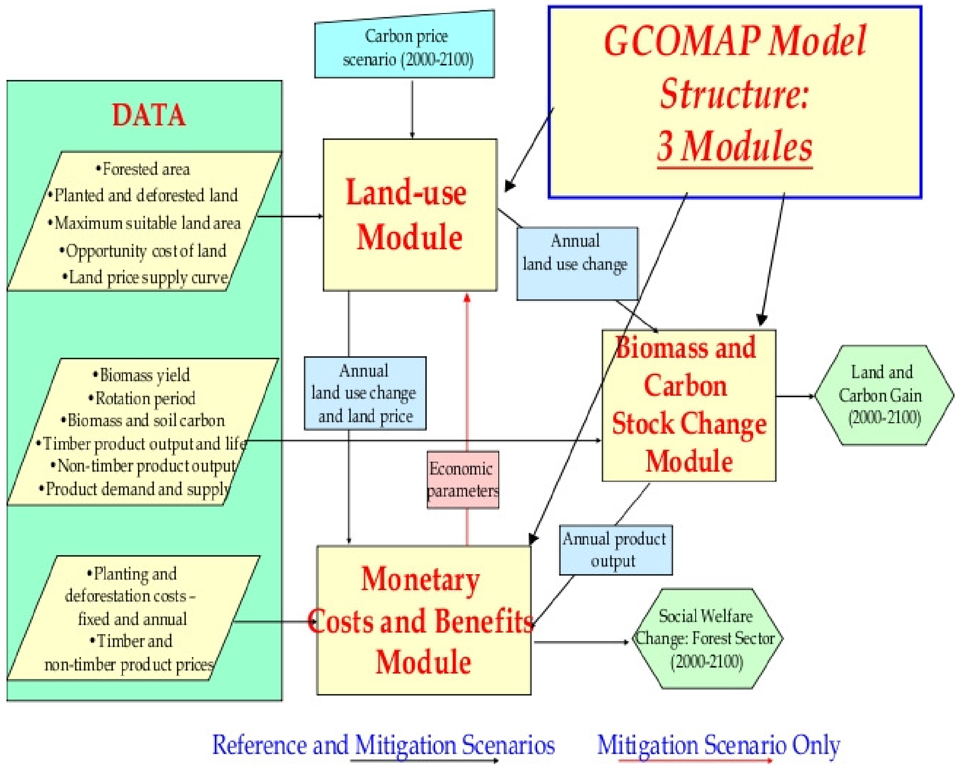


Table 2: Mitigation options, regions , and carbon pools in GCOMAP

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)	

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.

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. 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.[2] The carbon stock module tracks annual changes in carbon stocks in ten carbon pools (Figure A): 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.

[2] 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).

The GCOMAP model reported earlier (Sathaye et al. 2005 and Sathaye et al. 2006) used a perfect foresight approach, whereby a farmer or deforester would anticipate future carbon price paths and in response immediately begin to change the mitigation land area. In the current model, this process is slowed by up to 20 years to account for time delays that may be caused by real world barriers, market failures, and regulatory processes.

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 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[3]. 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. 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.

[3] 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.

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. 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 (Makundi and Sathaye, 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. 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.[4] 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).

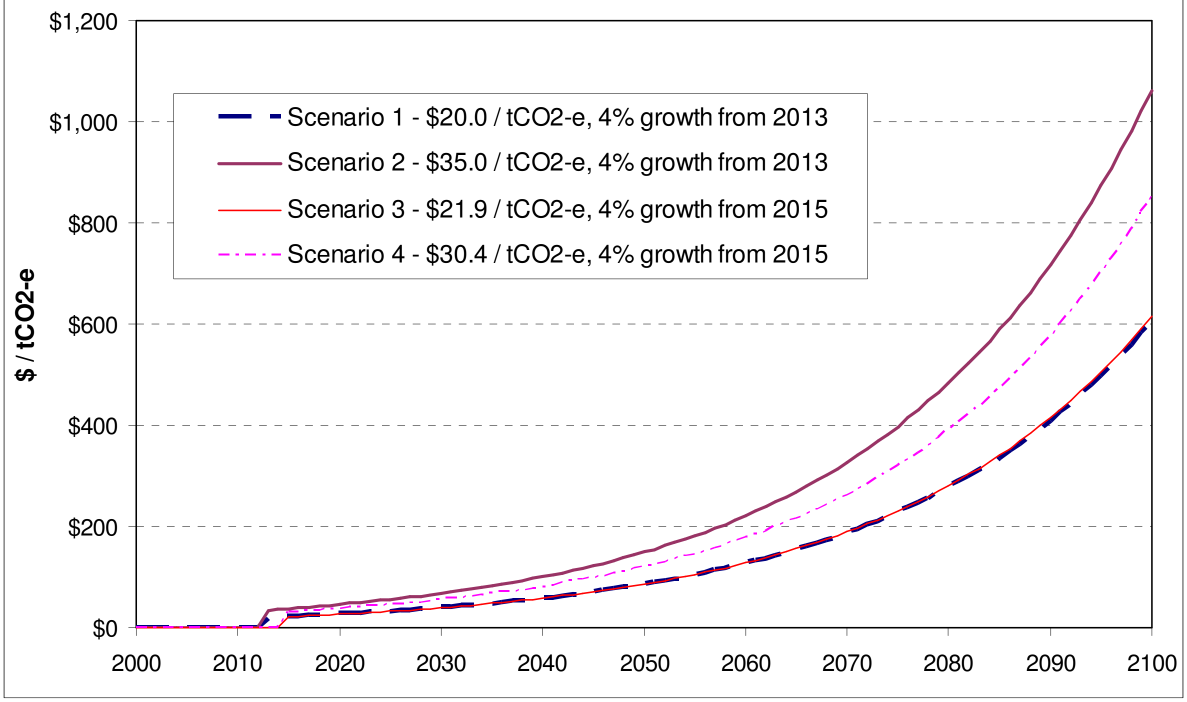
4. Scenarios

We analyze the incremental effect of four 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 four mitigation scenarios were developed for use in the Australia Review, and have different initial carbon prices and follow varying carbon price paths. The four carbon price scenarios are illustrated in Figure 1. Carbon price in each scenario increases at 4% per year. Scenario 1 has the

[4] 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

initial carbon price of \$21.90/t CO_2 in 2015, and Scenario 2 has a much higher initial price of \$35 / t CO_2 in 2013. Scenarios 3 and 4 have initial prices of \$20.0 and \$30.4 / t CO_2 in 2013 and 2015 respectively. The timing of carbon gains and the relative contributions of forestation and avoided deforestation in these four scenarios is different. The first and third scenarios are below \$100/tCO_2 in 2050, and reach about \$600/t CO_2 by 2100. The second and fourth scenarios reach \$1070 and \$650/ t CO_2 by 2100.

