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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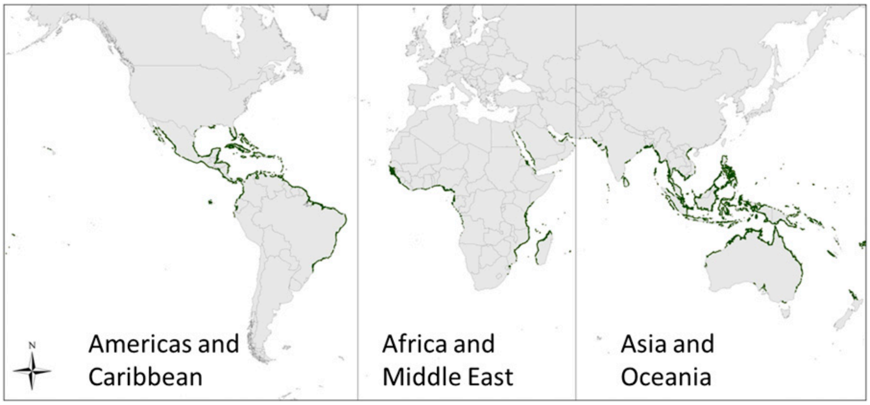

Fig. 1. A global map of mangroves and their division into three geographic regions. Compiled using data from Giri et al. (10).

(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

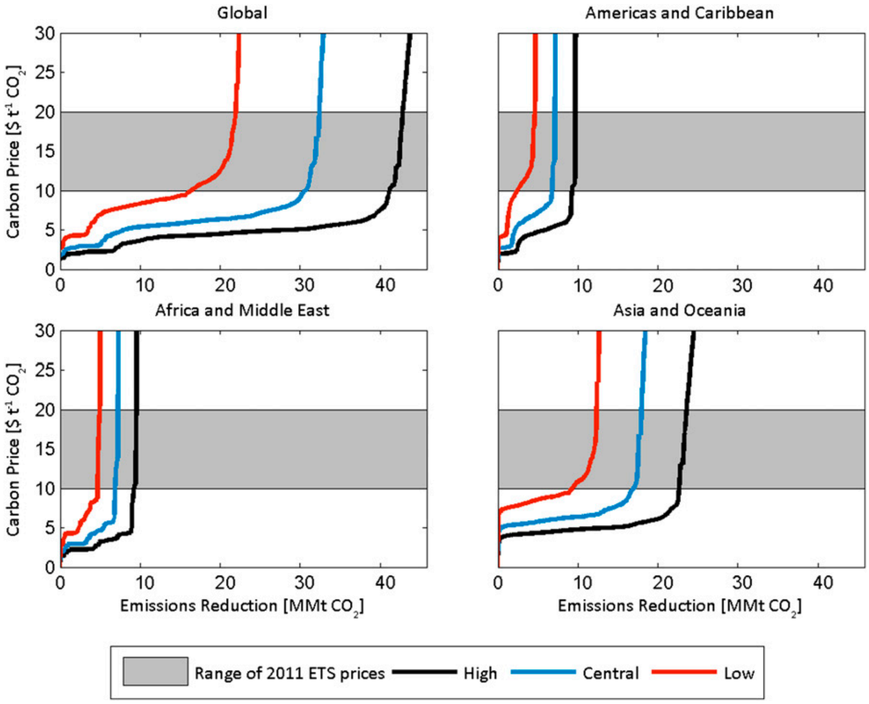

Fig. 2. Global and regional supply curves for emissions reductions from mangroves using low, central, and high estimates of avoided emissions. Supply curves were constructed by identifying the least-cost configuration of protections to generate different amounts of avoided carbon emissions, ranging from 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

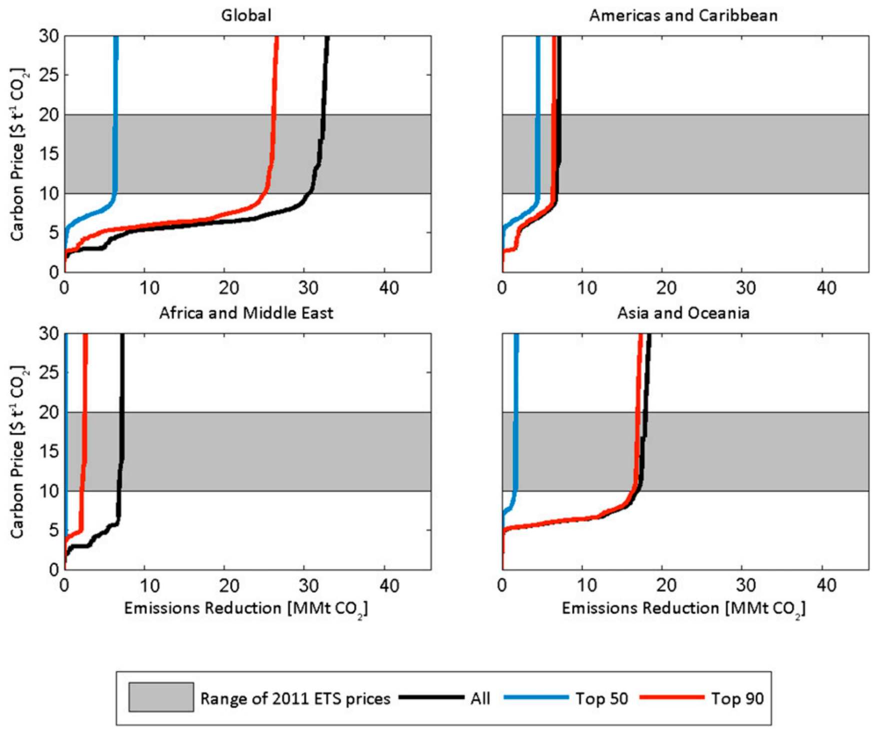

Fig. 3. Governance and the supply of emissions reduction from mangroves. The supply curves correspond to the central carbon case. The Top 90 line excludes the bottom 10th percentile of countries according to the government effectiveness rankings of the World Bank. The Top 50 line excludes the bottom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

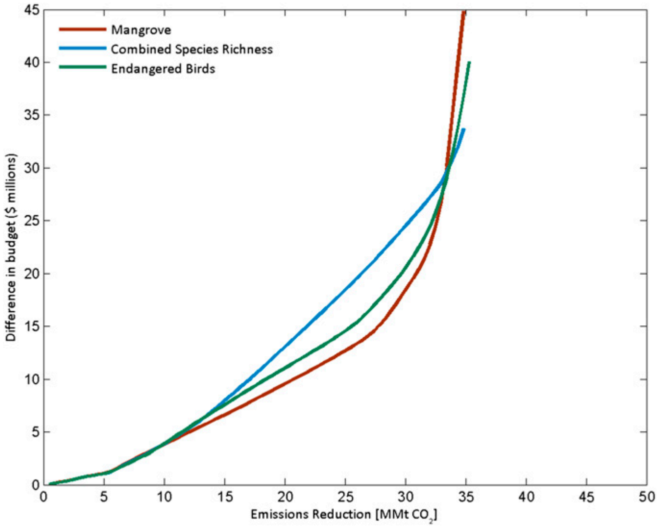

Fig. 4. Additional cost of using a targeting approach based on cobenefits. Supply curves use the central carbon estimate and were generated in a similar manner to the global and regional curves, except in this case, all mangrove hectares within a cell were assumed to be fully protected and cells were 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*).

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

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}.

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:

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

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 aboveground 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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Global economic potential for reducing carbon dioxide emissions from mangrove loss

Supporting Information

Contents

Introduction

The supplementary material includes additional information on the mangrove coverage; estimates of carbon storage; opportunity cost estimation; biodiversity assessment; robustness checks on the global supply curves using different spatial averages of estimated land values, targeting rules, and opportunity costs; the potential methane (CH_4) and nitrous oxide (N_2O) emissions from mangroves; and World Bank's Government Effectiveness index.

Mangrove Coverage

Table S1.1 lists mangrove areas by country and globally, using our estimates of mangrove coverage based on data from Giri et al. (2010). Country-level estimates are listed for the 20 countries with the greatest mangrove area. Indonesia has the largest area of mangroves for an individual country; 27,072 km^2 of mangroves (19.5% of global mangroves). Globally, mangroves are estimated to cover 139,163 km^2.

