Global economic potential for reducing carbon dioxide emissions from mangrove loss

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Mangroves are among the most threatened and rapidly disappearing natural environments worldwide. In addition to supporting a wide range of other ecological and economic functions, mangroves store considerable carbon. Here, we consider the global economic potential for protecting mangroves based exclusively on their carbon. We develop unique high-resolution global estimates (5′ grid, about 9 × 9 km) of the projected carbon emissions from mangrove loss and the cost of avoiding the emissions. Using these spatial estimates, we derive global and regional supply curves (marginal cost curves) for avoided emissions. Under a broad range of assumptions, we find that the majority of potential emissions from mangroves could be avoided at less than $10 per ton of CO_2. Given the recent range of market price for carbon offsets and the cost of reducing emissions from other sources, this finding suggests that protecting mangroves for their carbon is an economically viable proposition. Political-economy considerations related to the ability of doing business in developing countries, however, can severely limit the supply of offsets and increases their price per ton. We also find that although a carbon-focused conservation strategy does not automatically target areas most valuable for biodiversity, implementing a biodiversity-focused strategy would only slightly increase the costs.

emission offsets | deforestation | land-based carbon | carbon markets | ecosystem services

Mangroves are among the most threatened and rapidly disappearing natural environments worldwide (1). Mangroves are concentrated in the tropics, serve a wide range of ecological functions, and provide people with various economically valuable products and services (2). However, as a result of conversion to other uses, mangroves in many areas of the world are degraded and their area is substantially reduced relative to their historic range (2, 3).

Mangrove ecosystems provide nursery habitats for fish, crustaceans, birds, and marine mammals (2, 4, 5), and they also offer considerable carbon (C) storage (6–9). Recent findings indicate that each hectare of mangroves stores several times the amount of carbon found in upland tropical forests (8). Although mangroves cover only around 0.7% (around 140,000 km^2) of global tropical forests (10), they possibly store up to 20 Pg C (8), equivalent to roughly 2.5 times annual global carbon dioxide (CO_2) emissions. Moreover, if left undisturbed, the carbon storage by mangroves currently continues to expand through biological sequestration of CO_2 and carbon burial (9). If current trends in conversion continue, however, much of the carbon stored in mangroves along with its future accumulation could be lost (8).

Similar concerns relate to the general loss of tropical forests (11). Programs to reduce emissions from deforestation and degradation (REDD programs) are intended to address these concerns by encouraging developing countries to decrease forest-based emissions of CO_2 and, as such, generate carbon offsets. Carbon offsets can then be sold to buyers, typically in developed countries, who are voluntarily or under a regulatory requirement seeking to offset their CO_2 emissions. REDD programs are particularly attractive for their potential to provide low-cost options to mitigate global greenhouse gas (GHG) emissions in the near term (12). REDD has become prominent in international climate negotiations, under the United Nations Framework Convention on Climate Change, and in various regional and state programs, such as the recently rolled-out California's Global Warming Solutions Act, also known as AB 32 (13), as well as various bilateral agreements, such as the Indonesia-Norway REDD partnership (14). A REDD-type program to promote the conservation of mangroves and coastal ecosystems more broadly has been suggested and may be warranted (15).

Although the knowledge of mangrove carbon storage has improved in recent years (2, 8, 10, 15), a paucity of economic assessments of a potential carbon-credit system, similar to that of REDD programs, exist for mangroves (15). Here, our purpose is to address this gap by estimating the economic costs and benefits of protecting mangroves to maintain their carbon storage. Although the overall scope of our assessment is global (Fig. 1), we address essential spatial variation in various biophysical and economic conditions by developing localized estimates of the key variables, such as carbon storage (above ground, below ground, and soil carbon), mangrove loss rates, and the opportunity cost of avoiding emissions (preserving mangroves).

