Global cost estimates of reducing carbon emissions through avoided deforestation

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Tropical deforestation is estimated to cause about one-quarter of anthropogenic carbon emissions, loss of biodiversity, and other environmental services. United Nations Framework Convention for Climate Change talks are now considering mechanisms for avoiding deforestation (AD), but the economic potential of AD has yet to be addressed. We use three economic models of global land use and management to analyze the potential contribution of AD activities to reduced greenhouse gas emissions. AD activities are found to be a competitive, low-cost abatement option. A program providing a 10% reduction in deforestation from 2005 to 2030 could provide 0.3–0.6 Gt (1 Gt = 1 × 10^5 g) $CO_2 \cdot yr^{-1}$ in emission reductions and would require \$0.4 billion to \$1.7 billion$\cdot yr^{-1}$ for 30 years. A 50% reduction in deforestation from 2005 to 2030 could provide 1.5–2.7 Gt $CO_2 \cdot yr^{-1}$ in emission reductions and would require \$17.2 billion to \$28.0 billion$\cdot yr^{-1}$. Finally, some caveats to the analysis that could increase costs of AD programs are described.

carbon sequestration | climate change | reducing emissions from deforestation and ecosystem degradation (REDD) | marginal cost | tropical forest

Tropical deforestation is considered the second largest source of greenhouse gas emissions (1) and is expected to remain a major emission source for the foreseeable future (2). Despite policy attention on reducing deforestation, ≈13 million ha$\cdot$yr^{-1} of forests continue to be lost (3). Deforestation could have the effect of cooling the atmosphere (4), but it also leads to reductions in biodiversity, disturbed water regulation, and the destruction of livelihoods for many of the world's poorest (5). Slowing down, or even reversing, deforestation is complicated by multiple causal factors, including conversion for agricultural uses, infrastructure extension, wood extraction (6–9), agricultural product prices (10), and a complex set of additional institutional and place-specific factors (11).

Avoided deforestation (AD) was included alongside afforestation as a potential mechanism to reduce net global carbon emissions in the Kyoto Protocol (KP), but until recently, climate-policy discussions have focused on afforestation and forest management. Discussions about new financial mechanisms that include AD provide optimism for more effective synergies between forest conservation and carbon policies (11–14). In 2005, Papua New Guinea and Costa Rica proposed to the United Nations Framework Convention on Climate Change that carbon credits be provided to protect existing native forests (15). The proposal triggered a flurry of discussion on the topic. Soares-Filho *et al.* (16), for example, suggest that protecting ≈130 million ha of land from deforestation in the Amazon could reduce global carbon emissions by 62 Gt (1 Gt = 1 × 10^{15} g) CO_2 over the next 50 years.

Although the potential for AD activities to help mitigate climate change is widely acknowledged (16, 17), there is little information available on what the costs might be globally. This article uses three different global forestry and land-use models to estimate carbon supply functions for emission reductions from AD activities. The use of global models is preferred in the case of climate mitigation with land use for two reasons. First, differences across regions in the carbon content of forests, opportunity costs of land, and the costs of access can have important implications for costs. Second, large-scale adjustments, which are likely with policies to reduce deforestation, will affect prices globally. These global changes need to be considered when estimating supply functions (marginal costs) for emission reductions. In addition to being global, the models in this article are intertemporal, taking into account changes that occur over time, such as incentives for deforestation (e.g., demand for agricultural land depending on changes in population, income, and technology). Although agriculture is not explicitly modeled, our models do include different scenarios for agricultural land demand.

Comparing results from several models allows us to assess the sensitivity of results with respect to the use of different methods, datasets, assumptions about future markets, and other potentially important factors (carbon content of forests, interest rates, risk, etc.). Although we do not develop confidence intervals, the results provide a set of estimates that can help policy makers understand the potential cost range of AD.