Table SI.1. Country rankings for mangrove area (top-20 countries)

Rank	*Country*	*Mangrove area (km^2)*	*Percentage of total*	*Cumulative percentage*
1	Indonesia	27,072	19.5	19.5
2	Brazil	10,630	7.6	27.1
3	Australia	9,525	6.8	33.9
4	Mexico	7,302	5.2	39.2
5	Nigeria	7,047	5.1	44.2
6	Malaysia	5,616	4.0	48.3
7	Myanmar	5,082	3.7	51.9
8	Papua New Guinea	4,850	3.5	55.4
9	Bangladesh	4,375	3.1	58.6
10	Cuba	4,286	3.1	61.6
11	India	3,870	2.8	64.4
12	Guinea-Bissau	3,427	2.5	66.9
13	Venezuela	3,360	2.4	69.3
14	Mozambique	3,194	2.3	71.6
15	Madagascar	2,731	2.0	73.6
16	Philippines	2,596	1.9	75.4
17	Guinea	2,519	1.8	77.2
18	Thailand	2,496	1.8	79.0
19	United States	2,360	1.7	80.7
20	Colombia	2,147	1.5	82.3
	Global Total	139,163	100	100

Note: Table comprises our estimates using spatial data from Giri et al. (2010).

Figure S1.1 is a histogram of global mangrove area by latitude. Each bar in the histogram expresses the total area of mangroves (km^2) by 1 degree of latitude. We estimate that 94.7% of global mangroves are located in the tropics.

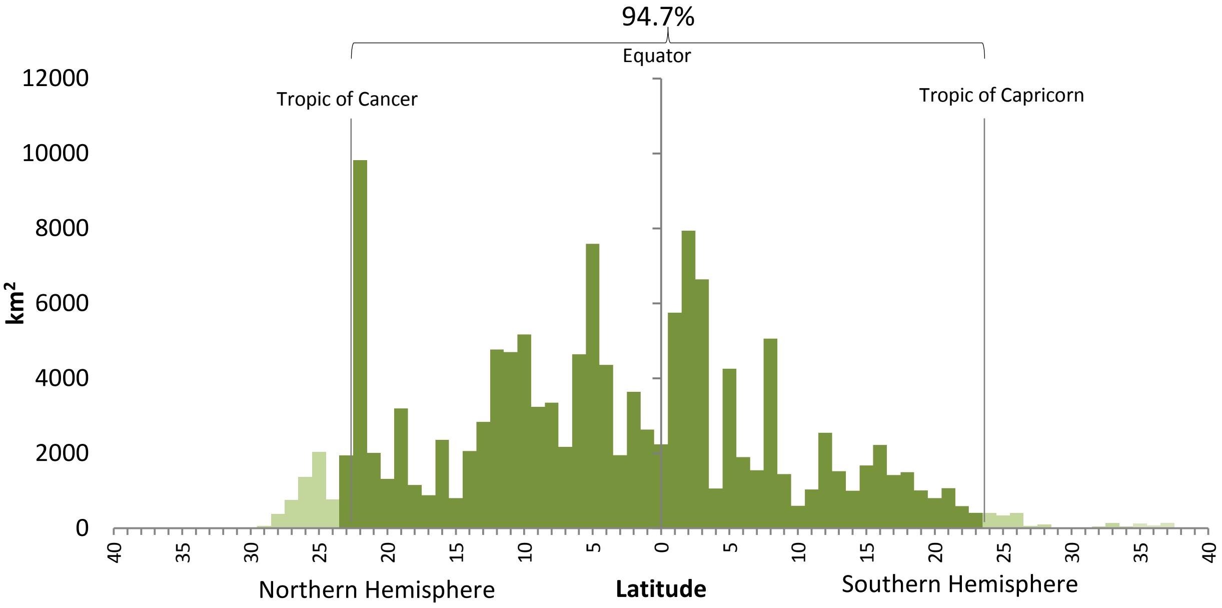

Figure SI.1. Global distribution of mangroves, by latitude. Each bar represents the area of mangroves (km^2) by 1 degree of latitude.

Mangrove Carbon Storage

We use available scientific information to predict the volume of mangrove carbon in locations around the world. We find considerable evidence of it varying by location. To address the spatial variability, we develop spatially differentiated estimates of carbon stored in mangroves, including aboveground and belowground biomass and soil carbon.

Carbon in aboveground and belowground biomass

Estimating the amount carbon stored in biomass requires predicting the volume of biomass and then projecting its carbon content. We predict mangrove biomass using a study by Twilley et al. (1992), which draws from a large number of studies to estimate the following regression equation of aboveground biomass (in Mg ha^{-1}) on latitude[1]:

$$\widehat{AG} = 298.5 - 7.291 \times Latitude$$

We combine predicted aboveground biomass with the mangrove coverage data to estimate the global distribution of aboveground biomass.

Our primary scientific information regarding the volume of belowground biomass in mangroves comes from Twilley et al. (1992) and Donato et al. (2011). Using their results, we predict that the volume of belowground living biomass is, on average, 60.8% of aboveground biomass. Although some studies suggest that the volume of belowground biomass may be greater than aboveground biomass, these findings sometimes include both living and dead biomass in the belowground calculations (Komiyama et al. 2008). We separately account for the dead belowground biomass as a component of soil carbon and, therefore, use the results from Twilley et al. (1992) and Donato et al. (2011) to project the volume of living belowground biomass. Our approach avoids confounding and double-counting different forms of belowground carbon.

Because the carbon content of biomass varies by plant and tree species, we use the results from Bouillon et al. (2008) and estimate that 41.5% of the mangrove biomass is carbon.

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[1] The predictive model from Twilley et al. (1992) has been used by Bridgham et al. (2006), Boullion et al. (2008), and Suratman (2008). Bouillon et al. (2008) assume a latitudinal distribution similar to that documented in Twilley et al. (1992) as the relationship was supported by new data.

Soil carbon

We combined the data sets by Chmura et al. (2003), Kristensen et al. (2008), and Donato et al. (2011) on soil carbon density. The Chmura et al. (2003) data set comprises soil carbon density measurements from 31 sites in Africa, North and South America, and the Pacific. The Kristensen et al. (2008) global data set was compiled from an extensive literature review of primary estimates from a large number of field studies. The resulting data set includes observations on the percentage of organic carbon in mangrove soils for 885 sites around the world.[2] Our third source, Donato et al. (2011), provides soil carbon measurements from 25 mangrove forests from the Indo-Pacific region.

Combining the above sources creates a data set with 941 observations on soil carbon density from 30 countries. These countries are distributed around the world and together account for 70.4% of the world's mangroves. We calculated country-level mean and median soil carbon densities for each of the 30 countries. We use the median estimates for our main result throughout the assessment (see Table SI.2 for the country-level summary of estimates).

After compiling country-level estimates of soil carbon, we summarized them according to the ten biogeographic regions developed for mangroves by Spalding et al. (2010). Using this aggregation, we find significant regional variation in soil carbon (Table SI.3).[3] For example, the mangrove soils of Southeast Asia (Indonesia, Malaysia, Thailand, the Philippines, and Vietnam) have an average and median density of 0.0418 g C cm^{-3} and 0.0332 g C cm^{-3}, respectively, whereas mangrove soils in South Asia (Bangladesh, India, and Sri Lanka) are estimated to have considerably less carbon (mean 0.0205 g C cm^{-3}; median 0.0201 g C cm^{-3}).

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[2] To combine data on mangrove soil carbon density with the Kristensen et al. (2008) measurements of %OC in mangrove soils, we follow Donato et al. (2011) and use an estimated relationship $\%OC = 3.0443*BD^{-1.313}$, where %OC denotes organic carbon (% weight) and BD is the bulk density (g cm^{-3}).

[3] Our data set contains observations in 8 of the 10 mangrove regions. We impute soil carbon density for the remaining 2 regions by taking an average between the two nearest geographical regions.

Table SI.2. Country-level estimates of soil carbon density in mangroves

Country	*Mangrove area*	*Mean g C cm^3*	*Median g C cm^3*	*Samples*	*Std. dev.*
Australia	9,525	0.0329	0.0334	47	0.00776
Bangladesh	4,375	0.0158	0.0158	2	0.00033
Belize	569	0.0535	0.0535	11	0.00088
Brazil	10,630	0.0288	0.0306	31	0.00692
China	0	0.0250	0.0248	88	0.00199
Colombia	2,147	0.0633	0.0610	3	0.00681
Ecuador	1,300	0.0377	0.0380	6	0.00214
French Guiana	857	0.0275	0.0544	141	0.00120
Guadeloupe	21	0.0545	0.0261	20	0.00587
Guam	0	0.0313	0.0310	3	n/a
India	3,870	0.0246	0.0236	38	0.00394
Indonesia	27,072	0.0454	0.0331	14	0.02098
Japan	0	0.0492	0.0490	10	0.00213
Kenya	322	0.0308	0.0301	153	0.00717
Madagascar	2,731	0.0219	0.0223	26	0.00251
Malaysia	5,616	0.0356	0.0341	51	0.00523
Mexico	7,302	0.0376	0.0338	17	0.00953
Micronesia	99	0.0460	0.0500	9	n/a
Mozambique	3,194	0.0228	0.0231	12	0.00405
New Zealand	314	0.0296	0.0302	20	0.00382
Papua New Guinea	4,850	0.0299	0.0288	113	0.00530
Republic of Palau	56	0.0460	0.0460	1	n/a
South Africa	14	0.1065	0.1065	6	0.00586
Sri Lanka	219	0.0431	0.0438	54	0.00753
Taiwan	0	0.0214	0.0214	2	0.00104
Thailand	2,496	0.0263	0.0239	43	0.00460
United States	2,360	0.0443	0.0440	15	0.01159
Venezuela	3,360	0.0219	0.0219	1	n/a
Vietnam, Philippines	4,729	0.0370	0.0374	4	0.00867
Total	98,023			941	
One average, unweighted by country mangrove area		0.0376	0.0370		
One average, weighted by country mangrove area		0.0353	0.0319		

Sources: Compiled from data in Kristensen et al. (2008), Bouillon et al. (2008), Donato et al. (2011).