More specifically, we draw from a broad range of data to develop unique spatially explicit, high-resolution (5′ grid, about 9 × 9 km) global estimates of the carbon stored in mangroves, projected emissions from mangrove loss, and the cost of avoided emissions. Using these data, we systematically examine the biophysical and economic potential of mangrove preservation for avoiding CO_2 emissions. We first estimate global and regional supply curves (marginal cost curves) for avoided emissions to assess the cost of different emissions reduction goals. Thereafter, we examine how political-economy considerations related to the barriers of doing business in developing countries could affect the supply of carbon offsets. Finally, we evaluate the potential of carbon-offset programs to promote biodiversity conservation and the additional cost of generating offset credits when targeting the purchase of offsets based on biodiversity goals. Our exclusive consideration of carbon and the potential for REDD-type programs is motivated by the urgent policy relevancy of the issue and not intended to overlook the broader ecological and economic rationales for the protection of mangroves.

Results

Estimates of the Cost of Avoided Emissions. According to our results, preventing mangrove loss has the potential of reducing global emissions for a cost of roughly \$4 to \$10 ton^{-1} CO_2

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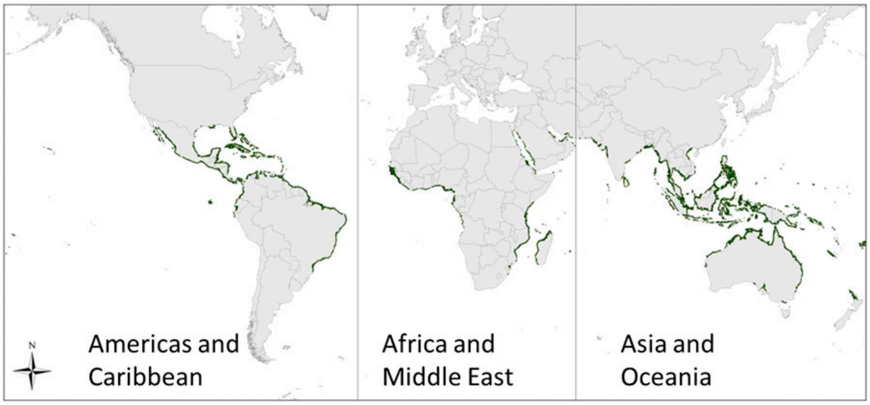

Fig. 1. A global map of mangroves and their division into three geographic regions. Compiled using data from Giri et al. (10).

(Fig. 2*A*). Dividing the world's mangroves into three regions by longitude (Fig. 1), we find that the Asia and Oceania region has the largest potential emissions offset supply, comprising roughly two thirds of potential global offset availability (Fig. 2*D*). The other two regions—Americas and the Caribbean (Fig. 2*B*) and Africa and the Middle East (Fig. 2*C*)—each supply approximately half of the remaining world supply.

The supply curves (Fig. 2) represent the minimum cost per ton (marginal cost) of avoiding different amounts of CO_2 emissions from mangroves. We construct the global and regional supply curves using spatially explicit assessments of the area of mangroves, the volume of carbon contained in them, the loss rate of mangroves, and the current costs of protecting them (*Methods*).

Because the degree of emissions triggered by land conversions in a particular location is only partially understood, we construct low and high estimates of potential offset supply to correspond to the range of approaches taken by recent studies (8, 15). Our central estimate is the midpoint of the range. Logically, the cases with low and high emissions profiles lead to a lower and greater potential supply of emissions offsets, respectively, in terms of both the total potential supply and the supply for given price per ton CO_2.

The economic attractiveness of avoiding GHG emissions from mangroves depends on how costly it is relative to reducing emissions from other sources, such as industrial sector. To examine this question, we contrast (Fig. 2) the estimated marginal cost of avoided CO_2 emissions from mangroves to the recent range of emissions-offset prices in the European Union's Emissions Trading System (EU ETS). The EU ETS is the world's largest emissions allowance trading system, and its credit prices well reflect other options for reducing CO_2 emissions, such as decreasing emissions from industrial and energy sectors.