Table 1. Average carbon per ha and number of ha for tropical forests in the three models used in this analysis

	t C/ha (million ha)		
Model	Central and South America	Africa	Southeast Asia
GTM	106 (913)	100 (352)	132 (202)
DIMA	86.4 (842)	87.7 (684)	74.7 (181)
GCOMAP	97.2 (965)	54.6 (650)	48 (286)

Marginal Cost Curves for AD

The three models used here are the Dynamic Integrated Model of Forestry and Alternative Land Use (DIMA) (18, 19), the Generalized Comprehensive Mitigation Assessment Process

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Table 2. Average annual ha deforested and carbon emitted as a result between 2005 and 2030

	Million ha·yr^{-1} (Gt CO_2·yr^{-1})			
Model	Central and South America	Africa	Southeast Asia	Global
GTM	4.84 (1.86)	4.58 (1.72)	2.23 (1.07)	11.65 (4.69)
DIMA	3.62 (1.15)	4.98 (1.61)	1.14 (0.31)	10.60 (3.22)
GCOMAP	4.31 (1.57)	5.99 (1.37)	1.90 (0.38)	12.20 (3.31)

Model (GCOMAP) (20, 21), and the Global Timber Model (GTM) (22, 23). A brief description of each model follows, but a more detailed discussion can be found in supporting information (SI) *Appendices 1–3*. DIMA assesses land-use options in agriculture and forestry in 0.5°-grid cells across the globe. The model predicts deforestation in forests where land values are greater in agriculture than in forestry and, vice versa, afforestation of agricultural and grazing lands where forestry values exceed agricultural ones. GCOMAP is a dynamic partial equilibrium model that analyzes afforestation in short- and long-run species and reductions in deforestation in 10 world regions. GTM is a dynamic optimization model that optimizes the land area, age class distribution, and management of forestlands in 250 timber types globally. Although the model also deals with afforestation and biofuels as mitigation options, this analysis focuses on results for AD.

To estimate the costs of reduced emissions from AD, each model must generate a baseline projection of future deforestation. The baseline is assumed to occur when AD carbon prices are \$0 t^{-1} CO_2. Each model's baseline embeds model-specific assumptions about future changes in economic conditions, *inter alia* population, technology, and trade. The economic assumptions for each model are described in detail in *SI Appendices 1–3*. In addition, carbon emissions from deforestation will depend on assumptions about the quantity of carbon in forest biomass (Table 1).

Different economic and biological assumptions cause the three models to present variable deforestation and carbon-emission projections (Table 2). Estimated deforestation fluctuates over time between 2005 and 2030, but Table 2 presents only the average. GCOMAP estimates the largest area deforested by 2030. GTM projects a smaller area of land deforested, but a larger emission of carbon because that model assumes the largest aboveground storage of carbon per ha. DIMA shows the lowest emission, because of both lower loss projections and lower carbon content assumptions in Latin America.

To determine the marginal costs of carbon storage resulting from AD, additional simulations are conducted with the three models assuming constant carbon prices ranging from \$0 t^{-1} CO_2 to \$100 t^{-1} CO_2. Higher carbon prices will induce the models to allocate more land to forests, and consequently less deforestation will occur. Reductions in carbon emissions from AD are obtained by comparing baseline emissions with the emission path when AD is compensated. The models project results for a longer period, but we present results here only for 2005–2030.

Marginal cost curves, with annual CO_2 emissions reduced on the *x* axis and the carbon price on the *y* axis, are shown for each