Table SI-3. Estimated mangrove soil carbon density, by biogeographic region

Biogeographic region	*Soil carbon density (mean)*	*Soil carbon density (median)*	*Observations*	*Coefficient of variation*	*Mangrove area (km^2)*	*Percentage of total area*
East Africa	0.0230	0.0233	197	0.103	7,304	5.25
Middle East	0.0217	0.0217	0	N/A	2,391	1.72
South Asia	0.0205	0.0201	94	0.089	9,035	6.49
South East Asia	0.0418	0.0332	112	0.342	45,600	32.77
East Asia	0.0250	0.0248	100	0.080	0	0.0
Australasia	0.0328	0.0333	67	0.229	9,839	7.07
Pacific Ocean	0.0305	0.0294	146	0.168	6,536	4.70
North and Central America	0.0400	0.0373	43	0.183	20,203	14.52
South America	0.0322	0.0342	182	0.128	19,299	13.87
West and Central Africa	0.0361	0.0357	0	N/A	18,957	13.62

Source: Meta-analysis of data from Chmura et al. 2003, Kristensen et al. 2008, and Donato et al. 2011

We find that there is considerably less variation in the soil carbon density within regions than between regions. The coefficient of variation for our entire regional-level soil carbon dataset is 0.355, but the within-region coefficients of variation range from 0.08 to 0.342, with a mean of 0.165. Because the amount of carbon in mangrove soil is relatively homogeneous within each region, accounting for the regional or country-level variation controls for much of the underlying spatial variability in soil carbon. The finding also suggests that for countries with missing primary data, soil carbon is more appropriately estimated using a regional rather than a global average. Therefore, we use regional estimates of soil carbon density to predict soil carbon pools for the remaining 30% of mangrove areas for which no primary data were available. For the Middle East and West and Central Africa, where the entire region lacked primary data, we use the estimates from adjacent regions.

Combining these data with information on mangrove coverage, we develop a globally-representative estimate of carbon density in mangrove soils. Using simple averages for each country, we find a mean 0.038 g C cm^{-3} and median 0.0370 g C cm^{-3} soil carbon density. A simple average, however, puts equal weight on observations of soil carbon from locations with large and small areas of mangroves in predicting the global average. Another measure is a weighted average that takes into account the geographic distribution of the mangroves. When we combine data on soil carbon with the extent of mangrove area that each observation represents (Giri et al. 2010), we obtain mean and median mangrove area–weighted global estimates of soil carbon density equal to 0.036 g C cm^{-3} and 0.0319 g C cm^{-3}, respectively. These estimates are about 25% and 14% greater than the most recent and (to our knowledge) the most systematically developed global estimate 0.028 g C cm^{-3} (Donato et al. 2011). The advantage of our estimate is that it uses the currently available data, including observations in Donato et al. (2011), combined with country-level assessments and mangrove-area weighting. For robust statistical inference, we use median soil carbon estimates in the main assessment.

Carbon accumulation

Bouillon et al. (2008) conducts a literature review of the studies estimating carbon accumulation due to biological sequestration and carbon burial by mangroves. Bouillon et al. (2008) find that despite differences in methods, the three studies included in the assessment all yield similar results regarding the annual accumulation of carbon by mangroves: 1.15 t C ha^{-1} y^{-1}.[4] We therefore use the Bouillon et al. (2008) estimate of 1.15 t C ha^{-1} y^{-1}.

Opportunity Costs

The basis of our opportunity cost estimates utilizes a spatially explicit data set developed by Naidoo and Iwamura (NI, 2007) that estimates potential gross agricultural revenues on a global $/ha basis from altogether 42 crops (Fischer et al. 2002) and 6 livestock types, based on crop productivity, livestock density, and global prices in 2000. The NI study draws data from an extensive global agro-ecological assessment by International Institute for Applied Systems Analysis and the Food and Agriculture Organization of the United Nations, encompassing world's main agricultural crops, including cereals, roots and tubers, pulses, oil crops such as rape and oil palm, fiber crops such as cotton, sugar crops such as sugarcane, fruit crops such as banana, and forage/fodder (Fischer et al. 2002).

We calibrate the NI data using the World Bank's country-level estimates of agricultural land value (World Bank, WB, 2011a). Using data on agricultural land areas, their crop yields, and other outputs (e.g., milk, meat, and fiber), the World Bank study estimated the annual output

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[4] None of the three studies provide standard errors for their estimates.

value of agricultural lands. The present value of potential agricultural net revenue is then discounted over a 25-year time horizon to arrive at the estimated land value.[5]

The calibration ensures that the country-level estimates based on the disaggregated NI data are consistent with the WB country-level measures. Unlike the NI data, the WB estimates are a measure of the overall net worth of agricultural lands, which is a more appropriate measure of the opportunity costs of conserving mangroves for their blue carbon than gross revenues. We find that the calibration scales up or down the NI estimates without obvious geographic patterns (see Table SI.5).

The calibration is done in several steps. First, because of differences in coverage across the globe in the two data sets, we use multivariate regression analysis to fill in missing values in the WB data.[6] The log-linear regression results for crops and livestock along with the set of explanatory variables are presented in Table SI.4. Note that the primary purpose of the model is to generate a prediction, not to examine causal relationships. The statistical significance of the estimates is therefore of lesser concern than, say, different measures of predictive power.

Second, using the WB data with missing data imputed for countries that have observations in NI but not in the WB data[7], we calculate a WB weighted average of the opportunity cost of land based on the amount of hectares in agriculture and pasture in the country. There are also a number of countries for which there is WB data but not data in NI.[8] In these cases, we use the country-level WB data in our calculations.

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[5] See “The changing wealth of nations: Measuring sustainable development in the new millennium” (World Bank 2011a) for a detailed description of the valuation methodology.

[6] Countries with mangroves at risk that are not included in either the World Bank or the NI data are ANT, ATG, BHS, BRB, CYM, GLP, GUM, KIR, MNP, MTQ, NCL, SLB, VGB, VIR, and WSM. See Table SI.5 for the country names. Together these countries account for 3.8 percent of global mangroves.

[7] The countries are ERI, GNQ, KHM, MMR, SOM, SUR, TLS, TZA, and YEM. These countries account for 7.2 percent of the global coverage of mangroves. See Table SI.5 for the country names.

[8] The countries are: COM, FJI, GRD, KNA, TON, VCT, and VUT. These countries account for 1.5% of the global coverage of mangroves. See Table SI.5 for the country names.

