Avoided Deforestation as a Greenhouse Gas Mitigation Tool: Economic Issues for Consideration

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ABSTRACT

Tropical deforestation is a significant contributor to accumulation of greenhouse gases (GHGs) in the atmosphere. Previous estimates of GHG emissions from tropical deforestation have been in the range of 1 to 2 petagrams of carbon (Pg C) per year for the 1990s, equivalent to 15% to 30% of global annual GHG emissions from fossil fuels. Currently, forestry activities under the Clean Development Mechanism (CDM) of the Kyoto Protocol are limited to afforestation and reforestation on areas that were not forested in 1990, excluding actions to avoid deforestation. However, interest in creating carbon credits for avoided deforestation was renewed after the 11th Conference of the Parties to the United Nations Framework Convention on Climate Change (COP11) decision in late 2005 to explore approaches to reduce emissions from deforestation. This paper examines the extent of baseline deforestation and associated carbon emissions and the economic potential for incorporating reductions in deforestation as an option for mitigating climate change. Using the Global Timber Model, which is a market model that accounts for above- and below-ground vegetative carbon stock, we find that there is a large potential for avoided

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deforestation to help reduce GHG mitigation costs. Mitigation ranges from an average of about 0.1 Pg C per year at $5/metric ton of carbon (t C) up to 1.6 Pg C per year at $100/t C.

Keywords: Avoided deforestation, climate change, forest management, greenhouse gas mitigation, sinks

1. INTRODUCTION

Tropical deforestation is a major source of GHG emissions, accounting for as much as 25% of global anthropogenic GHG emissions (Houghton, 2005). Temporary or partial forest removals for shifting cultivation and selective logging, as well as permanent forestland conversion to agricultural or other uses, contribute to releases of carbon stored in vegetation and soils to the atmosphere. Emissions depend on both the rate of deforestation and changes in carbon stock per hectare after deforestation, with changes in carbon stocks varying with land use, region, ecosystem, and use of the removed forest biomass. Burning results in immediate releases of forest carbon, whereas unburned organic matter releases carbon more slowly during the decay process. Loss of carbon may take place over 100 years or more for some wood products.

Although afforestation and reforestation activities on areas that were not forested in 1990 are eligible projects under the Clean Development Mechanism (CDM) for the first commitment period of the Kyoto Protocol (2008 to 2012), avoided deforestation was excluded because of concerns about additionality (adequately defining baselines such that mitigation can be measured relative to those baselines), permanence, and leakage (Schlamadinger *et al*., 2005). At a side event to the 9th Conference of the Parties to the United Nations Framework Convention on Climate Change (COP9 of the UNFCCC), Santilli *et al*. (2003) introduced a new proposal to add avoided deforestation activities as eligible projects, which reopened debate about including avoided deforestation. During COP11, held in Montreal from November 28 to December 9, 2005, Papua New Guinea and Costa Rica, on behalf of the Coalition for Rainforest Nations, proposed that parties to the UNFCCC address emissions from deforestation and create incentives for developing nations to manage these emissions. The COP11 decision proposed that parties to the UNFCCC be given an opportunity to provide their views on providing incentives for reducing deforestation before the 24th meeting of the United Nations Sessions of the Subsidiary Bodies, held in Bonn, Germany, in May 2006 (SBSTA 24). Twenty-one nations provided formal input by the time of the SBSTA 24 meeting, and an agreement was reached to continue considering the development of incentive mechanisms by which developing countries may reduce deforestation.

The concept of reducing deforestation has been widely discussed in the academic literature, but the idea of developing a program that gives countries incentives to reduce their deforestation has not been widely considered in international climate regimes. In addition, although a number of previous studies have examined the potential for avoided deforestation to play a role in GHG mitigation, relatively few authors have examined the associated costs of achieving different levels of emission reductions across multiple tropical regions. This paper examines the extent of baseline deforestation and the quantity of carbon at stake, practical problems and issues associated with including avoided deforestation, and the economic potential to incorporate reductions in deforestation as an option for mitigating climate change. The Global Timber Model, a market model developed by Sohngen *et al.* (1999) that accounts for above- and below-ground vegetative carbon stock, is used to quantify potential emissions reductions and costs.

2. DEFORESTATION AND CARBON EMISSIONS

The Food and Agricultural Organization (FAO) reported annual net forest cover losses of around 8.9 million hectares per year in the 1990s, falling to 7.4 million hectares per year in the early 2000s (United Nations, FAO, 2005). These losses amounted to a net loss in global forest cover of around 0.22% per year during the 1990s and 0.18% in the 2000s (Table 1). However, the global numbers mask substantial variation among the regions. In general, tropical regions are experiencing deforestation, and temperate regions are experiencing afforestation. Net forest cover change in the tropical forests of South America, Central America, Southeast Asia, and Africa is estimated to have been 11.5 to 11.6 million hectares of net forest loss per year since 1990, whereas forest cover increased in Europe, North America, and East Asia. Houghton (2003) suggests that deforestation rates were substantially higher in these same tropical regions during this period, around 15.8 million hectares per year in the 1990s. However, that study also suggests that afforestation occurred over large areas of land in East Asia, so that net forest cover change was around 12.1 million hectares.

The carbon consequences of these relatively large adjustments in forest cover are substantial. Not only is carbon lost to the atmosphere from net reductions in forest cover, but newly afforested or reforested lands store far less carbon per hectare (currently) than mature stands being deforested. In addition, the geographical variation in forest cover trends has important implications for carbon emissions because of the large differences in carbon stock per hectare across regions. In general, the tropical areas experiencing net deforestation have higher carbon stocks in forest biomass per hectare than temperate regions experiencing net afforestation. For instance, forests in North America have a weighted average of 117.8 metric tons of carbon per hectare (t C/ha), whereas Central America has 179.2 t C/ha and South America has 194.6 t C/ha (FAO, 2005).