In all three cases considered (low, central, and high supply), we project that the majority of available carbon offsets could be generated at less than \$10 ton^{-1} CO_2 (in 2005 US\$). This

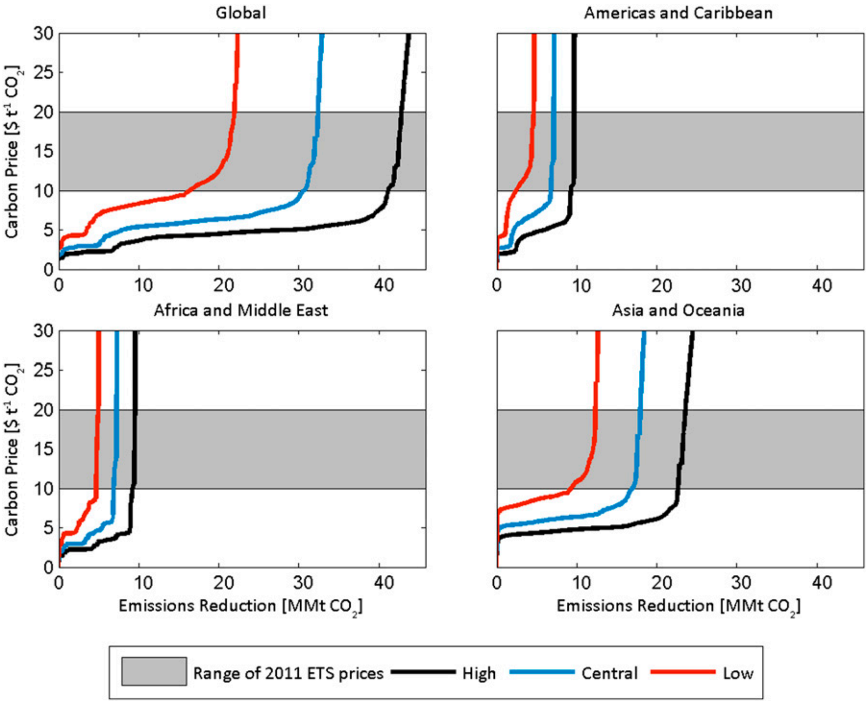

Fig. 2. Global and regional supply curves for emissions reductions from mangroves using low, central, and high estimates of avoided emissions. Supply curves were constructed by identifying the least-cost configuration of protections to generate different amounts of avoided carbon emissions, ranging from zero to total emissions avoided from new protections equal in area to projected annual mangrove loss (*Methods*).

estimate is below the recent EU ETS offset credit prices, which have remained between roughly \$10 and \$20 ton^{-1} CO_2, even in the current economic downturn (16). Our estimates are also below the recent estimates of damage cost caused by CO_2 emissions ("social cost of carbon"), including \$19 by the United States Government (17), \$12 by Nordhaus (18), and \$96 by Stern (19), with all estimates in 2005 US\$ ton^{-1} CO_2. Both comparisons above suggest that investing in reduced emissions from mangrove loss could be economically reasonable.

When evaluating the robustness of our results, we found that even highly unfavorable assumptions regarding the cost of avoiding emissions would add only around \$1 to the estimated per-ton cost (*SI Appendix*). An exception is when we approximate the opportunity cost for Indonesia and Thailand based solely on local estimates of potential returns from oil palm plantations (20) and shrimp mariculture (21, 22), respectively (*SI Appendix*). Assuming all mangroves in these countries face these pressures clearly overestimates the opportunity costs but nevertheless serves as a useful illustration. In this case, the supply curve shifts inward, such that in the high soil carbon case, the lower bound of the offset credit price (\$10 ton^{-1} CO_2) is met at around 60% of the total potential supply.

Mangroves are natural sources of methane (CH_4) and nitrous oxide (N_2O), the two primary GHGs besides CO_2 (23, 24). Although carbon offsets would potentially need to net out non-CO_2 emissions from protected mangroves, we find evidence that the discharges of CH_4 and N_2O would likely increase rather than decrease after land conversion (*SI Appendix*). Because mangrove protection would likely reduce emissions of non-CO_2 GHGs relative to the alternative (baseline) land use, it is not necessary to reduce the volume of emissions offsets because of non-CO_2 emissions.