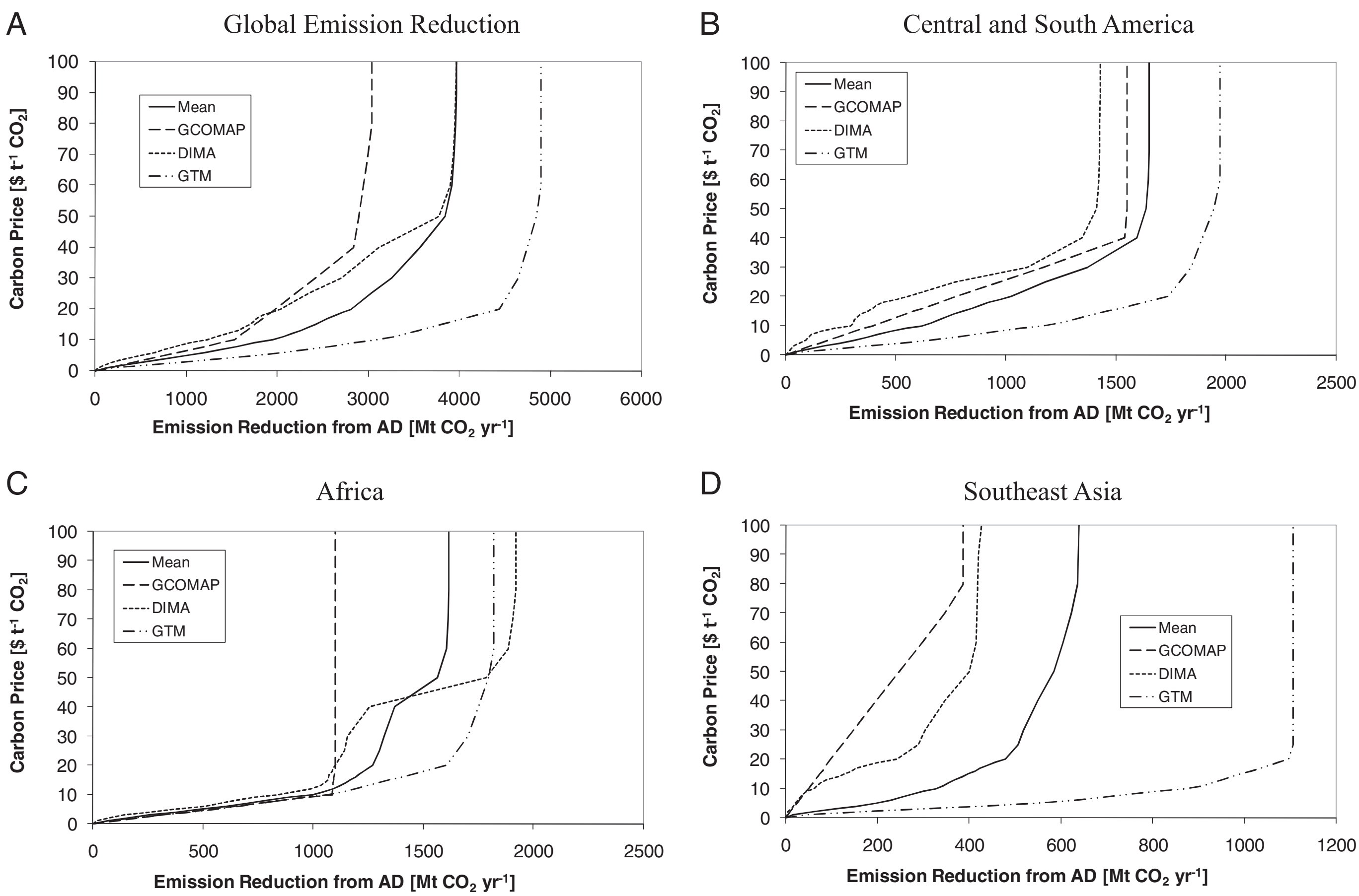

Fig. 1. Marginal costs in 2010 of emissions reductions with AD activities in three regions with predictions of the three models. (*A*) Global emission reduction. (*B*) Central and South America. (*C*) Africa. (*D*) Southeast Asia.