One of the first studies examining carbon implications of forest cover changes globally, Dixon *et al*. (1994), suggest that the net effects may lead to emissions of up to 0.9

Pg C/year (1 Pg is equal to 1 billion metric tons) for the entire world. DeFries *et al*. (2002), Potter *et al*. (2003), and Achard *et al*. (2002) similarly find that forests globally are a net source of emissions; DeFries *et al*. and Potter *et al*. both estimate a net global emission of 0.9 Pg C/year, consistent with Dixon *et al*. The global emissions estimate provided by Achard *et al*. is a bit higher at 1.1 Pg C/year. A study by Houghton (2003) indicates potentially far larger net emissions from deforestation of 2.2 Pg C/year during the 1990s.

The results above are based on forest inventory data and changes in land uses observed through satellites or by other means. Alternative methods for calculating the flux between forests and the atmosphere have been developed in what are commonly called inversion models (see Ciais *et al*. [2000]). The results from inversion model studies have generally suggested that forests are smaller net sources and likely net sinks globally. For instance, using these techniques, Ciais *et al*. (2000) find that ecosystems globally sequester around 1.3 Pg C/year (net of all deforestation, afforestation, and management processes). Gurney *et al*. (2002) find that deforestation in the tropics accounts for around 1.2 Pg C/year of emissions, but these emissions are more than offset by gains in ecosystem carbon elsewhere. As a result, their study estimates that ecosystems, on average, sequester around 1.3 Pg C/year globally. Plattner *et al*. (2002) find that net global sequestration in ecosystems is around 0.7 Pg C/year.

There is little debate that deforestation is occurring. There is, however, significant debate about the climate consequences of net changes in land use, including deforestation, afforestation, and reforestation. The implications of this debate affect the potential crediting of reduced deforestation as a GHG mitigation tool. For example, world bodies may decide that the uncertainties associated with the overall effects of reducing deforestation are too difficult to measure and verify to consider including in mechanisms like the CDM. Scientists and policy makers need to further examine the uncertainties implied by different estimates of global net carbon emissions (or sequestration), but questions about this uncertainty are not addressed in this paper.

3. POLICIES TO MITIGATE GREENHOUSE GAS EMISSIONS FROM DEFORESTATION

Countries have several different types of policy levers available to enhance carbon sequestration in forest biomass. The potential approaches can be categorized into three general types of programs: (1) project-based approaches that consider only individual carbon projects in individual areas, (2) comprehensive approaches that treat all forests as possible emission sources, and (3) indirect approaches aimed at creating systematic change in the forestry and land-using sector. Each is described below.

3.1 Project-Based Approaches

Currently, through the CDM's, country-specific, or private efforts, the world is largely following a project-based approach. This type of approach considers the forest sector as an offset for other sectors that have caps on GHG emissions in place. For instance, energy-producing sectors with emission caps could develop projects (*e.g.*, afforestation, reforestation, improved management) in specific forests to increase the overall quantity of carbon sequestered on those sites. Alternatively, the sectors that have caps can purchase offsets from project developers and credit those against their emissions.

Two established carbon markets that allow forestry credits to be used as offsets follow the project-based approach: the Australian New South Wales carbon market and the United States Chicago Climate Change carbon market (note that the caps undertaken on the

U.S. market are purely voluntary). Other trading systems may also eventually allow for the inclusion of forestry carbon credits through project-based approaches, although the largest market, the European Trading System (ETS), has no provisions at this time to allow forestry credits as offsets to emissions from the energy sectors.

Avoided deforestation projects are not currently eligible projects under the CDM for the first commitment period of the Kyoto Protocol (2008 to 2012) largely because of concerns about additionality, permanence, and leakage (Schlamadinger *et al*., 2005). These concepts have been widely discussed within the carbon literature, primarily in terms of project-based sequestration associated with afforestation and reforestation. Projects occur when individuals work to establish new carbon stocks through approved forestry activities on specific sites (*e.g.*, 50 hectares up to millions of hectares), to measure the carbon, and to receive credit for the carbon they have accumulated that is additional to the carbon that would have accumulated on the site without the project. Within the project-based world, it is extremely important for project managers to account for the potential influences of all of these issues. For the purposes of this avoided deforestation analysis, we provide a brief definition of each of these concepts in terms of project-based carbon sequestration.

3.3.1 Project-Based Additionality

This concept refers to ensuring that a carbon project accrues new carbon relative to a baseline. Baseline setting has been intensely discussed within the carbon sequestration literature, and there is no single approved methodology for setting a carbon baseline. However, individual project managers must develop a baseline, possibly working with experts, and then estimate the potential credits they will receive as a result of the project's activities. Over time, the managers must continue to validate their project baseline to show that their project area would have continued along the baseline without the project.

3.1.2 Project-Based Permanence

It is widely recognized that carbon emitted from fossil fuels has a long residence time in the atmosphere (typically assumed to have a half-life of 50 years). If carbon sequestered in forests is used as an offset against energy emissions that otherwise must be avoided, then it stands to reason that carbon in the forests should also have a long residence time in the forest. Carbon sequestered in forests, however, has the potential to be released back into the atmosphere as a result of harvesting activities, forest fires, or other disturbances. To ensure that carbon credits in forests are similar to carbon emissions in the atmosphere, project managers must take steps to ensure that projects provide permanent storage of the carbon emissions they have been contracted to offset.

Practically, this issue has been handled in sequestration policy by developing different classes of carbon credits with specific time limits. These are called temporary credits. Temporary credits can be used as offsets for a firm for a given period of time (30 years), and if the forest sequestration project continues sequestering carbon, the temporary credits can be extended. Thus, the notion now exists that carbon credits in forestry projects no longer need to be considered permanent, and managers can develop short-term projects that offset energy emissions only for the time limit of the credits (with the potential to extend).

3.1.3 Project-Based Leakage

Leakage is recognized as the loss of carbon that may occur when carbon sequestration projects are developed on specific pieces of land, and the projects cause subsequent losses of carbon elsewhere. These potential losses must be estimated by project managers and used to estimate the net gain of carbon caused by the project. Several estimates of leakage have been developed in the literature for different types of projects (see Murray *et al*. [2004] and Sohngen and Brown [2004]). The estimates reported in these two studies range from less than 20% to greater than 90%.