Table SI.4. Regression model to fill in missing data in WB dataset, by agricultural land type

	Cropland		***Pasture***			
Variables	***Coefficient***	***Std. error***	***Coefficient***	***Std. error***	***Variable definition***	***Source***
Constant	4.0909	3.0054	2.0363	5.0581	Southern equatorial region in Asia and Oceania	
Latitude	0.071289	0.065829	0.19023	0.11079	Latitude at country centroid	ESRI
Latitude squared	-0.00236	0.001609	-0.00319	0.002708	Latitude at country centroid squared	ESRI
Northern hemisphere	0.60193	0.42877	1.7073	0.72162	Equal to 1 if Latitude at Country Centroid greater than zero	Computed
Equatorial region	0.48579	0.59876	1.0093	1.0077	Equal to 1 if latitude within 5 degrees of equator	Computed
Americas, Caribbean	0.028303	0.4016	-0.35119	0.6759	Equal to 1 if longitude at centroid between -180 and -30	Computed
Africa and Middle East	0.005539	0.47084	-2.0187	0.79242	Equal to 1 if longitude at centroid between -30 and 60	Computed
Minimum average temperature	0.17529	0.12924	-0.12566	0.21751	Between 1980 and 2008	G-Econ vs.3.4
Maximum average temperature	-0.17011	0.10058	-0.00523	0.16927	Between 1980 and 2008	G-Econ vs.3.4
Average elevation	0.000997	0.000466	0.000306	0.000785	Elevation of land within 100 km of an ice-free ocean	G-Econ vs.3.4
Gross domestic product	2.8918	2.0098	1.2012	3.3825	GDP in 2009 scaled by 100,000	World Bank
Population density	9.59E-05	0.00021	8.94E-05	0.000354	In year 2010	World Bank
Share of land on coast	0.71291	1.0091	0.68355	1.6983	Amount of land within 100 km of ice-free ocean	G-Econ vs.3.4
Share of population on coast	0.82301	1.2485	-0.63174	2.1013	Share of population within 100 km of ice-free ocean	G-Econ vs.3.4
WB ease of doing business index	-0.00231	0.003685	0.004778	0.006202	World Bank country-level index in 2010	World Bank
	R2	0.43	R2	0.49		
	N	113	N	113		

Source: The G-Econ data (Nordhaus et al. 2006) is available at http://gecon.yale.edu/, the ESRI is available at http://www.esri.com/data/free-data/index.html and the World Bank data is available at http://data.worldbank.org/data-catalog/

Third, we calculate the ratio of the WB estimates to the country-level weighted average of the NI estimates. Table A.4 presents the two sets of estimates along with the ratio. We then multiply the cell-level estimates in NI with the ratio to get an adjusted spatially explicit estimate of land prices for agriculture. The calibration ensures that the country-level weighted averages of our estimates are equal to the WB estimates.

The calibrated data set covers approximately 38% of all observations and 45% of total mangrove area. To increase coverage, we use a nearest neighbor averaging routine for three different distances (13km, 26km, and 39km) to impute missing values at the cell level. Our coverage of mangroves on the global scale increases to 87% for 13km, 94% for 26km, and 95% for 39km. In addition to increasing coverage, the nearest neighbor routine essentially smoothens the opportunity cost surface (calibrated NI data).[9] We use the longest distance (39 km) for averaging in the main assessment to ensure greatest coverage.

Table SI.5. World Bank and NI data

Country	Code	World Bank	NI	Ratio	Mangroves (ha)	Share of global mangroves (percentage)
Aruba	ABW				33.433	0.000772
Angola	AGO	2.50	18.90	0.13	621.62	0.014361
Anguilla	AIA				4.9907	0.000115
Netherlands Antilles	ANT		0.00		22.268	0.000514
United Arab Emirates	ARE	252.80	3.96	63.77	160.9	0.003717
Antigua and Barbuda	ATG				103	0.002380
Australia	AUS	5.40	17.83	0.30	338.36	0.007817
Benin	BEN	49.90	23.51	2.12	272.76	0.006301
Bangladesh	BGD	180.40	783.60	0.23	2443.9	0.056458
Bahrain	BHR	449.60	1.08	417.06	21.125	0.000488
Bahamas	BHS				233.14	0.005386
Belize	BLZ	273.60	85.86	3.19	478.16	0.011046
Brazil	BRA	58.00	50.70	1.14	811.44	0.018746
Barbados	BRB				17.553	0.000406
Brunei	BRN	152.50	93.20	1.64	652.95	0.015084
China	CHN	68.50	135.73	0.50	0.085692	0.000002

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[9] In some cases, the nearest neighbor routine will pick up cells from a different country. Cells with missing data are excluded.

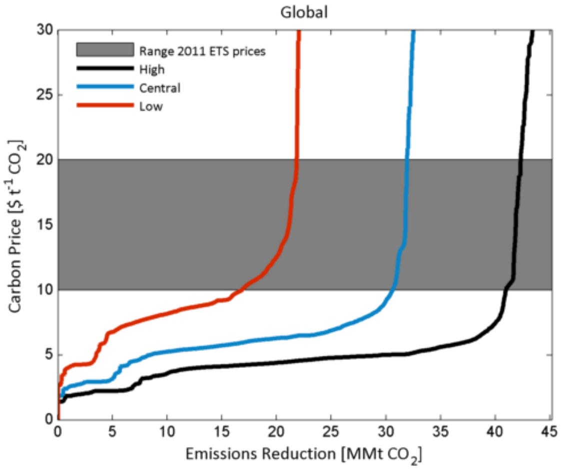
Country	Code	World Bank	NI	Ratio	Mangroves (ha)	Share of global mangroves (percentage)
Ivory Coast	CIV	25.50	69.88	0.36	50.065	0.001157
Cameroon	CMR	40.20	16.55	2.43	2422.6	0.055966
Democratic Republic of the Congo	COD				2220.6	0.051301
Congo	COG	3.10	6.01	0.52	58.628	0.001354
Colombia	COL	39.20	37.97	1.03	690.21	0.015945
Comoros	COM	59.70	59.70	1.00	9.1366	0.000211
Costa Rica	CRI	130.70	228.51	0.57	382.77	0.008843
Cuba	CUB	204.55	133.85	1.53	521.41	0.012046
Cayman Islands	CYM				583.46	0.013479
Djibouti	DJI	7.40	26.77	0.28	53.68	0.001240
Dominican Republic	DOM	113.80	92.09	1.24	182.17	0.004208
Ecuador	ECU	96.00	74.04	1.30	621.98	0.014369
Egypt	EGY	598.50	10.32	57.97	10.531	0.000243
Eritrea	ERI	42.78	53.81	0.79	56.42	0.001303
Fiji	FJI	187.00	187.00	1.00	388.1	0.008966
Micronesia	FSM				274.09	0.006332
Gabon	GAB	4.20	4.83	0.87	1058.7	0.024457
Ghana	GHA	32.90	83.80	0.39	273.45	0.006317
Guinea	GIN	10.60	33.37	0.32	1690.7	0.039059
Guadeloupe	GLP				137.98	0.003188
Gambia	GMB	13.70	97.14	0.14	814.59	0.018819
Guinea-Bissau	GNB	14.00	35.61	0.39	1211	0.027976
Equatorial Guinea	GNQ	144.19	4.69	30.76	351.61	0.008123
Grenada	GRD	178.30	178.30	1.00	23.513	0.000543
Guatemala	GTM	130.40	111.85	1.17	511.04	0.011806
French Guiana	GUF		5.18		1142.1	0.026385
Guam	GUM				15.599	0.000360
Guyana	GUY	45.10	8.80	5.13	319.7	0.007386
Honduras	HND	111.50	109.95	1.01	481.86	0.011132
Haiti	HTI	58.10	145.95	0.40	168.99	0.003904
Indonesia	IDN	87.10	53.95	1.61	506.48	0.011701
India	IND	120.50	182.62	0.66	663.92	0.015338
Iran	IRN	38.10	38.89	0.98	197.92	0.004572
Jamaica	JAM	174.80	67.82	2.58	141.42	0.003267
Kenya	KEN	27.90	51.28	0.54	423.41	0.009781
Cambodia	KHM	90.11	366.95	0.25	474.87	0.010970
Kiribati	KIR				17.947	0.000415
Saint Kitts and Nevis	KNA	233.00	233.00	1.00	26.098	0.000603
Liberia	LBR	12.50	94.95	0.13	142.86	0.003300

Country	Code	World Bank	NI	Ratio	Mangroves (ha)	Share of global mangroves (percentage)
Saint Lucia	LCA				23.332	0.000539
Sri Lanka	LKA	114.20	247.71	0.46	143.76	0.003321
Saint Martin	MAF				6.1055	0.000141
Madagascar	MDG	5.90	45.37	0.13	546.12	0.012616
Maldives	MDV	361.70	361.70	1.00	4.1166	0.000095
Mexico	MEX	25.50	59.86	0.43	556.53	0.012857
Marshall Islands	MHL				0.59591	0.000014
Myanmar	MMR	223.39	99.45	2.25	770.06	0.017790
Northern Mariana Islands	MNP				27.305	0.000631
Mozambique	MOZ	2.40	49.76	0.05	712.9	0.016469
Mauritania	MRT	1.70	1.31	1.30	0.91802	0.000021
Martinique	MTQ				77.321	0.001786
Mauritius	MUS	978.80	978.80	1.00	3.2698	0.000076
Malaysia	MYS	32.50	83.38	0.39	749.8	0.017322
Mayotte	MYT				57.476	0.001328
New Caledonia	NCL				192.94	0.004457
Nigeria	NGA	38.90	41.80	0.93	2148.4	0.049632
Nicaragua	NIC	33.80	87.36	0.39	482.85	0.011155
Nauru	NRU				2.5807	0.000060
New Zealand	NZL	74.90	78.68	0.95	185.59	0.004287
Oman	OMN	48.40	11.30	4.28	18.918	0.000437
Pakistan	PAK	145.50	51.12	2.85	548.29	0.012666
Panama	PAN	54.00	162.10	0.33	578.04	0.013354
Peru	PER	34.00	16.37	2.08	230.06	0.005315
Philippines	PHL	190.30	148.86	1.28	143.58	0.003317
Palau	PLW				313.83	0.007250
Papua New Guinea	PNG	188.90	8.11	23.31	684.97	0.015824
Puerto Rico	PRI	126.81	210.71	0.60	134.51	0.003107
French Polynesia	PYF				1.6679	0.000039
Qatar	QAT	431.10	2.92	147.56	29.675	0.000686
Saudi Arabia	SAU	1.70	2.18	0.78	51.564	0.001191
Sudan	SDN	10.70	34.52	0.31	13.689	0.000316
Senegal	SEN	11.30	55.01	0.21	770.49	0.017800
Singapore	SGP	0.90	0.90	1.00	42.143	0.000974
Solomon Islands	SLB				170.28	0.003934
Sierra Leone	SLE	21.00	76.32	0.28	1256.2	0.029020
El Salvador	SLV	183.90	149.93	1.23	782.71	0.018082
Somalia	SOM	7.62	17.13	0.44	73.07	0.001688
Suriname	SUR	139.04	8.00	17.37	911.92	0.021067

