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Blue Carbon: Coastal Ecosystems, Their Carbon Storage, and Potential for Reducing Emissions

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CARBON

Coastal Ecosystems, Their Carbon Storage, and Potential for Reducing Emissions

by Juha Siikamäki, James N. Sanchirico, Sunny Jardine, David McLaughlin, and Daniel Morris

Coastal ecosystems support a wide range of ecological services, for example, by providing primary nursery habitat for many species of fish, crustaceans, birds, and marine mammals.[1] Coastal ecosystems also serve as natural barriers to control storm damage, other natural hazards, and coastal erosion.[2] Besides these long-recognized ecological and economic benefits, coastal ecosystems are becoming touted for their considerable capacity to store and sequester carbon. "Blue carbon" is shorthand for the carbon found in coastal systems, especially in mangroves, seagrasses, and salt marshes.[3] Mangroves, salt marshes, and seagrasses are spread across the globe, albeit concentrated in the tropics, and at least one of the three can be found in almost every country that has a coastline.[4]

Despite their broad importance, mangroves, salt marshes, and seagrasses are among the most threatened and rapidly disappearing natural environments worldwide, with habitat loss rates similar or greater to those in tropical forests.[5] Disturbances including outright loss are typically associated with conversion to agricultural, aquaculture, residential, and industrial uses, and cause the release of all or some of the carbon they store, diminishing further sequestration of carbon dioxide from the atmosphere.[6]

Similar concerns about the effects of deforestation have elevated efforts to protect tropical forests. Deforestation is the second-largest anthropogenic source of carbon dioxide emissions,[7] and slowing it down has become integral to international climate policy. In particular, programs to reduce emissions from deforestation and degradation (REDD programs) are proposed to encourage developing countries with high deforestation rates to reduce their emissions in return for compensation from developed countries.[8] Rather than adopting high-cost mitigation actions domestically, developed countries could meet their emissions reduction commitments by financing emissions offsets in developing countries to achieve similar but less costly emission reductions through REDD. While the general development of and momentum for the REDD mechanism has slowed down, reflecting in part the remaining unresolved technical barriers (e.g., robust verification and monitoring of offsets) and the lack of comprehensive climate policy internationally and in the United States, the basic economic rationale for REDD remains strong.

Several international organizations and nongovernmental organizations (NGOs) have proposed developing an approach similar to REDD to protect blue carbon ecosystems. Although our overall knowledge of blue carbon systems is improving,[9] rigorous assessments to investigate the potential of blue carbon emission offsets, similar to that for REDD programs, have been missing (see Figure 1). Our recent studies[10] along with those of Murray et al.[11] and Pendleton et al.[12] addressed this gap.

Developing estimates of the volume of blue carbon offsets available through conservation activities requires several pieces of information (Figure 1). Besides determining the total area protected, information is needed on the area that would be susceptible for conversion (protected areas would not necessarily be converted entirely in the absence of protection, leaving some of the carbon in the ecosystems intact). To measure the volume of emissions avoided, one also needs estimates of the CO_2 emissions in case of habitat conversion (volume of carbon stored by the ecosystem), including carbon prone to be emitted from above- and belowground biomass,

Figure 1. Blue carbon offset accounting.

$$\left(\begin{array}{l}\text{Carbon}\\ \text{offset}\\ \text{credit}\end{array}\right) = \left(\begin{array}{l}\text{Share of protected}\\ \text{hectares susceptible}\\ \text{to conversion}\end{array}\right) \cdot \left(\begin{array}{l}\text{Number of}\\ \text{hectares}\\ \text{protected}\end{array}\right) \cdot \left(\begin{array}{l}\text{Carbon in}\\ \text{above ground}\\ \text{biomass}\end{array} + \begin{array}{l}\text{Carbon in}\\ \text{below ground}\\ \text{biomass}\end{array} + \begin{array}{c}\text{Carbon}\\ \text{in soil}\end{array} + \begin{array}{c}\text{Annual}\\ \text{carbon}\\ \text{accumulation}\end{array}\right)$$

and from the soils. Moreover, habitat loss prevents the ecosystem from continuing the sequestration of CO_2 from the atmosphere. Summing up all these elements, one can determine the additional carbon storage capacity contributed by the conservation activity.