These three concepts of additionality, permanence, and leakage have clear relevance for project-based carbon sequestration. Individual project developers who hope to have their credits validated as potential offsets of energy emissions must account for each of them. These issues are equally relevant for projects that focus on afforestation and reforestation, projects that focus on improving timber management, and potential projects that would focus on reducing deforestation. In the case of avoided deforestation, project managers would have to develop credible estimates of the amount of deforestation and carbon emissions that would have taken place in the project region in the absence of the project, account for the permanence of the carbon storage in forests where deforestation is being avoided, and estimate the extent to which reduced deforestation in one area contributes to increased deforestation in areas outside the project boundaries.

3.2 Comprehensive Approaches

Although project-based efforts focused on GHG reduction have been the world's primary focus for reducing emissions from land use and land use change to date, they are not the only way for individual countries to tackle carbon sequestration in forestry. Comprehensive programs would treat the forestry sector like other sectors as a potential emission source. Any increase in the overall carbon stock within the country's boundary from period to period would result in net credits, while any reduction would result in additional emissions that must be counted under the country's overall cap.

Within the context of a comprehensive approach, a country can use a range of policies (or a combination of policies) to sequester carbon or reduce emissions, including taxes on emissions from individual forests when they occur, subsidies on sequestration, or caps for individual landowners. The use of these policies would suggest that landowners retain the rights to the carbon embodied on the land. Alternatively, countries may nationalize all of the carbon embodied in forests and design programs to increase carbon in the forests through subsidy payments for related practices, such as reforestation, afforestation, improved forest management, and taxes on specific types of products with a short shelf life, for example.

The general idea of the comprehensive programs is that countries would treat emissions from forestry at the national level no differently than they treat emissions from other sources. As a consequence, they would also treat net national sequestration as an offset for emissions from other sources. Comprehensive programs mean that countries do not need to account for baselines, permanence, or leakage explicitly because they are counted implicitly. For this reason, this approach is the most "comprehensive," because it treats land use in a fundamentally similar way to nonforestry carbon emissions. The comprehensive approach would require a substantive investment in inventory data collection over a large proportion of the landscape and, thus, has not been widely considered in the policy realm.

3.3 Indirect Approaches

The use of project-based approaches designed to generate carbon credits as a GHG mitigation activity does not preclude government provision of carbon sequestration on lands they manage or own or on privately owned land. Many countries have programs aimed at altering specific types of land uses. For instance, the U.S. government pays some farmers to set aside farm land from production to improve habitat or streamside vegetation. These projects may improve carbon on those sites and, therefore, also be marketable as carbon credits. The rules could be written to allow individual landowners to sell the carbon credits on this land.

In addition, the United States and Europe subsidize certain types of agricultural practices or products and potentially increase the area of agricultural land devoted to those practices or products relative to what it would otherwise be. By altering these programs, the United States and Europe could alter the carbon in their land base. For example, traditional agricultural commodity programs could be adjusted to provide additional incentives for crops that are most suitable to conservation tillage. It is important to recognize that governments can, and may, try to influence carbon outcomes through policies that are not even directly related to carbon.

3.4 Summary of Policy Approaches

In general, considering the three key issues of additionality, permanence, and leakage is necessary in the context of the project-based approaches. Based on current experience, measuring carbon gains from reduced deforestation in the project-based world will be fairly complicated (see Brown *et al*. [forthcoming]). For the comprehensive approach, countries would do full carbon accounting on their landscape, all land would be included in the program, and all carbon emissions would be debited and sequestration credited. For the indirect approaches, carbon is only indirectly targeted through other policy mechanisms.

4. METHODS

This paper uses a global timber market and land use model that accounts for the change in above- and below-ground vegetative carbon stock associated with shifting land from forestry to agriculture and from agriculture to forestry. The model also accounts for other types of management changes in forestry that influence carbon outcomes, such as changes in management intensity, changes in rotation ages, and changes in plantation forests, but this paper focuses on presenting the carbon outcomes related to deforestation and land use change in tropical regions where deforestation is largest. The results presented here are consistent with the types of crediting systems discussed in Articles 3.3 and 3.4 of the Kyoto Protocol and in the UNFCCC and thus are considered appropriate for analysis.

4.1 Modeling Future Land Use Change

For the purposes of this paper, future land use change is modeled with the Global Timber Model (see Sohngen *et al*. [2005] and Sohngen and Mendelsohn [2006]). The model has been widely used for policy analysis in recent years, including analysis of regional carbon sequestration baselines (Sohngen and Sedjo, 2000), climate change impacts (Sohngen *et al*., 2001), and carbon sequestration analysis (Sohngen and Mendelsohn, 2003). The model is a dynamic optimization model that maximizes the net present value of consumers' surplus less costs of managing, harvesting, and holding forests.

A global demand function for timber logs is used to estimate consumer surplus in timber markets. Forests in 250 timber supply regions then feed this global demand. Age class distributions for forests were derived from local sources, where available, or assumed for regions without data on age classes. For temperate and boreal regions (most developed countries), age class distribution information was obtained from local sources. Tropical forests are assumed to be in old growth conditions, while age class distributions for subtropical plantations were derived from historical planting and harvesting rates.

Age class distributions and timber biomass growth functions were developed for each timber type. Cost functions for harvesting accessible and remote forests were developed from earlier estimates used in the study by Sohngen *et al*. (1999). Remote forests are those that have little infrastructure near them and consequently have high costs for timber extraction and transportation. Access costs in regions where data are not available are based on costs for similar forests in different regions of the world. Since all prices and costs in the model are denominated by 2000 U.S. dollars ($), the relative costs for harvesting or accessing forests are adjusted for differences in exchange rates.