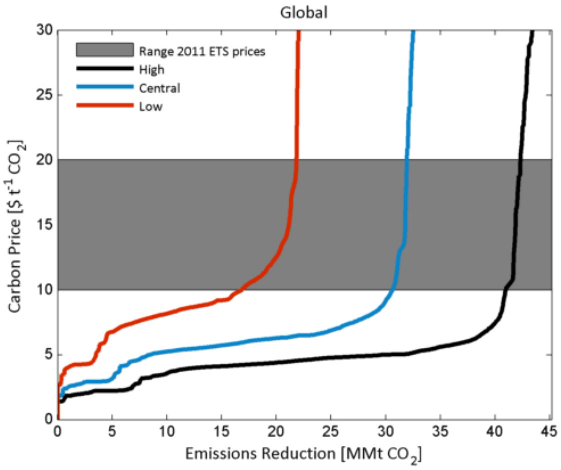
Country	Code	World Bank	NI	Ratio	Mangroves (ha)	Share of global mangroves (percentage)
Seychelles	SYC	54.10	54.10	1.00	99.71	0.002304
Turks and Caicos Islands	TCA				554.36	0.012807
Togo	TGO	14.90	35.50	0.42	20.746	0.000479
Thailand	THA	135.00	240.06	0.56	600.09	0.013863
Timor-Leste	TLS				31.305	0.000723
Tonga	TON	146.40	146.40	1.00	88.479	0.002044
Trinidad and Tobago	TTO	81.80	12.44	6.58	181.82	0.004201
Tanzania	TZA	22.62	89.19	0.25	442.24	0.010216
United States	USA	38.80	86.76	0.45	499.93	0.011549
Saint Vincent and Grenadines	VCT	264.30	264.30	1.00	9.3508	0.000216
Venezuela	VEN	29.20	36.89	0.79	775.89	0.017924
Virgin Islands (British)	VGB				19.459	0.000450
Virgin Islands (U.S.)	VIR				16.999	0.000393
Vietnam	VNM	225.90	178.57	1.27	621.77	0.014364
Vanuatu	VUT	87.10	87.10	1.00	104.72	0.002419
Wallis and Futuna Islands	WLF				8.8359	0.000204
Samoa	WSM				19.075	0.000441
Yemen	YEM	27.89	8.84	3.16	37.342	0.000863
South Africa	ZAF	13.60	70.70	0.19	169.72	0.003921

While we present the results for the largest distance, we find that the estimates of the global supply of carbon offsets from mangroves are not sensitive to the average distance. Figs SI.2 a-c reproduces global supply curve estimates using all of the three averaging distances considered, indicating that the alternative averaging distances result in nearly identical estimates of supply.

a. 13-km nearest neighbor



b. 26-km nearest neighbor



c. 39-km nearest neighbor (used in paper)

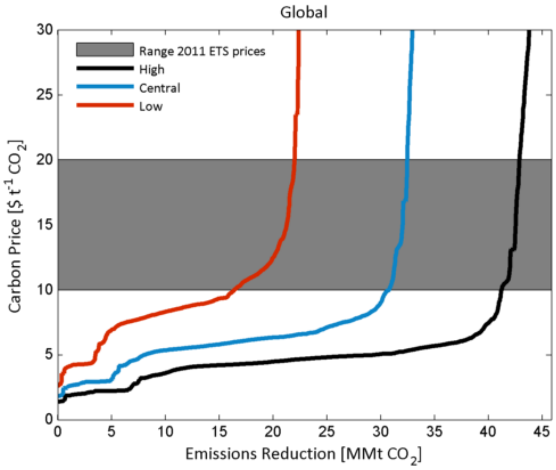


Figure SI.2 Global supply curves using different distances for nearest neighbor averaging

Biodiversity Measures

More than 70 different species of mangrove are known to exist, though the total number somewhat varies depending on the definition of a mangrove. Mangrove species are often divided into eastern (Indo–West Pacific) and western (Atlantic–East Pacific) floral groups, with almost no overlap in species between them (Spalding et al. 2010). The eastern group is considerably richer in mangrove species—more than 60, versus a dozen in the western group. Nevertheless, all mangrove species share some basic characteristics. For example, they grow in or adjacent to intertidal areas and have adapted to cope with that environment, evolving different forms of aerating roots to transport oxygen to roots submerged in water or anaerobic soils.

Figure SI.3 maps mangrove species richness by country using data from IUCN (2010). The map shows that Southeast Asia and southern Asia are the regions with greatest number of mangrove species. In the western hemisphere, the center of mangrove species diversity is in Central America and Colombia, especially on the Pacific coast. The map also shows the difference between the eastern and western group in the number of species.

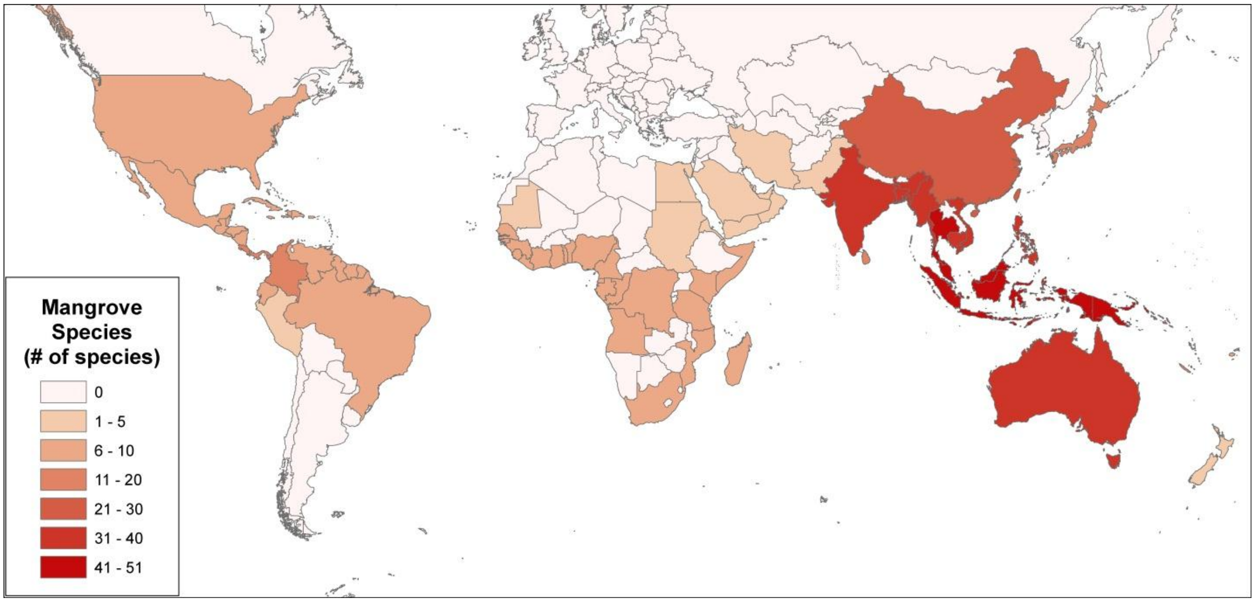
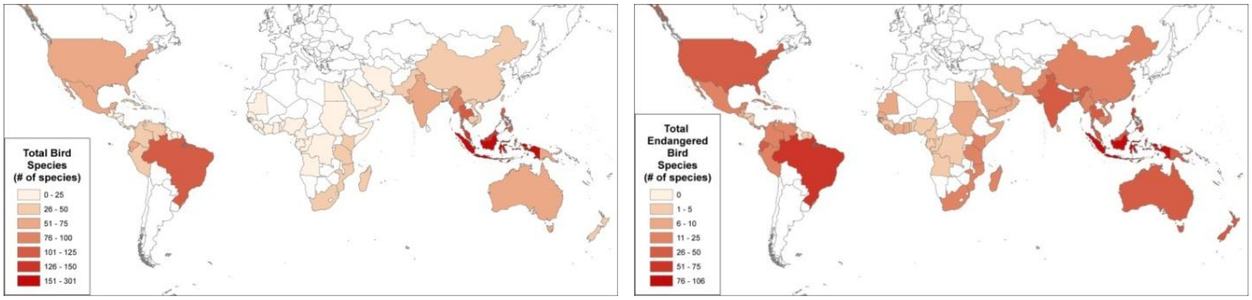