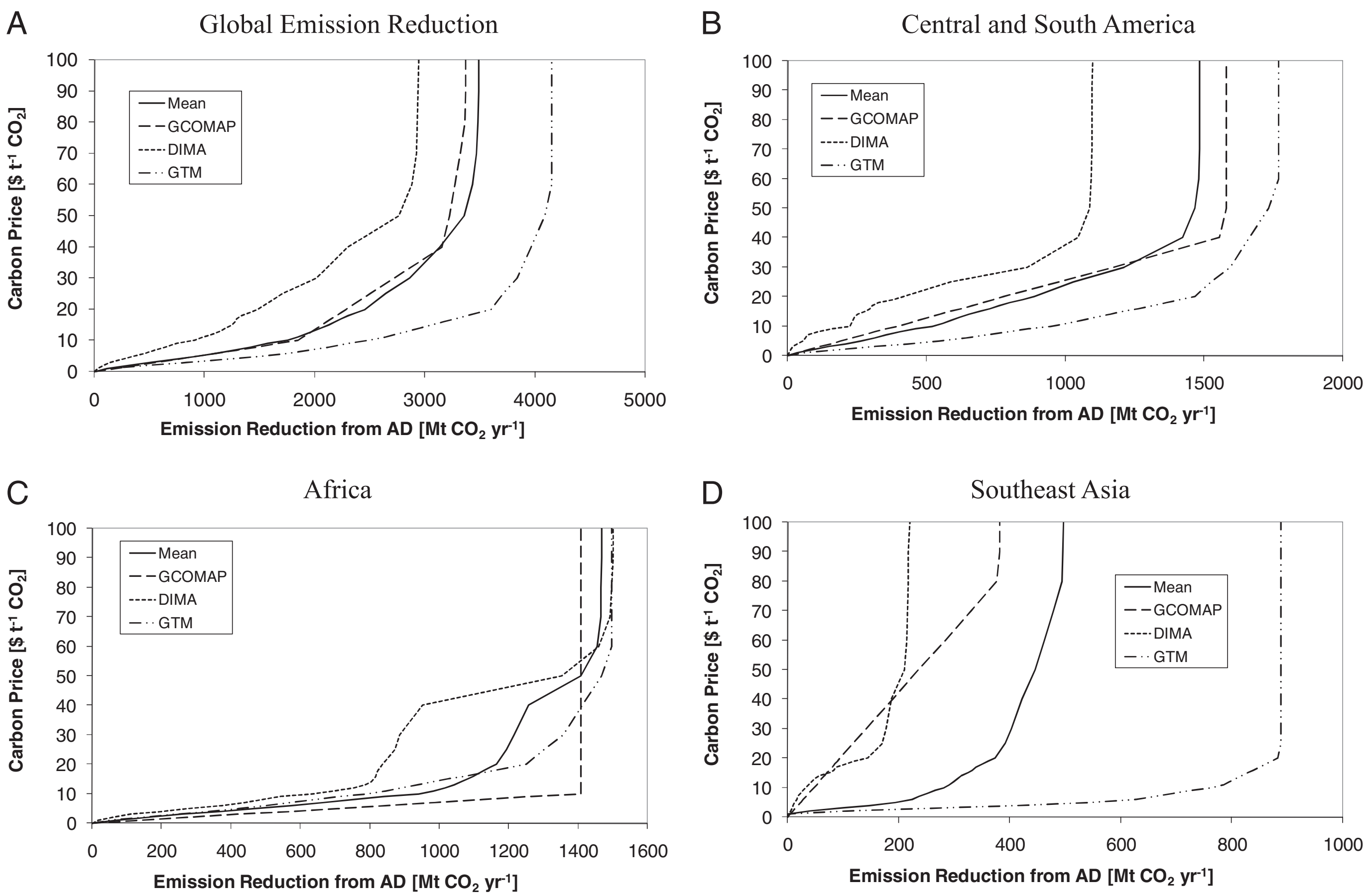

Fig. 2. Marginal costs in 2020 of emissions reductions with AD activities in three regions with predictions of the three models. (*A*) Global emission reduction. (*B*) Central and South America. (*C*) Africa. (*D*) Southeast Asia.

model for 3 years [2010 (Fig. 1), 2020 (Fig. 2), and 2030 (Fig. 3)]. Forest owners would maintain land with the lowest-valued alternative uses (lowest conservation opportunity costs) in forests at the lowest carbon prices, whereas progressively higher carbon prices are required for land with higher opportunity costs.