In addition to accounting for the costs of harvesting and accessing forests, land opportunity costs are modeled with land supply functions. The land supply functions represent land moving from nonforest use to forest use in response to an increase in the (rental) value of forest use. Land supply elasticity is assumed to be 0.25 for all regions in the model, indicating that a 1% increase in forestland rental values will increase forestland area by 0.25% at initial land rents and forestland areas. Although the analysis contained in this paper does not present sensitivity analysis on this particular parameter, Sohngen and Mendelsohn (2006) found that a 50% increase or decrease in the elasticity estimate reduces or increases potential global sequestration by 20%. The results for total potential sequestration were found to be slightly more sensitive to assumptions about the elasticity of land supply in South America than the global average, but less sensitive in the other tropical regions examined in this paper (Central America, Southeast Asia, and Africa).

To simulate changes in land use over time, the land supply functions in tropical regions shift inward over time. This model does not solve forestry and agricultural land markets simultaneously, but it does simulate a path of agricultural expansion (or contraction) in all regions of the world by shifting the land supply functions. Shifting the land supply functions inward increases the opportunity costs of holding land in forests and therefore spurs additional conversion of land over time.

4.2 Incorporating Carbon Prices

When implementing the carbon price scenarios, we assumed that additional carbon gained above the baseline is rented at an annual rental rate consistent with the carbon prices listed above. The annual rental rate is

$$R_C = r*P_C,$$

where R_C is the rental rate for carbon (the annual value paid per t C for holding carbon in the ecosystem), r is the interest rate, and P_C is the price of carbon. The formula above assumes that the price of carbon remains constant, an assumption maintained throughout this analysis. If carbon prices were instead assumed to rise, the formula for calculating the rental value would need to be adjusted to account for increases in the price.

For the scenarios analyzed for this paper, all carbon gains relative to the baseline are credited, including carbon gains from land use change (*i.e.*, reduced deforestation and afforestation), carbon gains from increasing management intensity, carbon gains from increases in rotation ages, and carbon gains from product storage. In addition, carbon gains in all regions of the world are paid the same amount. We only present results for four regions where deforestation is the largest, however. By providing these incentives, we account for the global nature of carbon policy. Only net gains are credited, and carbon gains are paid exactly what they are worth for the time they are stored, so the carbon storage implied by these results does not need to be further corrected for additionality, permanence, and leakage concerns. This method for crediting carbon is consistent with the comprehensive approach described above. Other approaches for crediting would need to be corrected for the issues above, as discussed in Murray *et al*. (2004) and Sohngen and Brown (2004).

4.3 Baseline Model Projections

Baseline deforestation in the tropical regions modeled is projected to be 13.1 million hectares/year over the period 2005 to 2015 (Table 2). On net, the model projects a loss of around 11.8 million hectares/year in tropical forest regions over the next 10 years. These estimates are largely consistent with the estimates from the earlier studies discussed above. As a result, deforestation is projected to add around 1.5 Pg C to the atmosphere each year over the next 10 years and, when reforestation is considered, to lead to net losses of 1.4 Pg C/year. These estimates are roughly consistent with many of the estimates of tropical deforestation discussed above. Note that it is not only the net change in forestland that affects emissions, but also area deforested, as well as area afforested or reforested and carbon stock per hectare under different conditions.

Over the next 50 years, the model projects that deforestation slows (Figure 1). The rates of decline in deforestation are consistent with predictions that the demand for agricultural land will slow in the future. Reductions in the demand for agricultural land are driven by assumed increases in agricultural productivity of 2 to 3% per year (Nin *et al*.,

2003) and a slowing of population growth, both of which would reduce the demand for land for agriculture.

5. COST AND POTENTIAL FOR EMISSION REDUCTIONS FROM AVOIDED DEFORESTATION

Over the last few years, the carbon market has become significantly larger (LeCocq and Capoor, 2005). Most of the trading occurs with energy projects and not with land use projects. Further, currently an institutional infrastructure is not available for trading carbon credits derived from reducing deforestation. The results presented below, therefore, provide policy makers with estimates of the potential size of the credit market if forestry actions, and specifically reductions in deforestation, are incorporated into current policies.

Sohngen and Sedjo (forthcoming) conducted a study of six carbon price scenarios as part of the Stanford Energy Modeling Forum EMF-21 modeling exercise. The six carbon price scenarios consider a range of potential carbon price changes, including scenarios with rapidly increasing prices and scenarios with slower price increases. Across the scenarios, 73% to 88% of the carbon stored in tropical regions results from land use change. The authors did not report whether the land use change specifically was reducing deforestation or increasing afforestation; they just aggregated the total land use change. However, the baseline trends in that study are consistent with the baseline results presented above (Sohngen and Sedjo also relied on the Global Timber Model), suggesting that reducing deforestation would have important effects.

To more directly address the potential for reducing deforestation, we modeled changes in land use and subsequent reductions in deforestation across a set of constant carbon price scenarios. These carbon price scenarios assume constant carbon prices for the entire 21st century. The constant carbon prices range from \$5/t C to \$100/t C (\$1.36/t CO_2 to \$27.25/t CO_2). Although additional price effects with the policies examined below are likely because of market interactions, the results provide first-cut estimates of how carbon prices could potentially influence levels of deforestation and afforestation globally. Future model developments must take into account agricultural markets in different regions to analyze a broader set of policies.

Considering the change in deforestation rates associated with different carbon prices is useful because some countries may consider adopting indirect carbon policies that focus on altering the rate of deforestation rather than policies that target carbon explicitly. Assessing the relationship between the rate of deforestation and carbon prices can give policy makers a sense of what changes in the rate of deforestation would be feasible for different carbon prices. The results of the analysis indicate that average annual tropical deforestation rates could be reduced by 8.4% to 15.3% each year for a carbon price of \$5/t C (Table 3). The largest changes are projected to occur in Africa and Central America for this scenario. For higher carbon prices, not surprisingly, larger reductions in deforestation occur. At \$100/t C, the results suggest that deforestation can virtually be stopped. Central America and Africa obtain the largest reductions in the rate of deforestation for lower carbon prices, but all regions have approximately a 100% reduction when carbon prices are \$100/t C. Africa has the lowest land values and the largest total deforestation initially, so that carbon incentives have a fairly large effect there for low carbon prices. Central America has less total deforestation initially, so even fairly small changes in the rate of deforestation are large in percentage terms. SE Asia and South America have higher land rental values; consequently, it takes higher CARBONprices to induce similar percentage reductions in the rate of deforestation.