This article summarizes our recent assessments of the carbon storage in blue carbon ecosystems and the economic potential for preserving it.[13] We first discuss where blue carbon ecosystems are found. We then present estimates on how much carbon they store (above- and belowground biomass and soil carbon) and sequester (annual accumulations), and projections of future carbon emissions due to coastal land development. Next, we explain the potential economic attractiveness of blue carbon conservation by highlighting our estimates of the relatively low cost of reducing emissions from coastal environments. Both biophysical and economic conditions relevant to our assessments are highly variable across the globe, so we have focused on identifying the geographic variability of emissions from coastal ecosystems and the cost of avoiding them.

Blue Carbon Environments

Mangroves

Mangroves are intertidal forests featuring more than 70 species of trees and shrubs, including some ferns and at least one type of palm.[14] Mangroves are known for their typical aerial roots, which grow from the main stem above the soil. This highly specialized root structure enables mangroves to directly uptake gases from the atmosphere. Mangrove roots also trap and suspend nutrients, peat, and sediments, and mute the energy of incoming tides that might otherwise cause inland erosion.

Mangrove forests are especially effective intertidal colonizers, so they are found primarily in river deltas, estuaries, and coastal lagoons. Mangroves thrive with access to water with diluted salinity and regular nutrient influx. Open coastlines with relatively low wave energy can also present viable conditions for mangrove growth. In ideal conditions, mangroves can form a thick forest with canopy heights up to 30 m.[15]

Estimates of the global coverage of mangroves vary, but the most recent and rigorous spatial data on mangrove forests by Giri et al.[16] estimate a total area of 139,170 km^2 worldwide. Historically, the range of mangroves was considerably greater (200,000 km^2 or more), but the extent has steadily shrunk due to coastal development over the last several decades.

Mangroves are concentrated on both sides of the equator in the tropics (Figure 2), where about 95% of mangroves are found. The rest are found near tropical latitudes in temperate zones. In Southeast Asia, where roughly one-half of all global mangroves exist, thick bands of mangroves spread along the shores of Indonesian islands, and mangroves are also found on the coasts of Thailand, northern Australia, Burma, the Sunderbans in India and Bangladesh, and throughout the Philippines. Western Africa and South America each contain about 15% of the global total. North America, including the Caribbean, accounts for roughly 13% of the global total.

Indonesia is the country with by far the greatest mangrove area, accounting for nearly one-fifth of the global total area of mangroves (Table 1). The next four largest countries based on mangrove coverage—Brazil, Australia, Mexico, and Nigeria—are found dispersed on different continents. The geographic concentration of mangroves is highlighted by the fact that the top six countries have nearly half the world's mangrove area; the next nine countries contain an additional 25% (Table 1).

Seagrasses

Seagrasses are fully submerged and vegetated areas ("meadows") in shallow coastal waters, found off all continents except Antarctica.[17] Seagrasses are known as important shelter for aquatic animals and breeding ground for various fishes.[18] Seagrasses function as collection areas for sediments coming off the land and they also provide important links between coral reefs and terrestrials systems such as mangroves.[19]

Globally, seagrass ecosystems are estimated to cover about 319,000 km^2, or roughly twice the areas of global mangroves.[20] Seagrass ecosystems are relatively broadly distributed, but most (over 70%) are found between the Tropic of Cancer and the Tropic of Capricorn.[21]

Southeast Asia is the leading region for seagrass area, with about 25% of the world's total. Other important regions for seagrasses include North America, with about 18% of global seagrass areas, and western Africa, with about 15%. At the country level, Australia has the greatest area of seagrasses (nearly 13% of the global total). The 10 countries with the greatest seagrass area, which contain more than half of global seagrasses, include Saudi Arabia, the United States, Indonesia, Guinea-Bissau, Philippines, Cuba, Guinea, Mexico, and Papua New Guinea.

Salt Marshes

In addition to mangroves, salt marshes are the other major intertidal blue carbon habitat. They are often situated in environments similar to those of mangroves, including estuaries, deltas, and low-lying coasts that experience low wave energy.[22] Salt marshes, however, have a greater latitudinal extent than mangroves (in the tropics, areas suitable to become salt marshes typically are subjugated by mangroves) and are dominated by herbaceous plants rather than trees. These plants are able to withstand high salinity and regular submersion due to high tides.