Governance and the Potential Supply of Avoided Emissions. Countries with mangroves differ considerably in governing institutions and the corresponding political, economic, and social risks and barriers associated with long-term conservation projects. Implementing offsets in certain counties may require investments in management and institutional change above and beyond the opportunity cost of avoided land conversion. It is also plausible that countries with problematic management and institutional environments could be effectively excluded from the market because of the costs associated with these risks and barriers. The magnitude of such costs is difficult to estimate and beyond the scope of this analysis. However, we use the World Bank index on governance effectiveness (25) to shed light on the potential impact of such considerations on the supply of carbon offsets. For illustration, we consider two cases that limit the potential supply of offsets to countries in the top 50th or 90th percentile of the governance index (*SI Appendix*).

The effect of this restriction is both to reduce the supply of carbon offsets (less carbon available) and to increase the price per ton (Fig. 3). Although using the governance index to exclude the lowest 10th percentile of countries does not drastically change global or regional carbon offset supply, removing the bottom half reduces the global offset supply by roughly three quarters. Even though they represent only a small share of potential offset supply, offsets from the Americas and Caribbean are remarkably robust to governance considerations. At the other end of the spectrum, the offset supply from Africa and Middle East is highly sensitive to potential exclusions based on governance considerations.

Potential for Carbon Offset Programs to Produce Cobenefits to Biodiversity. To examine the extent to which carbon-focused mangrove conservation may also contribute toward biodiversity goals, we combined our spatial assessments of potential offset supply with local estimates on species richness (*Methods*). We constructed alternative biodiversity-focused programs, which select mangrove areas for conservation based on the greatest mangrove species richness; combined species richness of birds, mammals, and mangroves; or the number of endangered birds. We then estimated

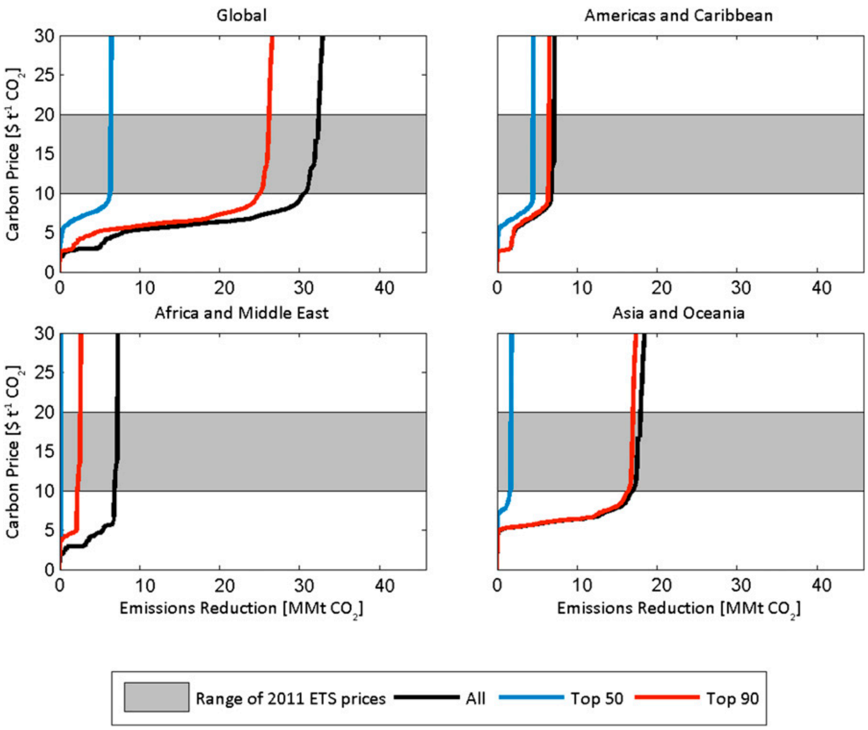

Fig. 3. Governance and the supply of emissions reduction from mangroves. The supply curves correspond to the central carbon case. The Top 90 line excludes the bottom 10th percentile of countries according to the government effectiveness rankings of the World Bank. The Top 50 line excludes the bottom 50th percentile.

the additional cost of achieving different emissions reduction goals under these alternative programs relative to the least-cost program (targeting mangroves within each country from lowest to highest cost, ton^{-1} CO_2, of avoided emissions) (*SI Appendix*).