Figure 1: Carbon Price Mitigation Scenarios



4.1 Reference Scenario – Land Use Change

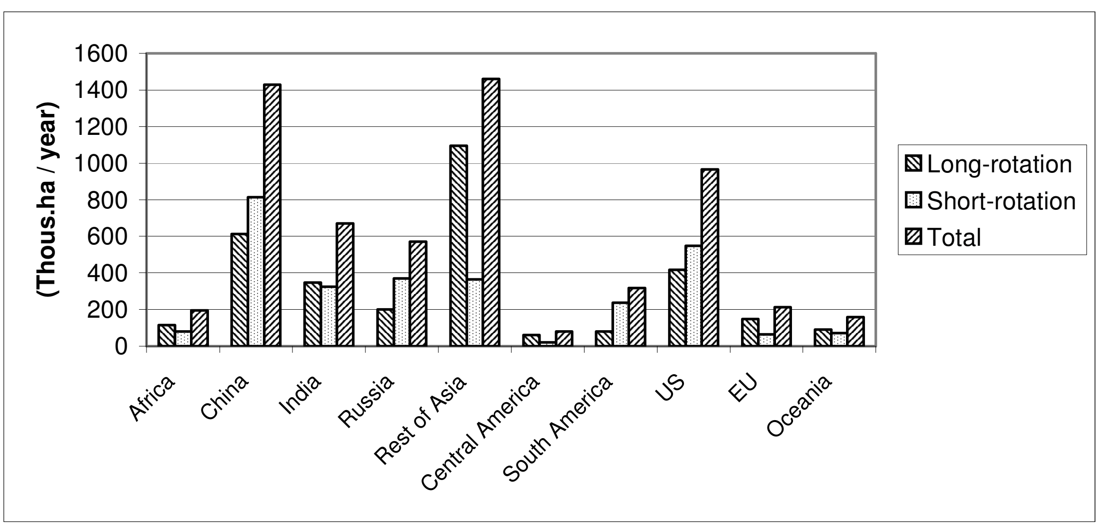
The amount of carbon sequestered through forestation and that released through deforestation depend critically on future reference case scenarios of land use change. Below, we describe the

elasticity of 1 reported for India and Oceania was considered uncharacteristically high and was excluded from the average.

historical land use change patterns, and our estimated availability of lands that may be suitable for tree planting in each region.

<u>Forestation</u>: 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. 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.

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.

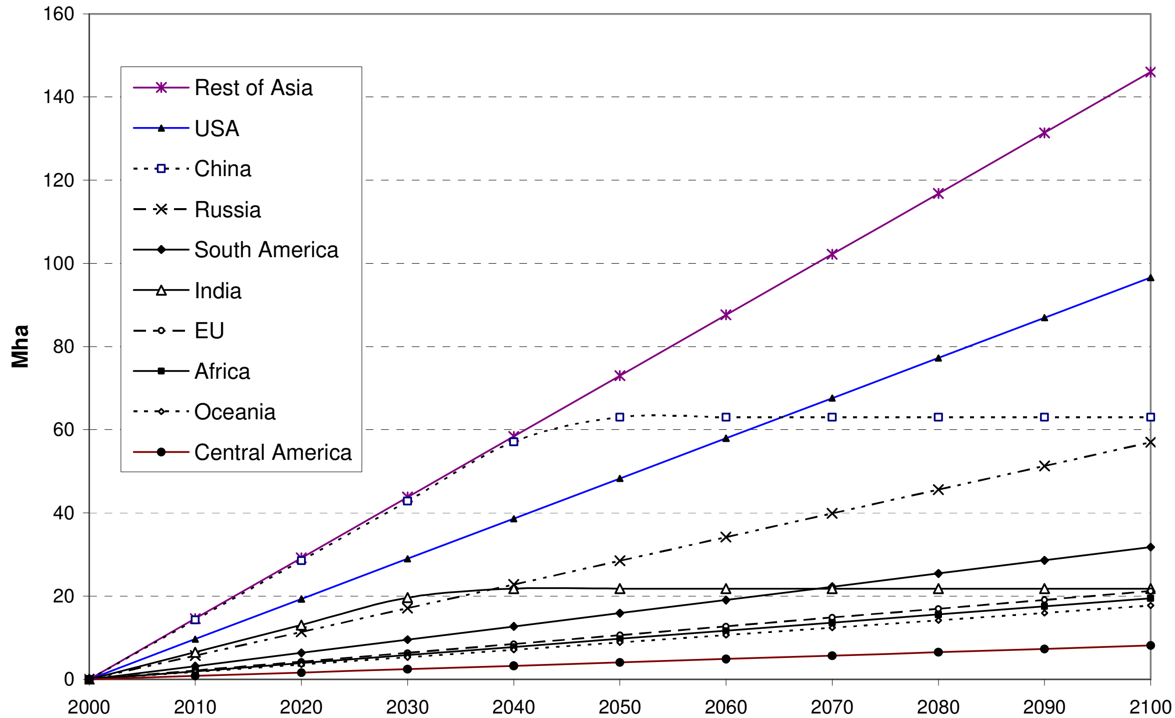
Finally, in China and India notably, but to some extent in Russia, the total land area is large but only a small fraction is suitable for planting. Table 3 shows the land area (including previously deforested land) that is deemed suitable for planting in each region. The comments column explains the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

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	

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.

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



Deforestation: 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). More recent FAO data indicates that the deforestation rate has slowed between 2000 and 2005 (FAO 2007). 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 (2004-

2007) from Brazil indicates that the decline may have accelerated during this period. Africa's rate of deforestation is still rising in step with its rural population's continued dependence on agriculture and primary resources.