Salt marshes are estimated to cover roughly 51,000 km^2 worldwide.[23] However, comprehensive spatial data at the global scale on salt marshes do not yet exist, so their geographic distributions cannot be comprehensively determined, although efforts are currently underway. Regardless, it is known that salt marshes are situated mostly in temperate areas and high latitudes. In tropical areas, they typically give way to mangroves.[24] Overall, the geographic distribution of salt marshes is considered at least as broad as that of seagrasses.[25]

Mangrove and seagrass areas overlap to some degree. For example, Southeast Asia is the world region richest in both mangroves and seagrasses. Almost one-half of all global mangroves cover the coasts of this region, and it accounts for about one-quarter of the known global seagrass area.

Figure 2. Global Mangroves.

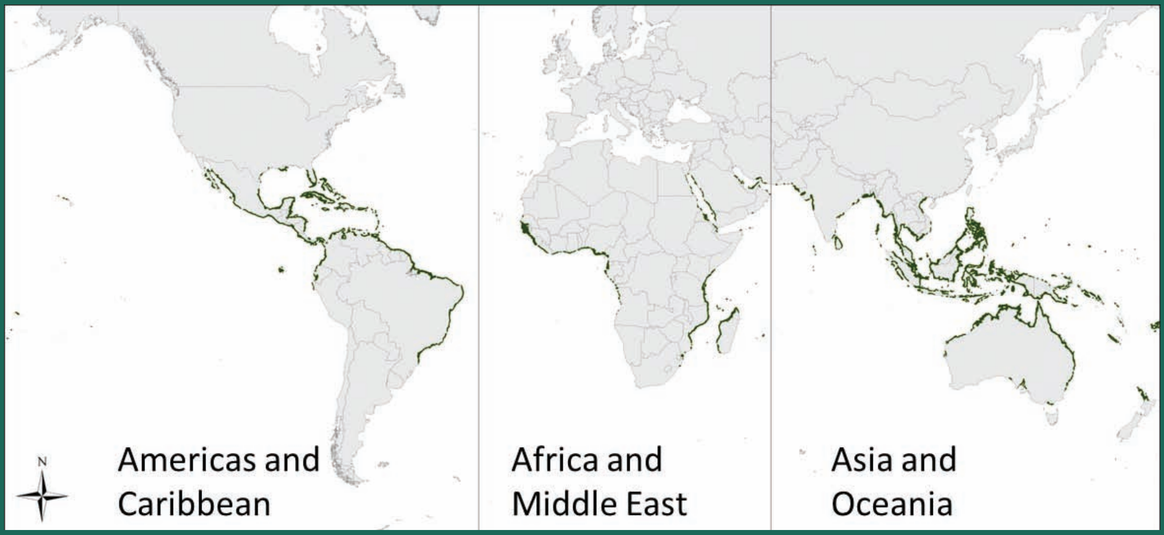

Table 1. Country rankings for mangrove area.

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

Carbon Storage in Blue Carbon Environments

The majority of carbon in coastal ecosystems is trapped in the soils, which makes blue carbon ecosystems different from many other forest ecosystems relevant in the context of avoided emissions from deforestation, such as tropical rain forests.[26] One of the key challenges in the context of blue carbon conservation, therefore, is to develop rigorous estimates of the soil carbon reservoirs in coastal ecosystems. To do so, we synthetized scientific literature and estimated how much carbon is contained in different blue carbon habitats and locations around the world (see Box 1). We focused on mangroves in large part because of the data limitations for salt marshes and seagrasses, but also because of the clear prominence of mangroves in the context of blue carbon.

Mangroves are remarkably rich in carbon, containing three to four times the volume of carbon typically found in boreal, temperate, or upland tropical forests.[27] According to our estimates, one hectare of mangroves comprises about 467.5 t C per hectare (1714 t CO_2e ha^{-1}) (Table 2 and Box 1), which is equivalent to the annual emissions from more than 330 passenger vehicles in the United States, on average (5.1 t CO_2 per vehicle, on average, 12,000 miles driven at the fuel consumption of 21 miles per gallon).