To illustrate changes in the annual amount of deforestation over the 50-year time period (2005 to 2055), Figure 2 shows the area estimated to be deforested in the baseline case and the five carbon price scenarios for South America. Reductions in deforestation occur initially and remain at a fairly consistent level for most of the period. At $100/t C, as noted above, deforestation is stopped. Results are similar for the other tropical regions modeled.

In the baseline, tropical deforestation is projected to lead to around 55.7 Pg of cumulative carbon loss over the period 2005 to 2055 (Table 4). For $5/t C, this could be reduced to a loss of around 50.4 Pg or a gain of around 5.3 Pg C by 2055. At higher prices, more carbon is saved. For $50/t C, most of the losses are avoided by 2055. Note that, in the $50/t C case, deforestation still occurs in all regions, but substantial areas of land that were deforested previously are converted back to forestland, so that the net losses from forests are fairly small over the time frame. For $100/t C, forest areas rise substantially relative to the baseline, and around 76 Pg of additional carbon are stored.

Figure 3 presents abatement cost curves for reducing emissions from deforestation for each of the tropical regions. At all carbon price levels, Southeast Asia offers the largest emissions reductions and Central America the smallest in absolute terms. Southeast Asia has relatively lower opportunity costs per hectare and higher carbon density per hectare on average, leading to its lower cost estimate. Costs are higher for Central America because that region generally has less land available for sequestration. Africa has similar marginal costs as Southeast Asia for lower levels of sequestration, although the curves diverge above

350 Tg C per year. Marginal costs for South America fall in between those for the other regions.

For the $5/t C scenario, the rental values necessary to achieve these changes are estimated to range from $23/ha/year to $33/ha/year (Table 5). For the $100/t C, they are 20 times larger, ranging from $466/ha/year to $659/ha/year. Because of differences in carbon levels among the forest types in the region, the potential payments vary substantially.

An important point to recognize with these payments is that the total cost of the program would be higher than these values alone if implemented as project-level activities because the programs must also account for leakage (see Murray *et al*. [2004] and Sohngen and Brown [2004]). That is, to ensure that the carbon gains associated with reducing deforestation do not have leakage, the programs must also ensure that there are no carbon losses elsewhere as a direct result of the program aimed at reducing deforestation.

Figure 4 shows the estimated reductions in deforestation that could be achieved in each of our tropical regions as a function of rental rates per hectare per year. The lowest marginal costs for reducing deforestation appear to lie in Africa, followed by South America, Southeast Asia, and Central America. Interestingly, the ordering of marginal costs for reducing deforestation differs from the ordering of the marginal costs of reducing carbon shown in Figure 3. The largest difference exists with Southeast Asia. That region can sequester more carbon per hectare than other regions; thus, for less land use change, it achieves lower marginal costs for sequestration.

It is useful to put these results in context of other studies available. Two studies are of particular interest because they have done large global analyses. Sathaye *et al*. (Forthcoming) find that reducing deforestation can provide 34 Pg C by 2050 for $100/t C on 454 million additional hectares of forestland. The results in the present analysis are larger, implying potentially 76 Pg C, although the total land use change is smaller (422 million additional hectares). These differences suggest that the model used in this study assumes more carbon is saved with each hectare preserved. The model used here also assumes more carbon emissions in the baseline associated with deforestation. Kindermann *et al*. (2006) find that reducing deforestation can lead to around 1.4 Pg C per year between 2005 and 2025 for $100/t C. In this analysis, we find that around 1.6 Pg C per year can be preserved globally for $100/t C by reducing deforestation. Kindermann *et al*. do not present land area changed over the time period, nor do they present results by region, so it is not possible to further assess differences in the studies.

Although the results in this analysis are higher than the two other studies available that have examined economic consequences, they do not appear to be out of line with noneconomic studies. Soares-Filho *et al*. (2006), for example, examine potential carbon emissions from deforestation in the Amazon Basin. They suggest that in the baseline up to 210 million hectares may be deforested over the next 50 years. This estimate is larger than our estimate of around 136 million hectares of deforestation in all of South America. Based on this result and geographically detailed estimates of carbon losses from the forests that they simulate to actually be deforested, they find that 32 Pg C could be emitted over the next century, or 158 t C per hectare. Our estimate is that 17 Pg C will be lost over the same time period, or around 120 t C per hectare. One of their scenarios that protects land from deforestation increases total land in the region by 130 million hectares and preserves 17 Pg C from being emitted through deforestation by 2050. Although they do not present costs for their analysis, this is similar in scale to our $100/t C scenario, which preserves 167 million hectares (reduced deforestation and afforestation combined here) and gains around 22 Pg C, or 132 t C/ha. Our results appear to be well within line of the potential for sequestration within the region when compared to Soares-Filho *et al*. (2006), although our results imply that the carbon gains they suggest could cost as much as $75 to $100/t C.

6. CONCLUSIONS

This paper develops an economic analysis of the potential costs of reducing deforestation as a method to help mitigate climate change. Although the option of reducing deforestation was first described in the UNFCCC in the early 1990s and subsequently in the Kyoto Protocol of the late 1990s, policy makers have not yet developed mechanisms by which countries can be given credit, or incentives, for reducing the deforestation occurring within their boundaries. At the recent COP11 meeting in 2005, a decision was made to explore approaches that could be used to help reduce deforestation. This paper attempts to provide information relevant to that discussion and, in particular, to provide information on the potential costs of reducing deforestation globally. We used a global timber market and land use model that projects baseline carbon emissions from deforestation and other forestry-related land use activities. Carbon prices were then introduced into the model, and the resulting changes in deforestation and carbon are presented in the paper. To our knowledge, this paper is one of the first to consider how different carbon prices will affect potential levels of deforestation in tropical countries over time.