Under all biodiversity-focused strategies, the added total cost from following a biodiversity-focused strategy is at most upward of $30 million to $35 million annually, with significantly lower extra costs for low levels of total avoided emissions (Fig. 4). Therefore, added costs from a more biodiversity-focused approach appear to be relatively small, on the order of around $1 or less per ton CO_2 (*SI Appendix*).

Discussion

Here, we evaluate whether the carbon benefits from mangrove conservation outweigh the cost of their provision. Although undoubtedly there will be locations where preventing mangrove loss could be excessively costly, we find that preserving mangroves by and large provides relatively low-cost opportunities to mitigate CO_2 emissions. In most areas of the world, we find that preventing a ton of carbon emissions from mangrove deforestation is competitive (less costly) relative to reducing a ton of carbon emissions from currently regulated GHG sources in developed countries. The estimated cost of avoiding emissions from mangrove loss is also below the recent monetized estimates of damage caused by GHG emissions.

Any global assessment requires several assumptions, entails considerable aggregation, and comprises substantial uncertainties. We address these issues by constructing a spatially high-resolution assessment focused on local variation in the key variables. We also present our estimates as ranges to reflect uncertainties and key information gaps. Regardless, we emphasize the qualitative rather than quantitative aspects of the findings. Accordingly, under a broad range of assumptions, avoiding mangrove losses has the potential of being economically justified on the basis of avoided CO_2 emissions alone.

Although our results suggest that preserving mangroves may often be warranted simply on the basis of reducing carbon emissions, coastal conservation would also bring other benefits, such as biodiversity protection and benefits to fisheries and local communities (26, 27). These additional benefits could be considerable and would add further justification for protecting mangroves.

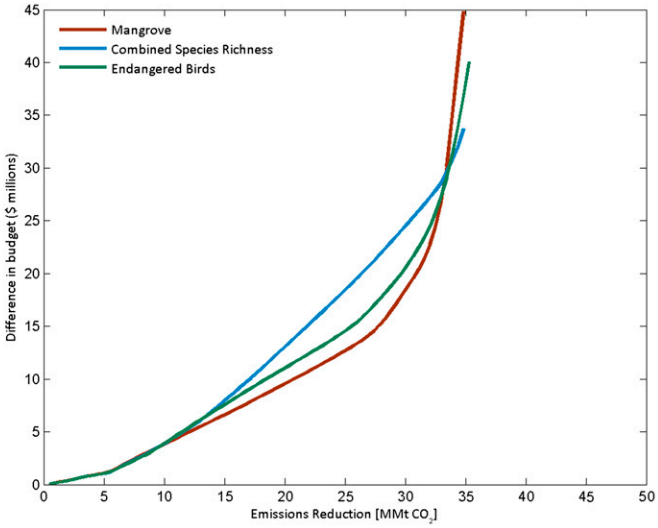

Fig. 4. Additional cost of using a targeting approach based on cobenefits. Supply curves use the central carbon estimate and were generated in a similar manner to the global and regional curves, except in this case, all mangrove hectares within a cell were assumed to be fully protected and cells were included in the country supply until the country-level deforestation hectares were met. The additional costs to supply different levels of CO_2 were generated by calculating the differences in costs between the targeting approach and the lowest-cost scenario (*SI Appendix*).

Our assessment is based on current information, but the opportunity costs of mangrove conservation and the potential revenue from carbon offsets will change over time. In general, we expect the price of mangrove-based offsets to rise as opportunities to generate additional offsets become more constricted (28). Predicting the rate of increase along with the price at which other substitute offsets and other technological solutions become more cost-effective is difficult because of the regulatory and technological uncertainty associated with CO_2 mitigation. Nevertheless, if no major changes in the supply and demand of emissions allowances and the overall cost of GHG abatements occur, a realistic prediction would be that the price of offsets would rise at the rate of interest until the relative price of mangrove offsets becomes equal to the GHG mitigation cost of a substitute source.