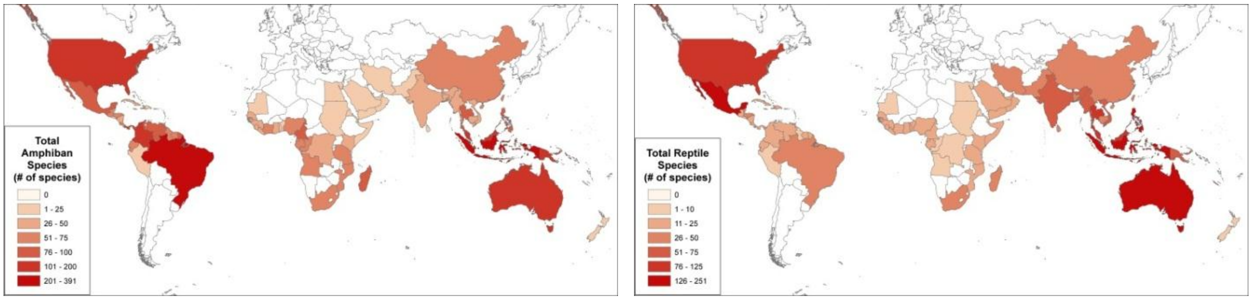
Figure SI 3. Mangrove species richness, by country. Compiled using data from IUCN (2010).

Southeast Asia is clearly the global center of mangrove species richness. In combination with other results from our study, this suggests that blue carbon conservation should concentrate in areas particularly rich in mangrove species. However, practically no species overlap exists between the western and eastern mangrove species groups (Spalding et al. 2010), so a global approach to preserving mangrove species richness might also suggest protecting western mangroves. Because conservation efforts focused on avoiding carbon emissions due to mangrove loss likely would concentrate in Southeast Asia, additional programs may be required to ensure the protection of western mangrove species.



a. Birds

b. Endangered birds



c. Amphibians

d. Reptiles

Figure SI.4. Bird, endangered bird, amphibian, and reptile species richness associated with mangroves, by country. Compiled using data from BirdLife International (2011) and IUCN (2010).

The importance of mangroves in biodiversity conservation obviously extends beyond mangrove species richness. Mangroves support a wide variety of other species, and considering the potential for their conservation is therefore also relevant. Among terrestrial vertebrates, birds are an important species group using mangroves for nesting and roosting sites as well as food. Using detailed spatial data on avian species ranges from BirdLife International (2011), we calculate the number of bird species in mangrove areas by country (Figure SI.4a). This assessment shows that Southeast Asia has the greatest number of bird species associated with mangroves. The global distribution of species richness is somewhat more even when looking only at the endangered bird species (Fig. SI 4b), but Southeast Asia nevertheless emerges as the global hotspot for birds associated with mangroves.

Figures SI.4.c-d are based on our assessment of data from IUCN (2010) to map the number of amphibian and reptile species associated with mangroves by country. Although amphibians are relatively broadly distributed and their number is particularly high in both South America and Southeast Asia, intertidal areas with relatively high salinity of water generally do not favor this class of vertebrates, which instead occur near or adjacent to mangroves. Efforts to protect amphibians will therefore not likely focus on mangroves.

Figure SI.5 illustrates the distribution of correlation coefficients between per ton cost of carbon and mangrove species richness, biodiversity richness, and number of endangered bird species across the countries with mangrove deforestation. Biodiversity richness measures the total number of mangrove, bird, reptile, marine and terrestrial mammal, and amphibian species in the each cell. The distributions of correlation coefficients, however, clearly highlight the variability within each country. For example, whereas the global correlation of mangroves and per ton cost is –0.046, the range goes from less than –0.8 to 0.6. The implication is that in some parts of the world, cost per ton is negatively correlated with mangrove species richness and the likelihood of co-benefits for mangrove species richness is large (i.e., costs are decreasing when biodiversity is increasing). On the other hand, other countries have correlation coefficients greater than 0.5, implying that places with high species richness also have high opportunity cost of protection. The other indicators reveal similar patterns in terms of the correlation coefficients and potential for co-benefits.

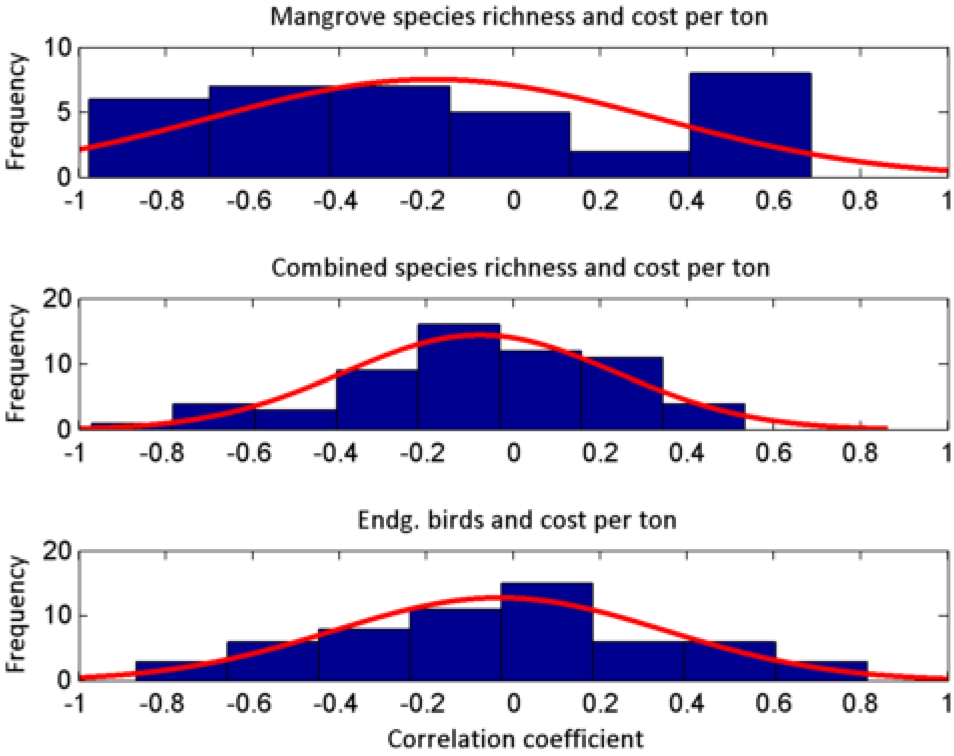


Figure SI 5. Distribution of correlation coefficients in countries with current mangrove losses

Robustness Checks across Targeting Cases

While we draw from country-level assessments of mangrove loss from the FAO, no information currently is available on the more precise location of land use change within a particular location in a country. In the main assessment, we focused on a case, where providers of offsets need to protect all at-risk mangroves within a cell while at the same time the offsets are spread out across all the cells within a country. The case implicitly assumes that the provider of the offset can also successfully target the region within each cell that is subject to deforestation.

Here, we examine three alternative cases that further illuminate and bound the potential range of the marginal cost of avoided emissions (Fig. SI.6). The purpose of these robustness checks is to examine how possible variations on the within-country occurrence of mangrove deforestation (hereafter, targeting) could affect our main results.

The first case, which we denote as the "carbon cost," illustrates the lower envelope of costs, where targeting is successfully based on the per-ton cost of avoided emissions. Within each country, the mangrove parcels are sorted by the carbon price and only the lowest are included in the supply curve (until the country emission baseline is met). The "carbon cost" case is a potential outcome if buyers of offsets had perfect information on the per-ton cost of avoided emissions. Of course, the information is subject to scientific, policy, and economic uncertainties but the case does highlight the potential returns from information gathering.

The second case, "land rent (low)," focuses on the supply side of the offset market where risk of mangrove deforestation is perfectly and negatively correlated with land prices (returns from land). That is, mangroves in areas (in our analysis, cells) with the lowest opportunity cost are the locations where mangroves are at risk and are therefore the locations where offsets are available.