The results generally indicate that substantial emission reductions can be accomplished over the entire 25-year period examined. For \$20 t^{-1} CO_2, the models project that the average global emission reduction from AD activities between 2005 and 2030 would be in the range of 1.6 to 4.3 Gt $CO_2{\cdot}yr^{-1}$. For higher prices (\$100 $t^{-1}CO_2$), the models project emission reductions of 3.1–4.7 Gt $CO_2{\cdot}yr^{-1}$. The time path of marginal costs suggests that the low-cost emission reductions occur earlier on. At \$100 t^{-1} CO_2, the emission reduction averaged for all three models in 2010 is 4.0 Gt $CO_2{\cdot}yr^{-1}$, but this falls to 3.1 Gt $CO_2{\cdot}yr^{-1}$ by 2030. Marginal costs tend to rise over time because the lowest-cost opportunities are adopted first and rates of deforestation decline, while later the opportunity costs of land rise because of rising productivity in agriculture.

The marginal cost curves differ across models for a number of reasons, including the input datasets (e.g., underlying estimates of the opportunity costs of land), modeling methodologies and assumptions, and ecological parameters (e.g., carbon per ha). GTM has lower land opportunity costs and higher carbon densities per ha than the other two models, and consequently model simulations using GTM generally result in the lowest marginal cost estimates (the largest emission reduction per dollar spent; see Figs. 1*A*, 2*A*, and 3*A*). GCOMAP has the highest global estimates of marginal costs in 2010, but by 2020 and 2030, DIMA projects the highest global estimates of marginal costs. The marginal costs in DIMA become substantially more expensive over time.

As expected, the marginal costs of emission reductions will vary by region (24). The three models suggest unanimously that the lowest-cost region is Africa, followed by Central and South America and Southeast Asia. Over 2005–2030, the models project that Africa could provide 0.9–1.5 Gt $CO_2{\cdot}yr^{-1}$ for \$20 t^{-1} CO_2, whereas Latin America could provide 0.8–1.7 Gt $CO_2{\cdot}yr^{-1}$, and Southeast Asia could provide 0.1–1.1 Gt $CO_2{\cdot}yr^{-1}$. At \$100 t^{-1} CO_2, the projections rise to 1.4–1.7 Gt $CO_2{\cdot}yr^{-1}$ for Africa, 1.1–1.9 Gt $CO_2{\cdot}yr^{-1}$ for Latin America, and 0.3–1.1 Gt $CO_2{\cdot}yr^{-1}$ for Southeast Asia.

Costs to Reduce Deforestation by 10% and 50%

Current AD policy proposals focus on compensating reductions in deforestation vis-à-vis predefined national baselines. Countries would estimate their projected baseline deforestation rates for a given period (using methods not yet determined), and then agree to develop policies at the national level to reduce the rates of change. Presumably, with compensated reductions, they would then be paid *ex post* for the reductions they achieve. How much would it cost to achieve 10% and 50% reduction levels between 2005 and 2030? The three models can conveniently link deforestation rates to specific carbon and land rental payments (Table 3).

Our results indicate that a 10% reduction in deforestation rates over the time period would cost \$2–5 t^{-1} CO_2, and a 50% reduction in deforestation rates would cost \$10–21 t^{-1} CO_2. Payment levels in the 10–50% range could generate substantial