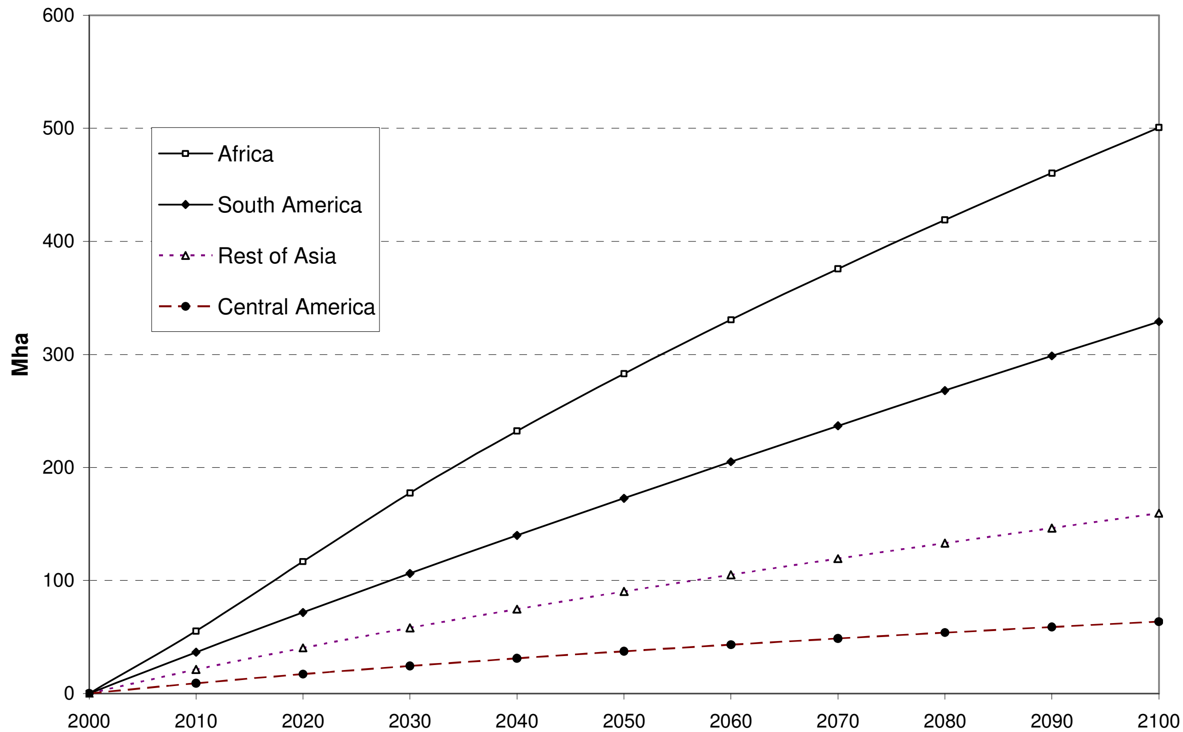
Table 4 shows the annual percent change in deforestation rates for 1990 and 2000, and our projection of the deforestation trend to 2100 for each of the four tropical regions. The deforestation rate during the last decade increased in Africa at 0.026% per year, while it declined in the other three study 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.

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.

5. Results

We analyze four 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.

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

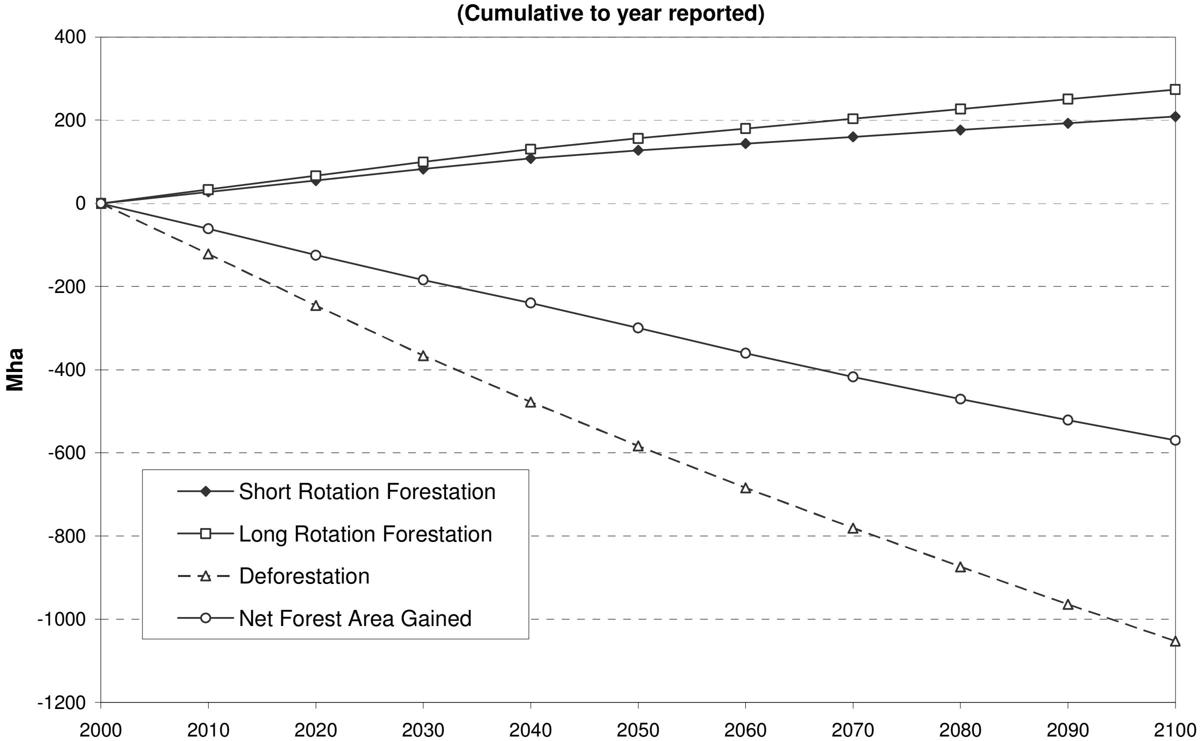
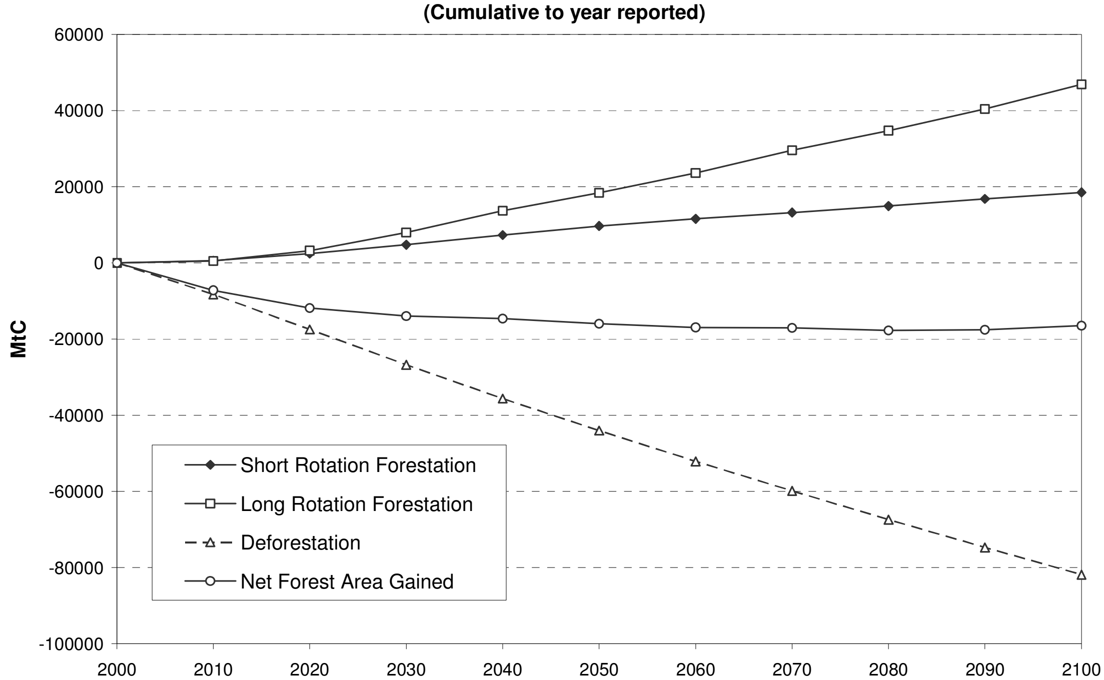