The results of the analysis presented in this paper indicate that there is large potential for reduced deforestation globally to help reduce the costs of reducing GHG emissions. For $100 per t C ($27.25/t CO_2), deforestation can potentially be virtually eliminated. Over 50 years, this could mean a net cumulative gain of 76 Pg C relative to the baseline and 422 million additional hectares in forests. For lower prices of $5 per t C ($1.36/t CO_2), only about 5 Pg C additional could be sequestered over 50 years. The largest gains in carbon occur in Southeast Asia, which gains nearly 30 Pg C for $100/t C, followed by South America, Africa, and Central America, which gain 22, 19, and 6 Pg C for $100/t C, respectively. The effects of carbon incentives on land use could be fairly substantial. For $5/t C, the model projects that there would be around 3 million additional hectares of forestland in the four regions analyzed by 2055. For $100/t C, the model projects that almost no deforestation occurs, and the four regions would have an additional 422 million hectares of forestland.

Although the $100/t C carbon scenario implies substantial potential for carbon sequestration, it is important to recognize that the total cost of this type of program would be exceptionally large. Based on the average carbon per hectare in tropical forests today, policy makers, or traders in the carbon market, would have to pay $465 to $660 per hectare per year to ensure that land does not convert to agriculture. Across the four regions considered above—Southeast Asia, South America, Africa, and Central America—the total costs of reducing deforestation would be $2.5 trillion at the $100/t C price, suggesting very large overall costs.

The results assume that forests are part of a comprehensive global approach for reducing GHG emissions. A comprehensive approach requires that all land be monitored and included in the program. These monitoring costs have not been incorporated into the estimates. One would expect that the actual costs of achieving sequestration through reduced deforestation would be more expensive than indicated above if these monitoring costs were considered and if efforts were undertaken to prevent leakage.

Currently, the main approach for incorporating forestry into global climate policy is through efforts undertaken on individual projects, not through a comprehensive approach as modeled. Projects must account for additionality, permanence, and leakage. Incorporating these factors into project design raises the costs of carbon sequestration. Thus, actually achieving the levels of carbon potential suggested above through the project-based approach would cost more than the estimates above indicate, though it is outside the scope of this study to determine how much more expensive the project-based approach would be.

Even though this study has provided estimates of potential carbon sequestration from reducing deforestation in several regions of the world, readers should recognize that the model used for the analysis does not fully account for all possible adjustments in land markets in those regions. For instance, one would expect that, as more land is devoted to forestry with carbon incentives the price of agricultural products would increase. This would in turn raise the costs of further sequestration. The price changes in agriculture are in reality endogenous, although this model has assumed they are exogenous. Thus, the costs are likely to be higher than estimated here in reality. Developing modeling tools to account for the endogeneity in prices between agricultural and forestry markets is an important future research direction.

In addition, the model used in this analysis is fairly aggregated with respect to land uses in tropical regions. In practice, there is much more spatial heterogeneity across the landscape, and actual carbon sequestration programs would need to take this heterogeneity into account when considering policies for reducing deforestation. Developing models that have more spatial resolution could help policy makers better target programs to specific regions or areas within the large, "continental" scale results presented in this study.

Nonetheless, when our results for South America are compared with the more spatially disaggregated results of Soares-Filho *et al*. (2006), the results are similar (although the present analysis appears more conservative). More spatial resolution, thus, may provide policy makers with more information about where reductions in deforestation could occur, but the additional data will not necessarily alter the estimates of the marginal costs of sequestration from reduced deforestation presented here.

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Table 1. Forest Cover Change, 1990–2005

Region	Total Forest Cover (1 000 ha)			Change in Forest Cover, 1990–2000		Change in Forest Cover, 2000–2005	
	1990	2000	2005	Annual Change (1 000 ha)	Annual Rate of Change (%/year)	Annual Change (1 000 ha)	Annual Rate of Change (%/year)
Africa	699 361	655 613	635 412	-4 374.8	-0.65%	-4 040.2	-0.63%
Asia	574 487	566 562	571 577	-792.5	-0.14%	1 003.0	0.18%
East Asia	208 155	225 663	244 862	1 751.8	0.81%	3 839.8	1.63%
SE & S Asia	323 156	297 380	283 127	-2 578.6	-0.83%	-2 850.6	-0.98%
W & C Asia	43 176	43 519	43 588	34.3	0.08%	13.8	0.03%
Central America	102 008	95 086	92 626	-692.2	-0.70%	-492.0	-0.52%
Europe	989 320	998 091	1 001 394	877.1	0.09%	660.6	0.07%
North America	608 782	612 428	613 223	364.6	0.06%	159.0	0.03%
Oceania	212 514	208 034	206 254	-448.0	-0.21%	-356.0	-0.17%
South America	890 818	852 796	831 540	-3 802.2	-0.44%	-4 251.2	-0.50%
Total	4 077 290	3 988 610	3 952 026	-8 868.0	-0.22%	-7 316.8	-0.18%

Source: United Nations, Food and Agricultural Organization, 2005.

Table 2. Projections of Deforestation and Net Changes in Forestland and Carbon Changes Caused by Land Use Change in Tropical Regions, 2005–2015

Region	Deforestation	Net Change in Forestland	C Loss from Deforestation	Net C Loss from Change in Forestland
	Million ha/yr		Tg C/yr	
Africa	5.3	5.1	535.3	531.4
Central America	1.2	0.7	128.1	125.5
South America	4.0	3.5	428.1	417.0
Southeast Asia	2.6	2.5	367.5	363.4
Total	13.1	11.8	1 459.0	1 437.2

Source: Authors' calculations for this study.

Table 3. Reduction in Average Annual Deforestation Rate, 2005–2055

Region	Carbon Price ($/t C)				
	$5	**$10**	**$20**	**$50**	**$100**
Africa	-15.3%	-28.0%	-43.9%	-78.0%	-97.4%
Central America	-17.7%	-39.3%	-65.2%	-83.0%	-94.7%
South America	-8.4%	-16.2%	-28.9%	-62.3%	-101.5%
Southeast Asia	-9.8%	-18.9%	-34.1%	-69.8%	-96.4%
Total	-14.0%	-28.3%	-47.0%	-76.7%	-98.1%

Source: Authors' calculations for this study.