The third case reverses the "land rent(low)" case by assuming that the mangrove deforestation risk is perfectly and positively correlated with land prices. That is, the mangroves in areas where the opportunity cost is highest—potential agricultural revenues are greatest or other factors are driving the price of land (e.g., development) are subject to deforestation and are therefore the locations where potential offsets are available through additional protections. We denote this case "land rent (high)".

At the outset, we know that the "carbon cost" will by definition provide the lowest cost per ton of avoided emissions, and that the "land rent (high)" will represent the highest cost per ton of avoided emissions. Together these cases highlight the potential range that could emerge.

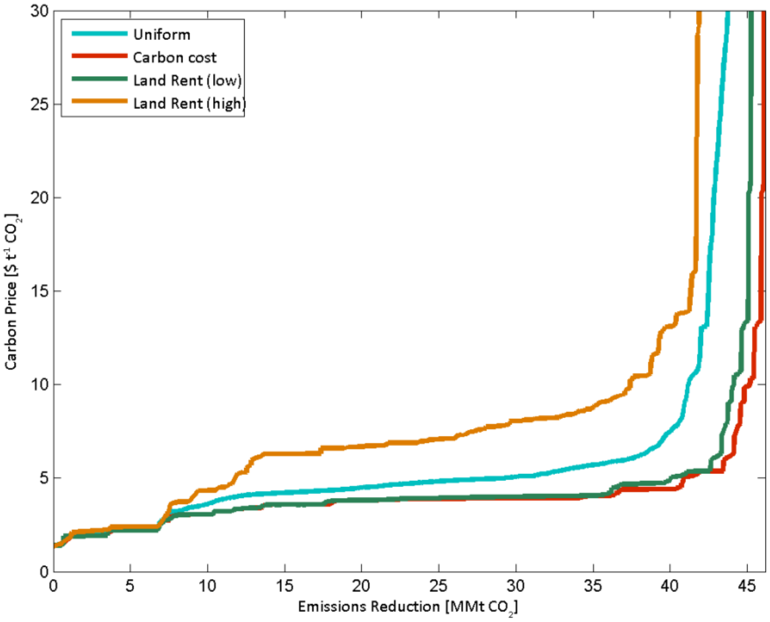


Figure SI.6 Global supply curves for the different targeting cases

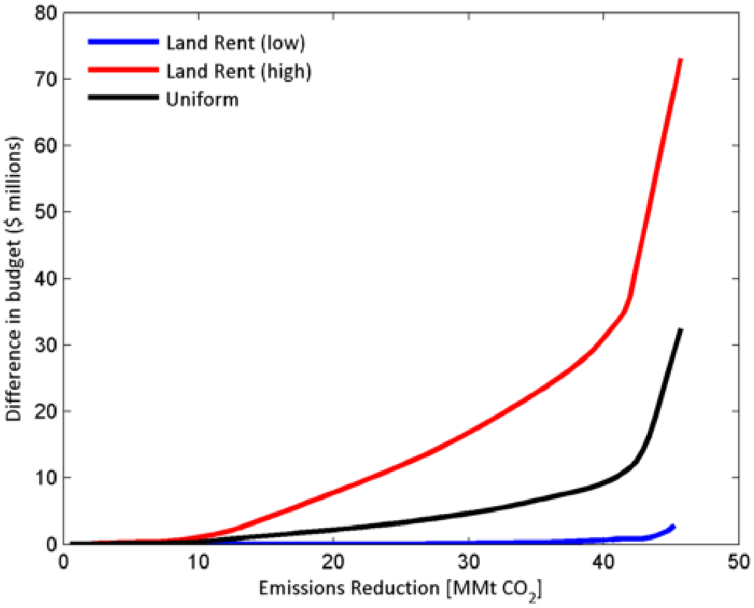


Figure SI.7 Cost differentials between the targeting cases

Figure SI.7 summarizes the differences in the overall cost of mangrove carbon conservation across the cases for different levels of carbon offsets. We measure the differences off of the lowest cost case (carbon cost). As expected, different targeting cases result in different estimated costs of achieving the same targets. We find that the increment in cost associated with the low land rent case is small, on the order of \$1-2 million. The difference between the uniform targeting (assumed in the main assessment) and cost-per-ton case is substantially greater, and the high land rent case further increases the cost differential relative to the cost-per-ton case.

While empirically the differences between the above cases could have been quite large, we find overall that the differences are relatively small given the potential size of a carbon market. Additional costs are largest at high carbon volumes and between the high land rent and cost-per-ton carbon cases, so we use them to illustrate the findings. When a program is purposed to an area of mangroves equal in size to their annual losses , the program under the high land rent scenario is about \$30 to \$40 million more costly than in the lowest cost case (cost per ton). The cost increment is about \$1 ton^{-1} C, or slightly less than \$4 ton^{-1} CO_2.

These additional assessments further strengthen our overall findings. While our main assessment projects that most emissions from mangrove deforestation could be avoided at costs around \$4-\$10 ton^{-1} CO_2, we find that even the most disadvantageous assumption regarding the opportunity cost of land would only add around \$4 to the estimated per-ton cost. Therefore, under a broad range of assumptions and within the relevant range of potential emission reduction targets, the cost of avoided emissions remains competitive relative to the carbon emissions offset prices in the EU ETS; between about \$10 and \$20 ton^{-1} CO_2 in 2011-May 2012 (European Energy Exchange 2011).

Robustness Checks with Oil Palm and Shrimp Mariculture

While our current opportunity cost estimates are based on 2007 agricultural land rent data, recently oil palm has become an important crop in Indonesia and a driver of deforestation (Butler et al. 2009). Furthermore, Indonesia has expressed interest in increasing land devoted to oil palm production from 9.7 million hectares to 18 million hectares by 2020 (Koh and Ghazoul, 2010). Because Indonesia holds 19.5% of the world's mangroves, the mangroves are "carbon-rich" relative to the sample average[10], and Indonesia can potentially provide a sizable proportion of the global mangrove carbon offset supply, we check the robustness of our results by calibrating the NI data using estimates of the net present value from oil palm in Indonesia (Butler et al. 2009).[11]

In addition to checking the robustness of our results to oil palm, we also consider the implications that mangroves in Thailand are often converted to shrimp farms (Sathirathai and Barbier 2001). Although Thailand only holds 1.8% of the world's mangroves and the mangroves are not particularly "carbon-rich" relative to the global sample, we believe that the robustness check is valuable, as the returns from shrimp farming can be much higher than agriculture. We use the Sathirathai and Barbier (2001) estimate for the net present value of shrimp farming.[12]

Table SI.6 illustrates the change in the calibration ratio taking into account the oil palm in Indonesia and the shrimp farming in Thailand.[13]

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[10] For example, we estimate the average soil carbon in Indonesian mangroves to be 0.045 g C cm^{-3} (with a median of 0.033 g C cm^{-3}) while our estimated global average is 0.035 g C cm^{-3} (the global median is 0.0319 g C cm^{-3}).

[11] Butler et al. (2009) model Indonesian oil palm yield functions to provide NPV estimates for Indonesian oil palm using World Bank prices and midpoint values of published costs data. In their high yield scenario, the NPV over 30 years is $9,630/ha and in their low yield scenario, the NPV over 30 years is $3,835/ha. As the timeframe considered in this report is 25 years, we use their model to calculate NPVs over 25 years, which are $9,036/ha and $3,576/ha for high and low yield scenarios respectively (and $8196.56/ha and $3,478.73/ha once converted into 2005 dollars). To estimate an upper bound for opportunity cost of Indonesian land, we focus on the high opportunity cost estimate and adjust all NI data in Indonesia by a factor of ((8196.56/53.953)=151.9).

[12] Sathirathai and Barbier (2001) note that shrimp ponds are productive over 5 years and have a 5-year NPV of $8,336.47. In 2005 dollars, the 5-year NPV is $9193.46/ha. The average opportunity cost for Thailand in the NI data is $240.06. Therefore, we adjust NI data for all mangrove cells in Thailand by a factor of ((9193.46/240.06) = 38.3).

[13] Although China is a top exporter of farmed shrimp (FAO 2011), our results will be not be greatly affected by the opportunity cost estimates in China, because they have less than 0.001% of mangroves.

Table SI.6 Alternative Opportunity Cost Estimates (\$ ha^{-1}, on average) for Indonesia and Thailand, original estimates using Naidoo and Iwamura (2007) and WB (2010) versus new estimates accounting for oil palm in Indonesia and the shrimp farming in Thailand

Country	World Bank	NI	Original Calibration Ratio	New Calibration Ratio
Indonesia	87.1	53.95	1.61	151.9
Thailand	135	240.1	0.56	38.3

After re-calibrating opportunity cost data in Indonesia and Thailand, we again use nearest-neighbor averaging to increase data coverage. The opportunity cost estimates presented in this section are 39-km spatial averages of our newly-calibrated NI data.