Figure 6 shows the changes in carbon stock in the reference case. Carbon stock declines until 2080 and then increases up to 2100. The decline in the earlier years is caused by the higher deforestation rates in the earlier decades. In the latter decades, deforestation rates decline and carbon stocks from 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 stabilizes after 2080. 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 27.7 Gt C stock and the US 15.4 Gt C stock in 2100 out of a total stock of 65.4 Gt C in short- and long-rotation forestry.

Figure 6: Reference Case - Carbon Stock Change (Cumulative to year reported)



5.2 Mitigation Cases

Table 5 shows the results for carbon sequestration and emissions avoided in the four carbon price scenarios for 2050 and 2100. The land area and carbon benefits gained in the price scenarios are consistent with the trends in carbon prices for the four scenarios. We focus our discussion below on a low and a high carbon price path scenario, i.e., Scenarios 1 and 2. Scenario 1 has a $21.90

initial price in 2015 rising at at 4%/year reaching $614 by 2100 and Scenario 2 has a $35 initial carbon dioxide price in 2013, rising at 4%/year that reaching $1062 by 2100. Scenario 1 has the lower amount of land area and carbon benefits gained by 2050 and 2100. The results for Scenario 3 are very similar to those for Scenario 1 and those for Scenario 4 lie in-between Scenarios 1 and 2.

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

Scenario [b]	**Carbon Price (\$/t CO_2)**		**Land Area Gained (Mha)**		**Carbon Benefits Gained (Mt C)**	
CO_2 Price + Annual Increase	**2050**	**2100**	**2050**	**2100**	**2050**	**2100**
1. \$21.90 in 2015+ 4%	\$86	\$614	587	1,181	47,644	126,639
Forestation			220	345	20,383	61,624
Avoided deforestation			366	836	27,261	65,016
2. \$35 in 2013 + 4%	\$149	\$1,062	728	1,319	62,822	145,541
Forestation			306	428	31,136	76,043
Avoided deforestation			422	891	31,686	69,498

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 2012, and begin increasing with the stated value in 2013.

Scenario [c]	**Carbon Price (\$/t CO_2)**		**Land Area Gained (Mha)**		**Carbon Benefits Gained (Mt C)**	
CO_2 Price + Annual Increase	**2050**	**2100**	**2050**	**2100**	**2050**	**2100**
3. \$20 in 2013 + 4%	\$85	\$607	598	1,179	49,333	128,268
Forestation			216	327	20,862	62,045
Avoided deforestation			383	852	28,471	66,223
4. \$30.42 in 2015 + 4%	\$120	\$853	656	1,263	54,966	136,141
Forestation			266	404	25,750	69,125
Avoided deforestation			390	859	29,216	67,016

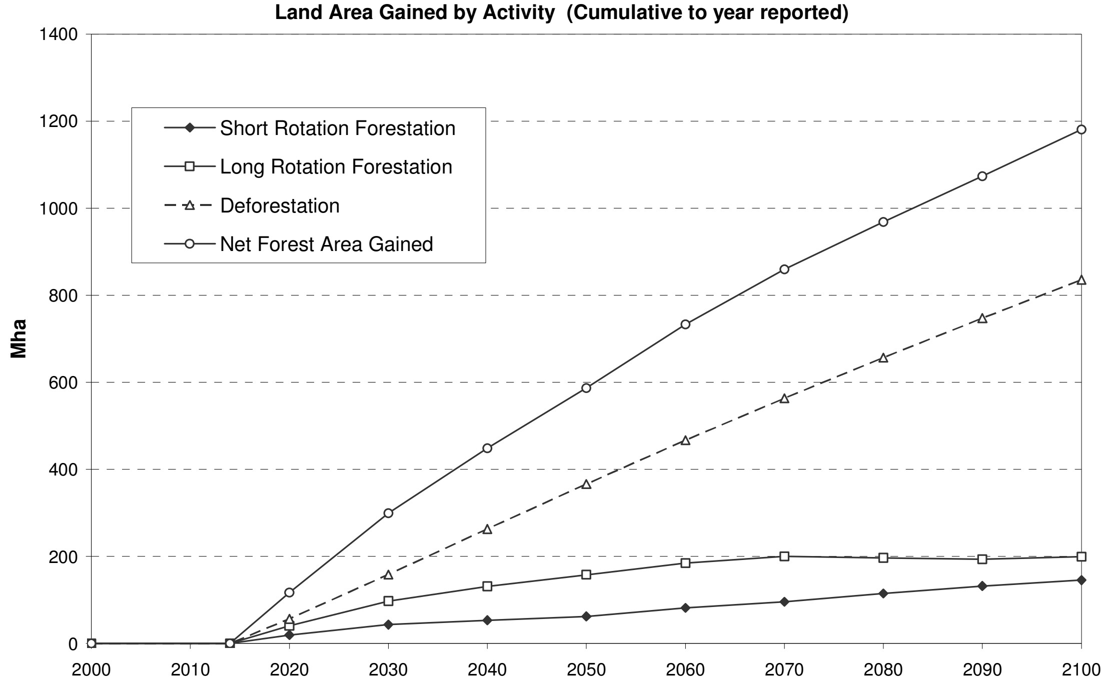
c) All carbon prices are zero until 2014, and begin increasing with the stated value in 2015.