Limitations in the management and institutional capacity in host countries present specific barriers for a potential carbon offset system. These limitations can hamper the implementation of conservation programs, increase their cost, and also impose investment risks associated with achieving emissions reductions. Our results highlight how governance-based considerations can affect the size of the market and, therefore, the potential role carbon offsets could have in the conservation of mangroves around the world. Extending capacity-building efforts already under way by the World Bank and nongovernmental organizations (29), intended to strengthen the necessary infrastructure and institutions for REDD programs as well as mangrove protection, could help alleviate these barriers.

Our analysis indicates that if the carbon offset market were to proceed with mangroves and offsets were provided at the lowest cost, some biodiversity gains would follow, but they may be limited relative to a more biodiversity-focused approach. Whether the additional benefits of a more biodiversity-focused approach outweigh the additional costs and whether biodiversity benefits from mangrove conservation could somehow be appropriated by the offset provider are open questions. If the gains could be appropriated, then there would be additional incentives for using a more biodiversity-focused strategy. For example, offsets that also guarantee specific cobenefits may be more valuable in the market, but experience in this context is limited.

This study highlights a number of important areas for future work. For example, although we examine the issue in the robustness checks, further estimates of the opportunity costs of protecting mangroves based on the potential economic returns from palm oil and mariculture would be informative, especially for Southeast Asia, where these activities frequently occur and approximately half of the global mangroves are situated. Furthermore, additional information on land prices would be valuable in locations where urban and tourism developments are the fundamental drivers of land-use change. Nevertheless, although nonagricultural development pressures can result in higher land prices than considered here, agriculture is the main driver of mangrove deforestation. For example, in Southeast Asia between 1975 and 2007, about 80% of deforested mangrove areas became agricultural lands (30). Therefore, our focus on agricultural rents as the opportunity cost of land is well justified.

Another key area of future research involves predicting the emissions profile after land conversions or other disturbances. The current literature offers only limited guidance in this regard. For example, all currently available assessments of emissions, including this one, posit that the different forms of land conversions in one location have similar emissions profiles. In reality, emissions will likely differ between, say, agricultural and urban development of mangroves. Emissions profiles of different forms of agriculture or mariculture may also differ, and further information on them would not only help estimate emissions but also configure land use changes, if otherwise unavoidable, to minimize emissions.

Additionally, large-scale conservation efforts may induce broader economic effects, especially locally. These effects could be considerable in some areas, potentially differentiating the opportunity cost of avoided emissions from our estimates. Therefore, formulating a better understanding of the local economy and its connections to mangroves and their alternative uses would also help better evaluate mangrove conservation options, particularly where communities are highly dependent on their potential alternative uses.

Mangroves are known to provide considerable benefits to fisheries, providing juvenile and adult fish populations with nursery habitat, food, and protection from predation. Studies also show that many fish species depend on both mangroves and coral reefs (4), and there is increasing evidence that coral reefs in the proximity of mangroves are considerably more productive for fisheries than reefs in mangrove-poor areas (4). Future work should consider, for example, methodologies for configuring conservation programs to most effectively incorporate the beneficial impacts of mangroves on fisheries (31).

Carbon stored in mangroves and other marine and coastal habitats, such as seagrass meadows and salt marshes, is often referred to as “blue carbon” (32). Although currently available scientific information prevents rigorous assessments of the economic potential of preserving seagrasses and salt marshes for carbon, future research should address that topic, including estimating the opportunity cost of preserving those habitats. Such assessments also call for a more thorough understanding of the value of other ecosystem services, such as those associated with nursery habitats for commercial fisheries, recreational fisheries, species conservation, storm protection, and water purification (33, 34).

On the other hand, information on mangroves is particularly relevant because they have the greatest potential to be incorporated into climate policy frameworks, especially in the near term. For example, mangroves may already fit within the general REDD architecture. However, soil carbon, which constitutes the vast majority of carbon in mangroves, generally is excluded from carbon offsets in REDD. Therefore, a critically important issue in the context of mangroves and other blue carbon is the need to develop a framework to include soil carbon in offset programs.