Figure SI.8 the presents the global supply curves under the high and low soil carbon assumptions. The curves using original opportunity cost data are superimposed on curves using high opportunity cost (HOC) data. As expected, for each carbon level, the new curves lie to the left of the old curves representing an inward shift of global supply.

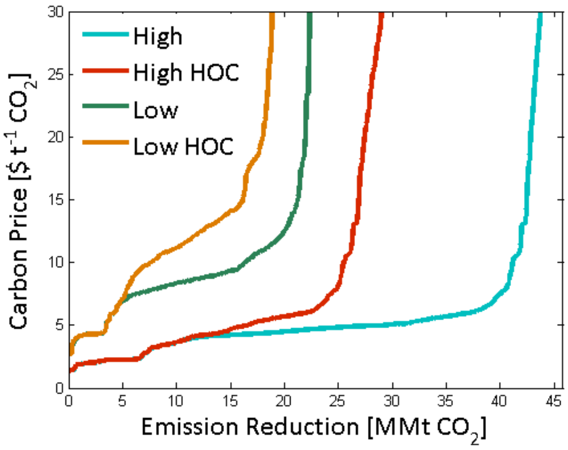

Figure SI.8 Global supply with low and high soil carbon estimates with and without the high opportunity cost (HOC) estimate for Indonesia and Thailand

Potential for Methane and Nitrous Oxide Emissions

Mangroves sequester carbon dioxide from the atmosphere, but they also comprise a natural source of methane (CH_4) and nitrous oxide (N_2O), both of which are potent and important GHGs (Purvaja and Ramesh 2001; Purvaja 2004; IPCC 2007). These emissions are related to anoxic conditions due to tidal flooding, which periodically prevail in the soil of mangrove ecosystems and cause denitrification and methanogenesis. While the potential of mangrove wetlands as sources of GHGs is widely recognized, detailed information on the magnitude of GHG emissions from mangrove forests is rather limited. Albeit estimates of methane emission vary by study and location, current findings unambiguously suggest that methane and nitrous emissions from mangroves are small relative to the volume of carbon stored in them (and potentially released as a result of land development). For example, Krithika et al. (2008) estimate that mangroves in South India release, on average, about 0.09 tons CH_4 ha^{-1} yr^{-1}. For Puerto Rico, Sotomayor et al. (1994) estimate emissions of about 0.16 tons CH_4 ha^{-1} yr^{-1}. Converting to CO_2 equivalents, these estimates suggest that methane emissions from mangroves are similar to emission of roughly between 2.1 and 3.6 tons CO_2 ha^{-1} yr^{-1}. Nitrous oxide emissions similarly vary by study and location. For example, for India, Krithika et al. (2008) estimate that N_2O emission are equivalent to between roughly 0.4 and 0.9 CO_2 ha^{-1} yr^{-1}.

While emissions of methane and nitrous oxides from mangroves and other natural ecosystems are important to include in overall assessments of GHGs and climate change, the critical aspect in the context of this assessment is to determine how potential land conversions alter methane and nitrous oxide emissions. More specifically, projected emissions from mangroves converted into agricultural and other alternative uses provide an emissions baseline relative to which emissions under a conservation option would be evaluated against in assessing the GHG benefits from avoided conversion (and emissions). If emissions of methane and nitrous oxides under conservation are greater than under alternative land uses, then the overall GHG benefits from protecting mangroves would be smaller than estimated by focusing only on carbon emissions. On the other hand, if alternative uses have relatively greater methane and nitrous oxide emissions than natural mangroves, then the avoided emissions from mangrove protections would be greater than when estimated based on carbon only.

Comprehensive and globally representative estimates of methane and nitrous oxide emissions from mangroves converted into agricultural and other alternative land uses are not available, but the currently available estimates suggest that emissions under alternative land uses are likely greater than emissions from standing mangroves. In particular, rice farming on wetlands is considered one of the chief agricultural sources of methane (Sass 1999; Sass et al. 1999; IPCC 2000, 2007; Yan *et al.*, 2003). For example, according to IPCC (2000), rice cultivation annually generates between 20-100 Mt of methane emissions globally. This is equivalent to emissions of roughly 3 to 16 t CO_2 ha^{-1} yr^{-1} (average 10 CO_2 ha^{-1} yr^{-1})[14]. Additionally, agriculture and rice cultivation especially, is a chief alternative land use driving mangrove deforestation (Giri et al. 2008).[15]

The above evidence suggests that mangrove conservation likely would not increase but may even decrease emissions of methane and nitrous oxides relative to their baseline under alternative land uses. Therefore, mangrove conservation projects could potentially qualify for greater GHG offset credits than one would estimate solely based on avoided carbon emissions. However, any potential benefits from avoided methane and nitrous oxide emissions are extremely small relative to avoided carbon emissions so their inclusion or exclusion does not critically alter the assessment results.[16] Moreover, estimates to support more precisely quantifying the potential GHG benefits associated with methane and nitrous oxides are limited. Therefore, we consider the emission profiles of methane and nitrous oxides sufficiently similar under conservation and alternative land uses, so that the net effect from conservation on methane and nitrous oxides is effectively zero. Hence, we estimate potential emission offset credits from mangrove conservation solely based on avoided carbon emissions, thus, likely underestimating the full GHG reduction potential of mangrove protections.

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[14] The estimate of global emissions corresponds to roughly 140,000 km^2 of cultivated rice, The current rice cultivation area is greater. For example, in 2009, it was about 158,000 km^2 globally (FAO 2011a).

[15] Rice cultivation also generates nitrous oxide emissions, but their overall volume and global warming potential is small relative to methane emissions.

[16] For example, methane emissions from natural mangroves are in the range of few tons per hectare, while the avoided carbon emissions from mangrove protection are, on average, about 290 tons per hectare (central estimate).

Map of World Bank's Government Effectiveness Index

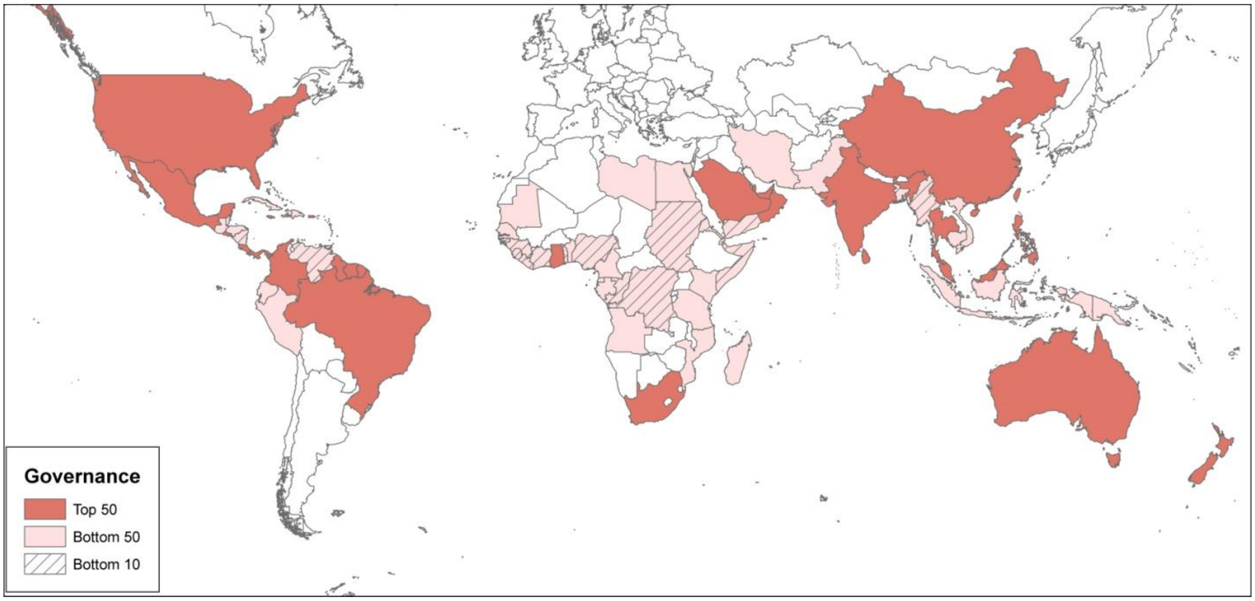

Figure SI.9 Countries with mangroves, categorized by World Bank governance index (World Bank 2011b, Kaufmann et al. 2010)

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