The higher the carbon price, the higher the land area planted and the carbon benefits gained by that date. By 2050, Scenario 1 has lower carbon price and the carbon benefit gained is lower in this scenario compared to that in Scenario 2, and the same holds true for 2100. Despite a much lower 2050 carbon price in Scenario 1 about 38% of the carbon benefits accrue by that date compared to slightly higher 43% in Scenario 2. The carbon price in Scenario 1 is sufficiently high to halt deforestation completely by 2050 in Africa, and bulk of it in the other three regions. As a result, compared to the same reference scenario, the carbon benefits gained are very similar. Subsequent to that period, the carbon benefits gained are almost the same about 38 Gt C between 2050 and 2100 in each scenario. On the other hand, there is more opportunity for additional land area to be planted beyond 2050 and the higher price results in 428 Mha of land area gained by 2100 in Scenario 2 compared to about 25% less or 327 Mha planted in Scenario 1. Because of plantation maturity periods ranging up to 40 years for short rotation plantation and up to 100 years for long rotation plantation carbon continues to accumulate up to 2100 and beyond due to these plantings. As consequence, the percentage of carbon gained that is sequestered through forestation rises from 43% and 49% in 2050 to 49% and 52% in Scenarios 1 and 2 respectively.

The model uses perfect foresight adjusted to account for a 20-year time delay due to government regulations and market barriers where land users “know” today the price path of C in future periods and use that knowledge to make land use decisions. The 20 year time delay slows the penetration of mitigation options. For instance, without the delay, land area available for planting in India would have been exhausted by 2034 in the reference case and by 2012 in the mitigation case, but with the delay, it is delayed until 2032. The 20-year delay slows the increase in the stock of carbon and also reduces the mitigation benefit of a global carbon price rise in the earlier years.

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 2020 for Scenario 1, for example. The net forest area gained however continues to increase starting in the initial year in 2015 for Scenario 1 for instance (Figure 7).

Figure 7: Scenario 1 ($21.9 / tCO2-e, 4% growth from 2015)
Land Area Gained by Activity (Cumulative to year reported)

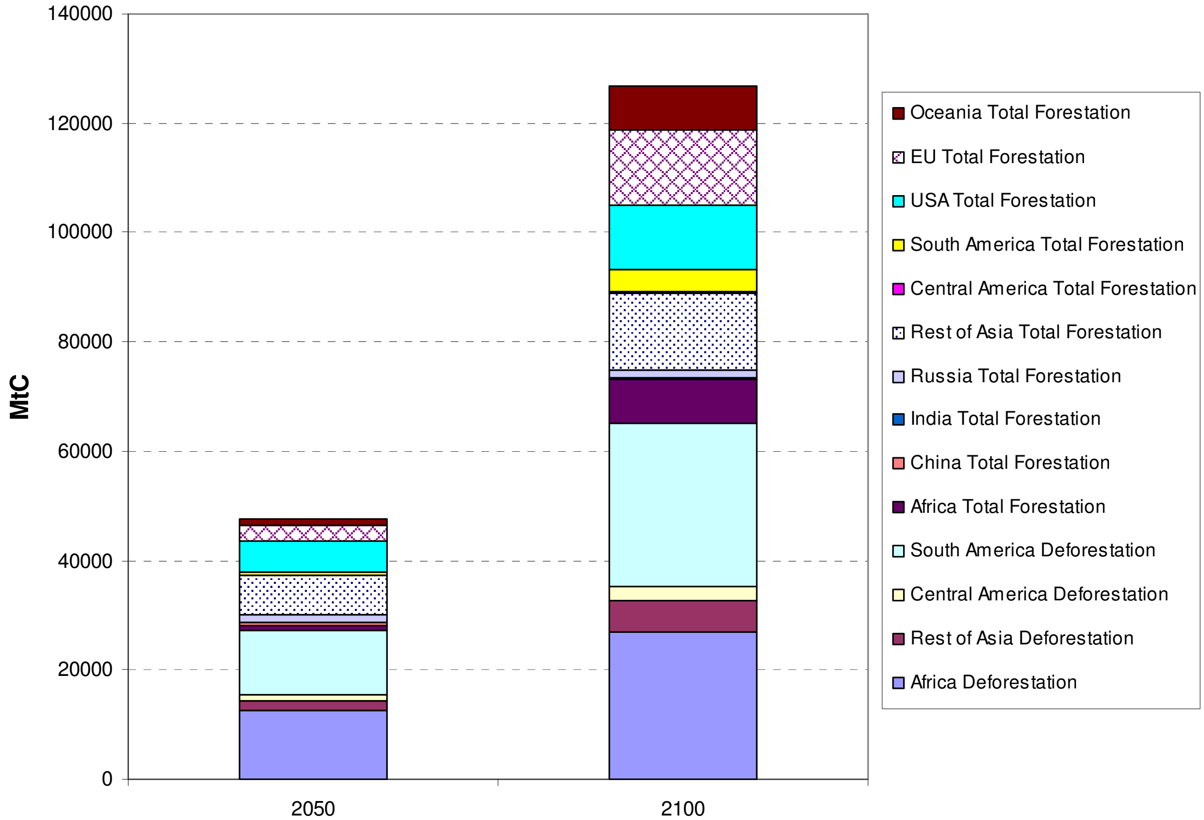


The regional distribution of carbon gains varies across scenarios. The total amount of land available for planting is limited in each region. For instance in India and China, due to the high planting rates in the reference case, the land cap is reached in 2040 and 2050 respectively. The mitigation scenario 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 in the reference case but in the Scenario 1 mitigation case, land caps are reached in Russia by 2040, Rest of Asia by 2080, USA by 2070 and Oceania by 2080.