Although uncertainty remains regarding various international, state, and regional climate policy frameworks, our results suggest the need for practical evaluations of mangrove-based carbon offsets, including rigorous local assessments of offsets as well as developing their robust verification and monitoring. Current policy programs, such as the Indonesia-Norway REDD partnership and the offset provision under California’s Assembly Bill 32, may already provide the necessary framework. For example, California has signed an agreement with Chiapas, Mexico, to provide forest offsets starting in 2015 (35). Our data suggest that carbon offsets from mangrove conservation in Chiapas could be competitive relative to the predicted permit price in California, but further study is needed.

Methods

We identify the geographic extent of mangrove ecosystems (Fig. 1) using the most recent and rigorous global dataset on mangroves (10). We divide the world surface area into a large number of regular quadrilaterals (grid cells), each with the side length of 5′ (about 9 km). For each of the 25,226 grid cells that currently comprise mangroves, we project current carbon storage (tons CO_2 ha^{-1}), including carbon above and below ground and in the soils, and accumulation (tons CO_2 ha^{-1} y^{-1}) by mangroves, mangrove loss rates (percent loss y^{-1}), emissions associated with mangrove loss (tons CO_2 ha^{-1}), the cost of avoiding emissions (\$ ton^{-1} CO_2), and the current protections of mangroves (see below and *SI Appendix*).

Carbon Storage. We estimate a latitude-based above-ground mangrove biomass according to Twilley et al. (5). Following Twilley et al. (5) and Donato et al. (8), we estimate that the volume of below-ground living biomass is 60.8% relative to the volume of above-ground biomass. Following Bouillon et al. (6), we estimate that 41.5% of the biomass is carbon (*SI Appendix*). To estimate location-specific volume of soil carbon, we develop country-level estimates of soil carbon density by compiling and analyzing 941 primary observations of mangrove soil carbon density available from the literature (6–8) (*SI Appendix*). Our globally representative estimate of soil carbon density is about 0.0319 g C/cm^{-3}. For annual carbon accumulation, we use the Bouillon et al. (6) carbon burial estimate of 1.15 t C ha^{-1} y^{-1}.

Table 1. Summary of carbon stock and burial by mangroves

	Per hectare, on average, globally		Global total	
	t C	t CO_2e	Pg C	Pg CO_2e
Biomass	147.5	540.8	2.1	7.5
Soil	319.0	1,169.7	4.4	16.3
Total stock	466.5	1,710.5	6.5	23.8
Annual accumulation	1.15	4.22	0.02	0.06

We find that mangroves contain, on average, altogether about 466.5 t C ha^{-1} (1,710.5 t CO_2e ha^{-1}) (Table 1). Globally, the carbon stock is estimated at about 6.5 Pg C (23.8 CO_2e). We estimate that if left undisturbed, uninterrupted carbon sequestration and burial annually expand mangrove carbon stock by about 16 million t C per year (60 million t CO_2e) (Table 1).

Mangrove Losses. We project mangrove losses using data on the change, between 1990 and 2005, in mangrove area by country from the United Nations Food and Agricultural Organization (FAO) (3). The annual mangrove loss between 1990 and 2005 was, on average, about 0.7%. To create cell-level projections of mangrove loss, we use a range of alternative approaches to determine how the total amount of mangrove loss by country is distributed within each country (*SI Appendix*). In the base case, mangroves within each country are subject to a uniform risk of development. Alternative cases represent intuitive lower and upper bounds for the opportunity cost of preserving mangroves. These cases are constructed so that mangrove areas of either lowest or highest opportunity cost of land are developed each year until reaching the country-level total projection of mangrove loss.

We use spatial data from the World Database on Protected Areas to net out the mangroves in each cell that are already protected (36). The assessment excludes countries where mangrove area had not declined according to the FAO. We also exclude 24 countries, mostly small island nations, for which data on mangrove losses are unavailable. These countries represent in total about 1.3% of global carbon storage in mangroves (*SI Appendix*).