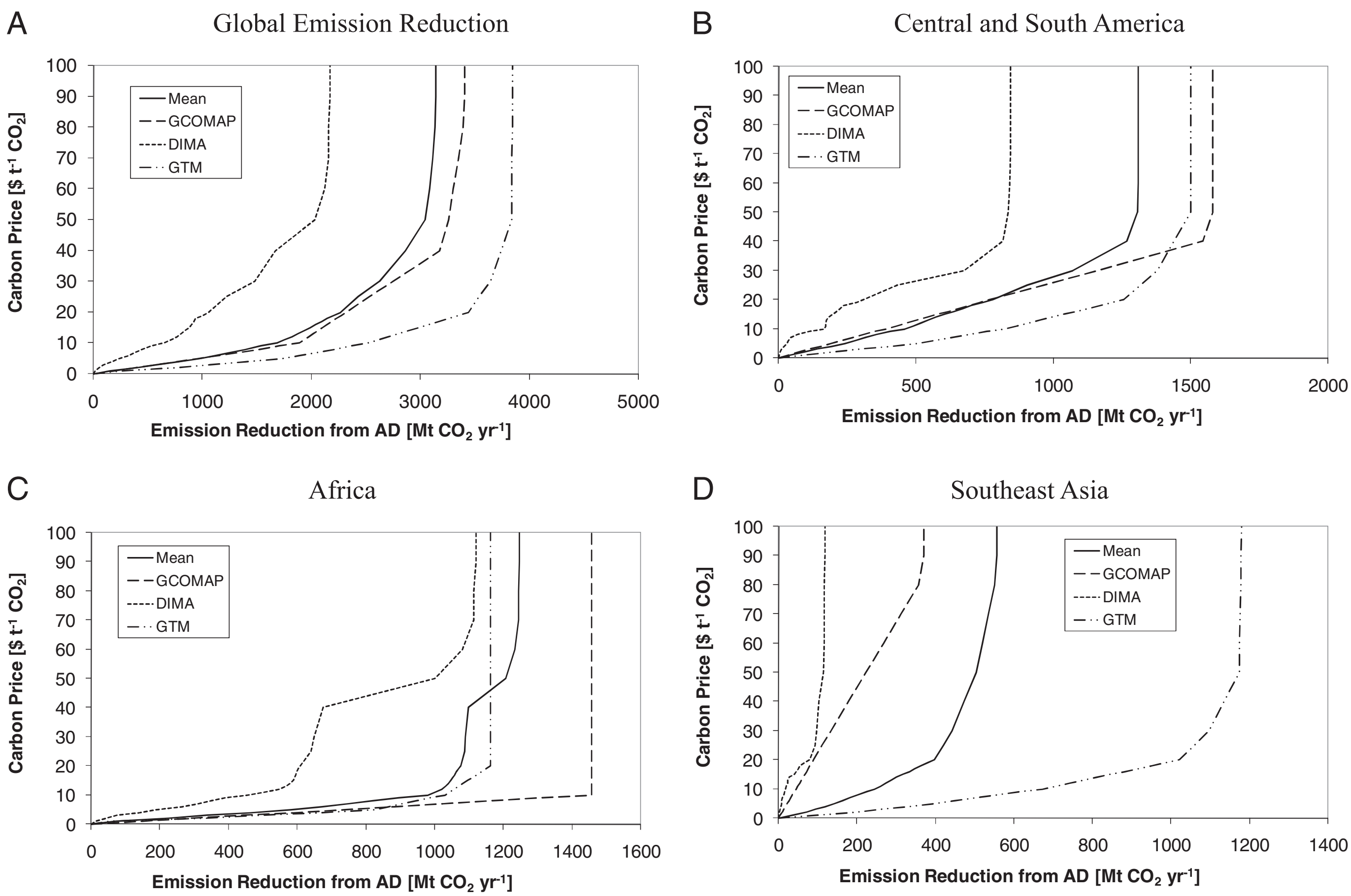

Fig. 3. Marginal costs in 2030 of emissions reductions with AD activities in three regions with predictions of the three models. (*A*) Global emission reduction. (*B*) Central and South America. (*C*) Africa. (*D*) Southeast Asia.

financial flows to landowners who reduce deforestation. Given the carbon intensities described above, carbon prices of \$2 t^{-1} CO_2 could translate into carbon rental values of \$20-\$35 $ha^{-1}\cdot yr^{-1}$ for standing forests, whereas carbon prices of \$10 t^{-1} CO_2 would trigger land rental values of \$85-\$252 $ha^{-1}\cdot yr^{-1}$. Agricultural rents at the margin of infrastructural improvements (e.g., along new roads in newly accessed regions), where most deforestation occurs, are quite often lower than these estimates, suggesting that in many cases carbon payments could provide powerful economic incentives for reducing deforestation.