The contribution to carbon gain varies by region over time (Figure 8). Rest of Asia, US and EU account for the more significant carbon gains through forestation in 2050, and the the three along with South America are the largest contributors to carbon gains in 2100 in Scenario 1. 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 or caps in late decades) are the main reasons for these results.

Figure 8 also shows the carbon gain from avoided deforestation by model regions. Africa and South America are the predominant contributors to this carbon gain. The two regions contribute about the same amount of reduced. 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 8: Scenario 1 ($21.9 / tCO2-e, 4% from 2015)
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 (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 less than \$20/t CO_2 in Africa, and about \$35/t CO_2

in Central America, \$41/t CO_2 in South America, and \$121/t CO_2 in the Rest of the Asia region would be sufficient to theoretically halt deforestation.[5]

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. In Scenario 1, deforestation is halted by 2013 in Africa, 2027 in Central America, 2027 in South America, and by 2059 in 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. The new REDD programs being initiated by the World Bank and other entities are expected to provide capacity building to deforesting countries and prepare them for reducing and eventually halting deforestation.

[5] 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.

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 four carbon price scenarios, the model estimates a global gain in carbon benefits between 126.6 Gt C and 145.5 Gt C or more than one Gt C per year, a significant amount. Despite the 20-year delay assumption to allow for the creation of carbon markets, the carbon price scenario is high enough to demand immediate sequestration and reduced deforestation response such that by 2050 one Gt C per year or more carbon benefits may be gained.

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 57% to 51% of carbon benefits gained by 2050 in Scenarios 1 and 2 respectively.

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.

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.

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. For deforestation activities, however, the carbon choke price is low enough to prompt complete halt to deforestation before 2050 in Africa, and Central and South America.

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Bibliography:

Adams, D. (1985). "A Spatial Equilibrium Model of African European Trade in Tropical Logs and Sawnwood." *Forest Ecology and Management*, **13**: 265-287.

Adams, D., B. McCarl and L. H. Farouk (1986). *The role of Exchange Rates in Canadian-US lumber trade*. CINTRAFOR Working paper no 8.

Adams D. and R. Haynes (1980). "The Softwood Timber Assessment Market Model: Structure, Projections and Policy Formulations." *Forest Science Monograph* **22**: 64.

Barraclough, S. and K. Ghimire, (2000). *Agricultural Expansion and Tropical Deforestation – Poverty, International Trade and Land Use*. Earthscan Publications, London.

Bhattarai, M. and M. Hammig, (2001). Institutions and the Environmental Kuznets Curve for Deforestation: A Cross-country Analysis for Latin America, Africa, and Asia. World Development **29**(6): 995-1010.

Boer, R. (2001). "Economic assessment of mitigation options for enhancing and maintaining carbon sink capacity in Indonesia." *Mitigation and Adaptation Strategies for Global Change* **6**(3-4): 2001.

Brown, S., Sathaye, J., Cannell M., Kauppi P., et al. (1996).*Mitigation Options in Forestry In: Climate Change 1995*: The IPCC Second Assessment Report, Volume 2: Scientific-Technical Analyses of Impacts, Adaptations, and Mitigation of Climate Change [Watson, R.T., M.C. Zinyowera, and R.H. Moss (eds.)]. Cambridge University Press, 1996.

Cairns, M., T. Kolchugina, D. Turner and J. Winjum. (1995). *The Contribution of Forest Land Use to Total National Carbon Flux: Case Studies in the Former Soviet Union, United States, Mexico and Brazil*. US EPA/600/R-95/044.

CMOF (2000). *Long Term Forestry Planning*. In J. Liu (ed).National Ecological and Environmental Planning. Chinese Commercial United Press, Beijing. Pp. 178-215.

Dale L. (2003). *Review of the Literature Covering Discount Rates Used to Evaluate Long-term Benefits of Forestry Projects*. Unpublished LBNL draft.

Dixon, R., P. Schroeder and J. Winjum. (1991). Assessment of Promising Forest Management Practices and Technologies for Enhancing the Conservation and Sequestration of Atmospheric Carbon and Their Costs at Site Level. USEPA, Washington DC.

ECE/FAO (1992). *Forest Resource Assessment*. (1990) The Forest Resources of the Temperate Zones. New York, Italy

Edmonds, J., M. Wise, H. Pitcher, T. Wigley, and C. N. MacCracken, (1996). An Integrated Assessment of Climate Change and the Accelerated Introduction of Advanced Energy Technologies. Pacific Northwest National Laboratory, Washington, DC.

EPA (2002). *Inventory of U.S. Greenhouse Emissions and Sinks: 1990-2000*. USEPA OAP, Washington D.C.

EPRI (2000). Technological Innovation and Research, Chapter 9: Western Surface Mine Permitting and Reclamation. Princeton.

FAO, Food and Agricultural Organization of the United Nations (1985). *Forest Product Prices 1965-1984*. Forestry Paper No. 61. Rome, Italy.

FAO, Food and Agricultural Organization of the United Nations (1992). *Forest Product Prices 1971-1990*. Forestry Paper No. 104. Rome, Italy.

FAO, Food and Agricultural Organization of the United Nations (1993). *Forest Resource Assessment 1990, - Tropical Countries* (TFRA 1990). Rome, FAO.

FAO, Food and Agricultural Organization of the United Nations (1997). *State of the World's Forests 1997*. Rome, Italy.

FAO, Food and Agricultural Organization of the United Nations (2000). *The Global Outlook for Future Wood Supply from Forest Plantations*. GFPOS/WP/03. Rome, Italy.

FAO, Food and Agricultural Organization of the United Nations (2001). *Forest Resource Assessment 2000*. Rome, Italy.

FAO, Food and Agricultural Organization of the United Nations (2002). *Yearbook of Forest Products 1996-2000*. FAO Statistics Series No 158. Rome, Italy.

FAO, Food and Agricultural Organization of the United Nations (2003a). *State of the Worlds Forests 2003*-Appendix 2 Data Tables. Rome, Italy.

FAO, Food and Agricultural Organization of the United Nations (2003b). *FORIS Data Base*. Rome, Italy.