Table 4. Summary of Gains from Sequestration Scenarios

		Carbon Price					
		Baseline	**$5/t C**	**$10/t C**	**$20/t C**	**$50/t C**	**$100/t C**
Africa	Hectares in 2055 (Millions)	202.8	206.9	219.2	246.1	312.9	357.5
	Carbon in 2055 (Pg)	62.3	64.5	66.5	69.4	77.1	81.4
	C Loss (2005–2055) (Pg)	18.6	16.5	14.4	11.5	3.8	-0.4
	C Gain over Baseline by 2055 (Pg)	—	2.1	4.2	7.1	14.8	19.0
Central America	Hectares in 2055 (Millions)	38.0	22.4	39	40.2	47.3	55.1
	Carbon in 2055 (Pg)	7.8	8.3	9.8	10.8	11.9	12.9
	C Loss (2005–2055) (Pg)	4.5	4	2.5	1.6	0.5	-0.5
	C Gain over Baseline by 2055 (Pg)	—	0.5	2	2.9	4.1	5.0
South America	Hectares in 2055 (Millions)	732.3	739.5	748.7	768.2	821.6	899.3
	Carbon in 2055 (Pg)	193.4	194.8	196.2	198.7	205.8	215.8
	C Loss (2005–2055) (Pg)	16.7	15.3	13.9	11.4	4.3	-5.7
	C Gain over Baseline by 2055 (Pg)	—	1.4	2.8	5.3	12.4	22.4
Southeast Asia	Hectares in 2055 (Millions)	127.7	134.5	141.2	153	184	211
	Carbon in 2055 (Pg)	38.8	40.1	42.2	47	58.1	68.7
	C Loss (2005–2055) (Pg)	15.9	14.6	12.6	7.7	-3.4	-13.9
	C Gain over Baseline by 2055 (Pg)	—	1.3	3.3	8.2	19.3	29.8
Total	Hectares in 2055 (Millions)	1 100.7	1 103.3	1 148.1	1 208.0	1 365.8	1 522.9
	Carbon in 2055 (Pg)	302.4	307.7	314.7	325.9	352.9	378.7
	C Loss (2005–2055) (Pg)	55.7	50.4	43.4	32.2	5.3	-20.5
	C Gain over Baseline by 2055 (Pg)	—	5.3	12.2	23.5	50.5	76.3

Source: Authors' calculations for this study.

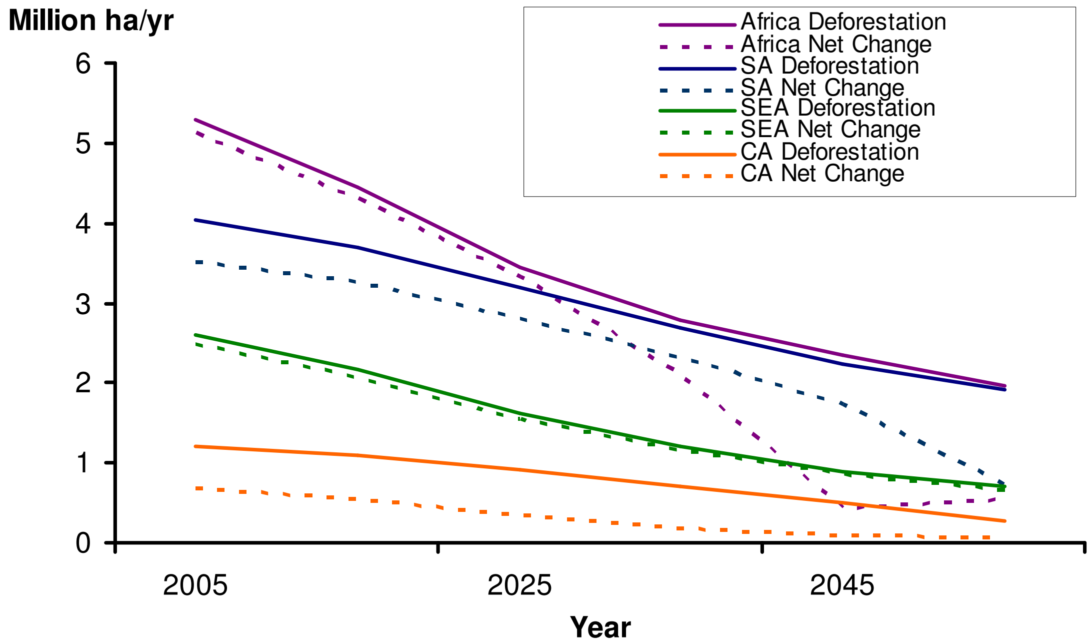
Table 5. Average Annual Rental Payments Required to Achieve the Land Use and Carbon Changes Estimated at Different Carbon Prices ($/hectare/year)

Region	Carbon Price ($/t C)				
	$5	**$10**	**$20**	**$50**	**$100**
South America	$29.84	$59.68	$119.37	$298.46	$596.98
	(3.17 , 34.13)	(6.35 , 68.27)	(12.72 , 136.54)	(31.92 , 341.35)	(64.2 , 682.7)
Central America	$23.22	$46.44	$92.96	$232.66	$465.83
	(3.19 , 33.46)	(6.39 , 66.93)	(12.81 , 133.87)	(32.2 , 334.69)	(64.91 , 669.38)
Southeast Asia	$32.93	$65.87	$131.77	$329.55	$659.37
	(3.06 , 61.21)	(6.13 , 122.43)	(12.3 , 244.86)	(30.88 , 612.15)	(62.83 , 1224.31)
Africa	$24.97	$49.94	$99.9	$249.83	$499.79
	(3.18 , 29.92)	(6.37 , 59.85)	(12.78 , 119.71)	(32.22 , 299.28)	(66.42 , 598.56)

Note: Range in rental payments across forest types in parentheses.