Present-value techniques are used to calculate the total costs of reducing deforestation by 10% and 50%. The annual costs of reducing deforestation between 2005 and 2030 are first calculated by multiplying the annual reductions in emissions by the carbon price. The present value of this stream of costs is then calculated, followed by the annual equivalent amount. For internal consistency, individual modelers used their own interest rates to calculate these costs. In the three models, reducing deforestation by 10% globally between 2005 and 2030 could provide 0.3–0.6 Gt $CO_2\cdot yr^{-1}$ in emission reductions globally, with annual equivalent costs of \$0.4 billion to \$1.7 billion yr^{-1}. Correspondingly, halving global forest loss could reduce emissions by 1.5–2.7 Gt $CO_2\cdot yr^{-1}$, triggering annual equivalent costs of \$17.2 billion to \$28.0 billion yr^{-1}.

Costs of these land-use actions compare favorably to other options for abating carbon emissions. A recent assessment, using three well known energy models, suggested that meeting a 550 parts per million stabilization target would require society to reduce CO_2 emissions by ≈3.5 Gt $CO_2\cdot yr^{-1}$ between 2010 and 2030, and would cost \$9 t^{-1} CO_2 (25). None of the models used in that study considered AD, but our estimates indicate that \$9 t^{-1} CO_2 could reduce deforestation by 10–50% over the next 30 years and provide an emission reduction of 0.8–2.5 Gt $CO_2\cdot yr^{-1}$. AD could thus provide substantial additional emission reduc-

Table 3. Carbon price in \$ t^{-1} CO_2 necessary to generate a 10% and 50% reduction in deforestation in 2030

	10% reduction, \$			50% reduction, \$		
Area	GCOMAP	DIMA	GTM	GCOMAP	DIMA	GTM
Central and South America	3.98	8.03	1.48	19.86	24.48	9.70
Africa	1.04	3.50	1.63	5.20	12.30	9.60
Southeast Asia	8.42	8.73	1.24	38.15	19.56	8.31
Globe	3.50	4.62	1.41	16.90	20.57	9.27

tions at costs levels consistent with the energy models, while providing numerous ecological and environmental benefits in addition to greenhouse gas mitigation.

These results imply that reducing emissions from AD is a relatively low-cost option, although those costs in absolute terms are not tiny. Reducing deforestation by ≈10% over the next 25 years would cost \$1.2 billion yr^{-1}. This estimate is lower than current global forestry investments of ≈\$18 billion yr^{-1} (26), but note that most current forestry investments are private and occur domestically in developed countries. Public funding of forestry through official development assistance (ODA) and official aid (OA) has averaged \$564 million during 1996–2004 (27). Although they have not to date been widely used for forest and land use projects, carbon markets may provide additional opportunities for AD funding in the future. The market for certified emissions reductions currently trades \$2.7 billion yr^{-1} (28), but it continues to increase. Resources available for AD will grow if a climate policy framework for post-2012 is developed with explicit reference to AD activities (29).

Additional Factors Influencing Costs

Examples of existing programs to protect forests in Costa Rica, Mexico, and India (11, 30) indicate that forest conservation is possible with well designed tools and well funded programs. Conversely, cases exist where few environmental services are paid for, and land users receive minimal payments with minimal incentive effects (31). Experiences with payments for environmental services are thus incipient. Some factors discussed in the above references, but not counted in our estimates, could increase total costs.