Fearnside, P.M. (1995). "Global Warming Response Options in Brazil's Forest Sector: Comparison of Project level Costs and Benefits." *Biomass and Bioenergy* **8**(5): 309-322.

Fearnside, P. M. (1997). Greenhouse Gases from Deforestation in Brazilian Amazonia: Net Committed Emissions. *Climatic Change* **35**: 321-360.

Fearnside, P.M. and Barbosa, R.I., (1998). "Soil carbon changes from conversion of forest to pasture in Brazilian Amazonia." *Forest Ecology and Management* **108**: 147-166.

Fearnside, P., (2001). "The Potential of Brazils forest sector for Mitigating Global Warming under the Kyoto Protocol." *Mitigation and Adaptation Strategies for Global Change* **6**(3-4): 355-372.

Foley J. and Ramankutty N. (2004). *A Primer on the Terrestrial Carbon Cycle: What We Don't Know But Should.* Chapter 14 in The Global Carbon Cycle. Eds. C.B. Field and M.R. Raupach, Island Press, Washington DC. pp. 526.

FFS (1995). *Handbook of Russian Forests*. Moscow.

FSI (1999). *Forest Survey of India*, Ministry of Environment and Forests. Dehra Dun.

Graveland, C., A.F. Bouwman, B. de Vries, B. Eickhout, and B.J. Strengers, (2002). Projections of multi-gas emissions and carbon sinks, and marginal abatement cost functions modeling for land-use related sources. RIVM report 461502026/2002, Bilthoven, Netherlands.

Houghton, R.A. 2003. Revised estimates of the annual net flux of carbon to the atmosphere from changes in land use and land management 1850–2000. Tellus. 55b: 378-390.

Hutjes, R., J. Huygen, G. Nabuurs, M. Schelhaas, J. Verhagen, and L. Vleeshouwers. (2001). Chapter 3 In: *Land use, climate and biogeochemical cycles: feedbacks and options for emission reduction*. Bilthoven, National research Programme Global Air Pollution and Climate Change, ALTERRA, PRI.: 221. Bilthoven, National Research Programme Global Air Pollution and Climate Change Report No 410 200 107.

IPCC (1996) *Climate Change 1995: Economic and Social Dimensions of Climate Change.* Bruce J., Lee H. and Haites E. (eds.) Cambridge University Press. Cambridge, UK.

ITTO (International Tropical Timber Organization) (2001). Annual Review of the World Timber Situation 1990-00. ITTO, Yokohama, Japan.

ITTO (International Tropical Timber Organization) (2003). Annual Review and Assessment of World Timber Situation (2003). ITTO, Yokohama, Japan.

Izrael, Y. A. and S.I. Avdjushin (1997). *Inventory of Sinks and Emissions Related to Terrestrial Ecosystems* – Russian Federation Climate Change Country Study: Final Report. Moscow.

Kaimowitz, D. (1996). *Livestock and Deforestation in Central America in Central America in the 1980's and 1990's*: A Policy Perspective. CIFOR, Jakarta, Indonesia.

Kerstetter J. and J. Lyons. (2001). Logging and Agricultural Residue Supply Curves for the Pacific Northwest. Washington State University, *US DOE* Contract #DE-FC01-99EE50616.

KFE (Kosikhinsky Forest Enterprise). (2000). Woodmark Forest Certification Public Report, Altai Region, Russia.

Kirschbaum. Miko U.F. (2000). "What contributions can tree plantations make towards meeting Australia's commitments under the Kyoto Protocol?" *Environmental Science & Policy* **3**: 83-90.

King, G.A. (1993). Net Primary Productivity of Non-forested Lands. Pages 179-194 *in* D. Turner, J. Lee, G. Koerper and J. Baker (eds.) The Forest Sector Carbon Budget of the United States: Carbon Pools and Flux Under Alternative Policy Options. EPA/600/3-93/093, Environmental Research Laboratory, Corvallis, Oregon.

Lubowski R., A. Plantinga and R. Stavins. (2001). *A National-Level Econometric Analysis of the Costs of Carbon Sequestration*. Presented at the and Agriculture Greenhouse Gas Modeling Forum Workshop, NCTC, , WV, Sept. 2001.

Lyons, A. (1997a). Farm Forestry: Plantation Establishment – Labour and Cost. Private Forestry in Tasmania, Hobart, Tasmania.

Lyons, A. (1997b). Farm Forestry: Plantation Income. Private Forestry in Tasmania, Hobart, Tasmania.

MAF (Ministry of Agriculture and Forestry) (2002). Forestry Statistics – Historical Price Series. Wellington, New Zealand.

Makundi, W. (1990). An Econometric Analysis of International Trade in Selected Forest Products with Emphasis on the Impact of Exchange Rate Fluctuations. A PhD Dissertation, University of California, Berkeley.

Makundi, W. and J. Sathaye (1992). Carbon Emissions and Sequestration in Forests: Case Studies from Seven Developing Countries - Vol. 1, Summary. LBNL - 32119.

Makundi, W., J. Sathaye and A. Ketoff (1995). COPATH - A Spreadsheet Model for the Estimation of Carbon Flows Associated with the Use of Forest Resources. *Biomass and Bioenergy*, Vol 8 No. 5: 369-380.

Makundi, Willy R. (2001). "Carbon Mitigation Potential and Costs in the Forest Sector in Tanzania." *Mitigation and Adaptation Strategies for Global Change* **6**(3-4): 335-353.

Manne, A. S. and R.G. Richels (2005). The Role of Non-CO2 Greenhouse Gases and Carbon Sinks in Meeting Climate Objectives. *Energy Policy*, this issue

Markandya A. and Halsnaes K. (2001). *Costing Methodologies.* Chapter 7 in *Climate Change 2001, Mitigation, WGIII Contribution to the Third Assessment Report.* Published by Cambridge University Press for the Intergovernmental Panel on Climate Change.

Masera, Omar R., Alma Delia Ceron and J. Antonio Ordonez. (2001). “Forestry Mitigation Options for Mexico: Finding Synergies Between National Sustainable Development Priorities and Global Concerns.” *Mitigation and Adaptation Strategies for Global Change* **6**(3-4): 291-312.

Mckillop, W. (1967). “Supply and Demand for Forest Products: An Econometric Study.” Hilgardia **38**: 1-132

Moulton and Richards, (1990). *Costs of Sequestering Carbon Through Tree Planting and Forest Management in the United States*. USDA-FS GTR WO-58.