Carbon Emissions After Land Conversion. We consider that 75% of carbon in the above-ground and below-ground biomass is emitted after land conversion (8, 15). We also assume that land conversion affects soil carbon down to 1 m and approximate a range of emissions to correspond to the range of assumptions in the literature. At the lower bound (8), a total of 27.25% of the soil carbon is released. At the upper bound (15), 90% of soil carbon is released. The midpoint of the lower and upper bounds serves as our central estimate of the soil carbon emitted after land conversion (*SI Appendix*). Our low, central, and high estimates of annual global emissions because of mangrove loss are about 84 million, 122 million, and 159 million tons CO_2.

Emissions Offset Credits from Additional Protections. We project for each hectare of mangroves the total avoided emissions (TAE) that could be credited as a carbon offset as a result of additional protection. For each grid cell (i = country, j = cell), we consider a 25-y time horizon and model offsets under the assumptions that they are granted only for the portion of the mangroves that are projected to be lost each year (*SI Appendix*). For example, when deforestation rate is 1%, protecting 100 ha of mangroves avoids emissions from the loss of 1 ha in year 1. In year 2, emissions are avoided from the loss of 1% of the remaining 99 ha. Continuing from one year to the next over the time horizon, TAE (tons CO_2/ha) is characterized by a finite geometric series as follows:

$$TAE_{ij} = \left[1 - (1+\delta_i)^T\right] * \left[M_{ij} * \left(CAB_{ij} + CBG_{ij} + CS_{ij} + T * CAA_{ij}\right)\right] \qquad [1],$$

where δ_i denotes the rate of change in mangrove area in country i between 1990 and 2005; T is the horizon of the contract (25 y); M_{ij} is the number of hectares of mangroves protected in country i, cell j; CAB_{ij} is the above-ground carbon content; CBG_{ij} is the below-ground carbon content; CS_{ij} is the soil carbon content; and CAA_{ij} denotes the annual accumulation of carbon stock (carbon burial), which projected losses we credit for T years.

Opportunity Cost of Avoided Emissions. The opportunity cost of avoided emissions is a function of the net present value of estimated economic returns from the most profitable land use (land value) for each cell, a one-time setup cost of the protected area, and the net present value of the annual costs of managing the protected area. For land value, we calibrate a spatial global dataset on potential agricultural gross revenues developed in Naidoo and Iwamura (37) to match the World Bank's country-level estimates of agricultural land value (38). This approach maintains the spatial variation in Naidoo and Iwamura and matches the World Bank land value estimates by country. We increase the coverage of the original Naidoo and Iwamura dataset by using a nearest-neighbor averaging routine for three different distances (13 km, 26 km, and 39 km). Our main results use the 39-km averaging but are robust to the averaging distance (*SI Appendix*). The onetime cost of setting up protection from mangroves (\$232 ha^{-1}) and the annual management cost (\$25 ha^{-1}) follow Murray et al. (15). We convert the per-year management cost into the present value of a stream of annual costs over a 25-y period using a 10% discount rate. The cost of avoided emissions (\$ ton^{-1} ha^{-1}) by cell equals the per-hectare opportunity cost of conservation divided by TAE (*SI Appendix*).

Global Emissions Reduction Supply. Global supply curves of avoided carbon emissions are estimated by identifying the least-cost spatial configuration of protections worldwide to generate different amounts of avoided carbon emissions, ranging from zero to the total emissions avoided from new protections of mangroves that are equal in area to the global projected annual mangrove loss. We examine various assumptions on how mangroves are likely to be converted. In the main assessment, we assume that mangroves in each grid cell within a country are subject to a constant risk of deforestation based on the country's deforestation rates. Other scenarios help develop realistic bounds for the cost of avoided emissions, as explained above (*SI Appendix*).

Governance Effectiveness. The World Bank index on government effectiveness (25, 39) combines data on the views of a large number of enterprise, citizen, and expert survey respondents in industrial and developing countries, including perceptions of the quality of public services, the quality of the civil service, the degree of independence of civil service from political pressures, the quality of policy formulation and implementation, and the credibility of the government's commitment to policy (*SI Appendix*).

Biodiversity. We used the geographic information system to construct grid-cell level indicators of species richness by using spatial data on mangroves, amphibians, reptiles, and marine mammals from the International Union for the Conservation of Nature (40). For birds, we used data from BirdLife International (41) (*SI Appendix*).

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