Source: Authors' calculations for this study.

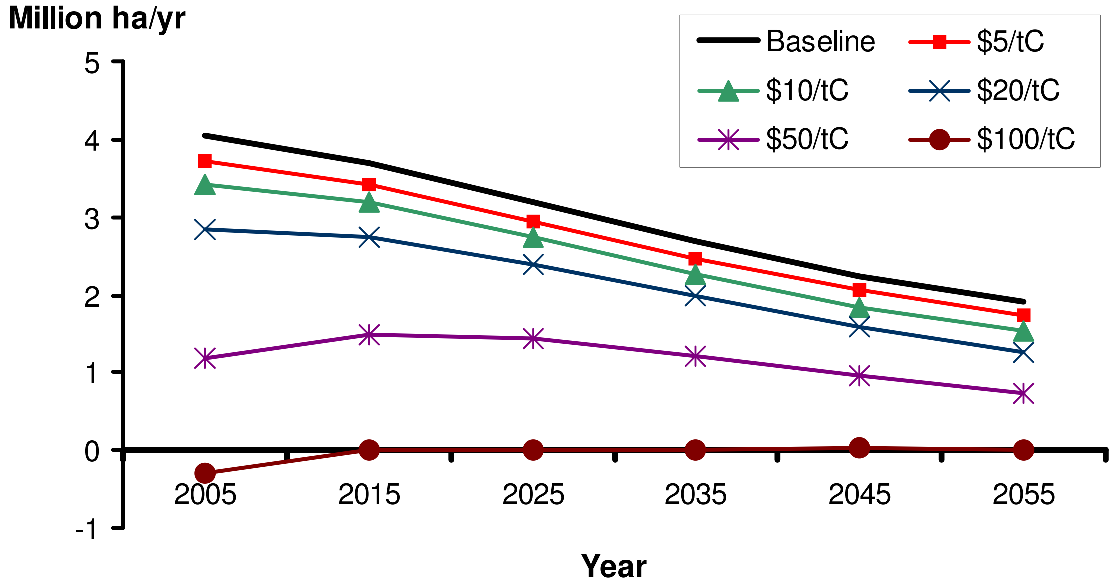
Figure 1. Projection of Future Land Use Change in Tropical Regions



Note: SA = South America; SEA = Southeast Asia; and CA = Central America.

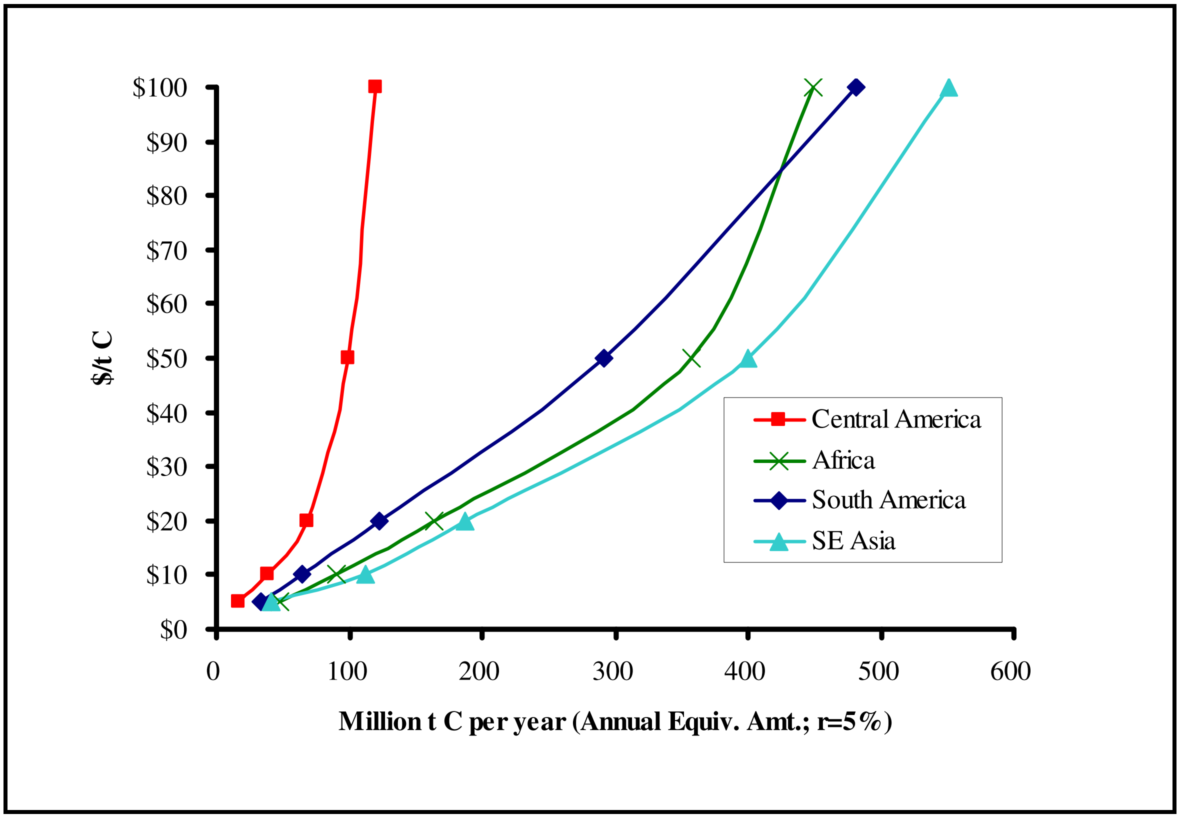
Source: Authors' calculations for this study.

Figure 2. Effects of Carbon Prices on the Time Path of Deforestation in South America



Source: Authors' calculations for this study.

Figure 3. Abatement Cost Curves for Avoided Deforestation: Estimates are the Gain in C Sequestration Relative to the Baseline from Reduced Deforestation Measured as the Annual Equivalent Amount of Gains from 2005–2055



Source: Authors' calculations for this study.

Figure 4. Supply Curve for Reducing Tropical Deforestation, 2005–2055