Moulton, R.J., F. Lockhart, and J.D. Snellgrove. (1995). *Tree Planting in the United States 1994*. USDA Forest Service. Cooperative Forestry. 18 p.

Moulton R., F. Lockhart and J. Snellgrove. (1996). *Tree Planting in the United States 1995*. USDA Forest Service, Washington D.C.

Nair, K. (ed). (2000). Insect Pests and Diseases in Indonesia. An Assessment of the Major Threats, Research Efforts and Literature. CIFOR, Bogor, Indonesia.

Nakicenovic N. et al., (2000). *Emissions Scenarios*. A Special Report of Working Group III of the IPCC. Cambridge University Press. pp. 599.

Nambiar, E., Tiarks, A. and C Cossalter (eds). (1998). *Site Management and Productivity in Tropical Plantation Forests*. In Workshop Proceedings held in Pietermaritzburg, South Africa, Feb 1998.

Nambiar, E., Tiarks, A. C Cossalter and J. Ranger (eds). (1999). *Site Management and Productivity in Tropical Plantation Forests*. In Workshop Proceedings held in Kerala, India, Dec 1999.

NEAP (1997). *Russian National Environmental Action Plan*. In The National Implementation of Agenda 21.

Nilsson, S., O. Sallnäs and P. Duinker. (1992). *Future forest resources of Western and Eastern Europe.* International Institute for Applied Systems Analysis. A report on the IIASA forest study. The Parthenon Publishing Group. England.

Pandey, D. (1983). *Growth and Yield of Plantation Species in the Tropics*. FAO, Rome, Italy.

Parks, P. and I. Hardie (1997). “Least-cost forest carbon reserves: cost effective subsidies to convert marginal agricultural land to forests.” *Land Economics* **71**(1): 122-136.

Peterson, C.E. (1993). Biomass and Carbon for Woodlands in the Western United States. Pages 143-149 *in* D. Turner, J. Lee, G. Koerper and J. Barker (eds). The Forest Sector Carbon Budget of the United States: Carbon Pools and Flux under Alternative Policy Options. EPA/600/3-93. Environmental Research Laboratory, Corvallis Oregon.

Petrov, A. (2001). *Financing Sustainable Forest Management in Russia and the CIS*: Alternative Mechanisms to Finance Participatory Forest and Protected Areas Management. Presented at the International Workshop on Financing Sustainable Forest Management, Jan. 2001, Oslo, Norway.

Potter, L. and J. Lee. (1998). *Tree Planting in Indonesia: Trends, Impacts and Directions*. CIFOR Occasional Paper No. 18.

Ravindranath N.H., Sudha P., and Rao, S. (2001). “Forestry for Sustainable Biomass Production and Carbon Sequestration in India.” *Mitigation and Adaptation Strategies for Global Change* **6**: 233-256.

Robinson, V. (1974). “An Econometric Model of Softwood Lumber and Stumpage Markets, 1947-1967.” *Forest Science* **20**: 171-179.

Roskovensky, G. (2000). Appalachian Stumpage-logging cost. *In* Crossties, Pennsylvania.

RSMD (2001). *Market Prices of Forest Products*, Vol. VII No 9, and Dec 2001. Delhi, India.

RUSAFOR (1994). *RUSAFOR-Saratov Afforestation Project*. Activities Implemented Jointly. Report to USIJI, Washington D.C.

Sands, R. and Leimbach, M. (2003). "Modeling Agriculture and Land Use in an Integrated Assessment Framework." *Climatic Change* **56**(1): 185-210.

Sathaye J., Makundi W. and Andrasko K. (1995). "A Comprehensive Mitigation Assessment Process (COMAP) for the Evaluation of Forestry Mitigation Options." *Biomass and Bioenergy* **8**(5): 345-356.

Sathaye, J., Makundi, W., Andrasko, K., Boer, R., Ravindranath N.H., Sudha, P., Rao, S., Lasco, R., Pulhin, F., Masera, O., Ceron, A., Ordonez, J., Deying, X., Zhang, X., and Zuomin, S. (2001). "Carbon mitigation potential and costs of forestry options in Brazil, China, India, Indonesia, Mexico, the Philippines, and Tanzania." *Mitigation and Adaptation Strategies for Global Change* **6**(3-4): 185-211.

Sathaye J., Makundi W., Dale L., Chan P., and Andrasko K. (2005). Estimating Global Forestry GHG Mitigation Potential and Costs: A Dynamic Partial Equilibrium Approach. LBNL – 55743.

Sedjo, R., and B. Sohngen (2000). *Forestry Sequestration of CO2 and Markets for Timber*. Discussion Paper 00-35. Resources for the Future.

Sist, P., C. Sabogal and Y. Byron (eds). (1997). *Management of Secondary and Logged-Over Forests in Indonesia*. In Selected Proceedings of an International Workshop held in Bogor, Indonesia, Nov 1997.

Sohngen B. and R. Mendelsohn (2002). *Optimal Forest Carbon Sequestration*. Draft paper presented at EMF21 Workshop in April 2002.

Sohngen B. and R. Sedjo (2005) Carbon Sequestration Costs in Global Forests. (*This Issue).*

US Forest Service (2001). *Agricultural Conservation and Forestry Statistics*. Timber Demand and Technology Assessment. RWU-4851.Washington, DC

US Department of Energy, Energy Information Administration (2003). *International Energy Annual 2001*. Washington, DC.

Varian, H., (1992) *Microeconomic Analysis*. (Third Edition). W.W. Norton & Company, New York.

VOLOGDA. (1994). *Vologda Reforestation Project. Activities* Implemented Jointly. Report to USIJI, Washington DC.

Watson R.T. and the Core Writing Team. (2001). *Climate Change 2001: Synthesis Report*. Printed by Cambridge University Press for the Intergovernmental Panel on Climate Change.

Watson, R.T., I. Noble, B., Bolin, N., Ravindranath, D., Verardo and D. Dokken. (Eds). (2000). *Land use, Land-use Change, and Forestry.* Printed by Cambridge University Press for the Intergovernmental Panel on Climate Change.

Xu D. and X. Zhang. (2002). Personal Communication

Xu D., Zhang, X., and Shi, Z. (2001). "Mitigation potential for carbon sequestration through forestry activities in Southern and Eastern China." *Mitigation and Adaptation Strategies for Global Change* **6**: 213-232.