First, setting up, implementing, and verifying projects to reduce deforestation could have additional costs beyond the carbon itself. For Clean Development Mechanism (CDM) type AD, afforestation, and other offsets projects, these "transactions" costs have been estimated to range from \$0.03 t^{-1} CO_2 for large projects to \$4.05 t^{-1} CO_2 for smaller ones, with a weighted average of \$0.26 t^{-1} CO_2 for all projects (32). Even if AD programs shift from the project-based approach and instead focus on country-level "compensated reductions," verification expenses could be higher yet because all tons of carbon in a country will have to be measured, not just the tons in areas where forest protection activities are undertaken.

Second, accounting for leakage could impose additional costs, given that current estimates of leakage in forestry projects range from 10% to >90% (33, 34). Transactions costs and potential leakage may partly explain why the contribution from afforestation in the CDM has been minimal in the KP. The cap on Annex I use of credits from afforestation is 1% of 1990 emissions, but actual uptake of existing projects suggests that only ≈1% of this 1% will be used for implementation during the first commitment period.

Third, the right type of incentive or policy to change land use will vary from country to country, and experimentation may take many failures before success is achieved. This may be particularly true in regions where there are no legal *a priori* owners of the land threatened by deforestation, and it is difficult to identify which actors are adequate targets for incentive payments (35). Experiences from microfinance schemes and payments for environmental services from forests (36, 37) do provide useful frameworks for how to deliver, but the implementation challenges of this novel tool would probably not be small.

Conclusion

Reducing emissions from deforestation, a major source of CO_2, could potentially be a highly cost-effective option for climate policy. Using three global forestry and land-use models, we calculate that emission reductions from AD activities could provide substantial quantities of carbon at prices suggested by energy models. For carbon prices of \$100 t^{-1} CO_2, emission reductions of 3.1–4.7 Gt $CO_2 \cdot yr^{-1}$ could be obtained through AD activities during 2005–2030. A 10% reduction in deforestation could be accomplished for \$0.4 billion to \$1.7 billion yr^{-1}, providing emission reductions of 0.3–0.6 Gt $CO_2 \cdot yr^{-1}$ during 2005 to 2030 if efficiently implemented. A 50% reduction in deforestation could reduce emissions by 1.5–2.7 Gt $CO_2 \cdot yr^{-1}$ during 2005 to 2030, but it would cost substantially more, \$17.2 billion to \$28.0 billion yr^{-1}. These estimates are based on economic models that do not consider transactions costs and other institutional barriers, which raise costs in practice. However, a 10% reduction in the rate of deforestation could be feasible within the context of financial flows available through the current CDM and ODA/OA assistance. Policymakers need to develop clear incentives for countries to adopt baselines and national targets so that systems can be developed to credit reductions in deforestation, thus paving the way for funding AD activities.

Methods

The three models used in this analysis have been developed separately by three different modeling groups. *SI Appendices 1–3* provide further details on each of the models. Each model calculates a baseline quantity of carbon sequestered in forests over a varying time horizon, which depends on the specific model. This analysis presents results only through 2030. The baseline for each model embeds model-specific assumptions about the future evolution of agricultural land rents, demand for forestry products, technology change, and other economic drivers (see *SI Appendices 1–3*). As a consequence of these economic processes, the models will project deforestation into the future and the resulting emissions of carbon into the atmosphere.

The models are then used to calculate the quantity of carbon in forests under alternative carbon price regimes. Carbon prices used in this analysis range from \$0 t^{-1} CO_2 to \$100 t^{-1} CO_2. These prices are held constant across the entire time horizon for each model. Because carbon has value, less deforestation occurs in the models under the carbon price scenarios. Emission reductions are calculated as the difference between net annual emissions with a positive carbon price and net annual emissions in the baseline between 2005 and 2030. The marginal cost of emission reductions is the carbon price under the different scenarios. For Figs. 1–3, the individual models are used to calculate the reduction in emissions from AD at the specific time periods analyzed (2010, 2020, and 2030).

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