Globally, mangroves contain about 6.5 Pg C (almost 26.8 Pg CO_2e), including carbon in above- and belowground biomass and in the first 1 m of soils (Table 2). The current total global storage of carbon in mangroves is comparable to the emissions produced over about a 4-year period by the entire U.S. economy (6.7 Pg CO_2e in 2011[28]).

We also 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 2). Comparing this estimate again to emissions from passenger vehicles suggests that each year, mangroves currently sequester a volume of carbon that is comparable to the annual CO_2 emissions from about 11.5 million passenger vehicles.

Salt marshes have slightly less carbon per hectare than mangroves, about 393 tons per hectare, or equivalent to annual emissions from 77 passenger vehicles, on average, in the United States. The global coverage of salt marshes (51,000 km^2) therefore results in a global total carbon stock of about 2 Pg C (Figure 3). However, current knowledge of the areal coverage of salt marshes is incomplete, so this estimate is subject to considerable uncertainty.

Seagrasses have the least amount of carbon per hectare, approximately 72 tons (equivalent to annual emissions from 14 passenger vehicles, on average, in the United States), but their large global coverage (319,000 km^2) results in a substantial estimate of total carbon stock, 2.3 Pg C (Table 2 and Figure 2).

Estimation of Carbon Storage

Mangroves

We projected location-specific carbon storage in aboveground biomass using a latitude-based prediction method pioneered by Twilley et al.[29] We then considered that the volume of belowground living biomass is 60.8% relative to the volume of aboveground biomass and that 41.5% of the biomass is carbon.[30] To estimate location-specific volume of soil carbon, we developed country-level estimates of soil carbon density by compiling and analyzing 941 primary observations of mangrove soil carbon density available from the literature (Bouillon et al. 2008; Kristensen et al. 2008; Donato et al. 2011).[31] For annual carbon accumulation, we used the carbon burial estimate of 1.15 t C ha^{-1} y^{-1} according to Bouillon et al.[32] Finally, we combined these spatially explicit estimates with local data on mangrove areas (see below) and aggregated the local estimates to construct global estimates.

Salt Marshes

A large proportion of biomass production in salt marshes is located in the subsurface and accumulates carbon in the soils.[33] Using the findings by Cebrian,[34] Bridgham et al.,[35] and Chmura et al.,[36] we estimated that mangroves contain, on average, 390 t C per hectare in the soils (assuming a 1-m depth of carbon-rich soils). Using the same sources, we also estimated that salt marshes feature a carbon burial rate of 2.1 t C ha^{-1} yr^{-1}, on average (Table 2).

Seagrasses

We estimated the volume of biomass carbon in seagrasses using the results of Duarte and Chiscano,[37] who compiled a data set containing large number of estimates on above- and belowground carbon. Combining findings by Duarte et al.[38] on the carbon burial rate of seagrasses and Kennedy et al.[39] on the share of organic matter associated with seagrass plant tissue, we estimated a carbon burial rate of 0.54 t C ha^{-1} yr^{-1}. For soil carbon in seagrass meadows, we used the findings from Laffoley and Grimsditch,[40] who estimated a soil carbon volume of about 70 t C ha^{-1}.

Table 2. Summary of carbon stock and burial estimates for blue carbon ecosystems (from Siikamäki et al.[41]).

	Storage, per ha (t C ha^{-1})	Storage, per ha (t CO_2 ha^{-1})	Storage, global total (Pg C)	Annual emissions, globally (millions tons C)
Mangroves				
Biomass	148	541	2.1	7.5
Soil	320	1173	4.5	16.3
Total stock	468	1714	6.5	23.9
Burial rate	1.15	4.2	0.016	0.06
Salt marsh				
Biomass	3.315	12.2	0.017	0.1
Soil	390	1430.0	1.989	8.5
Total stock	393.3	1442.2	2.01	2.0
Burial rate	2.1	7.7	0.011	10.6
Seagrass				
Biomass	1.54	5.6	0.049	0.3
Soil	70	256.7	2.233	9.6
Total stock	71.5	262.3	2.3	3.1
Burial rate	0.535	2.0	0.017	9.8

Figure 3. Global carbon storage (Pg C) and habitat area (1,000 km²) of mangroves, salt marshes, and seagrasses.

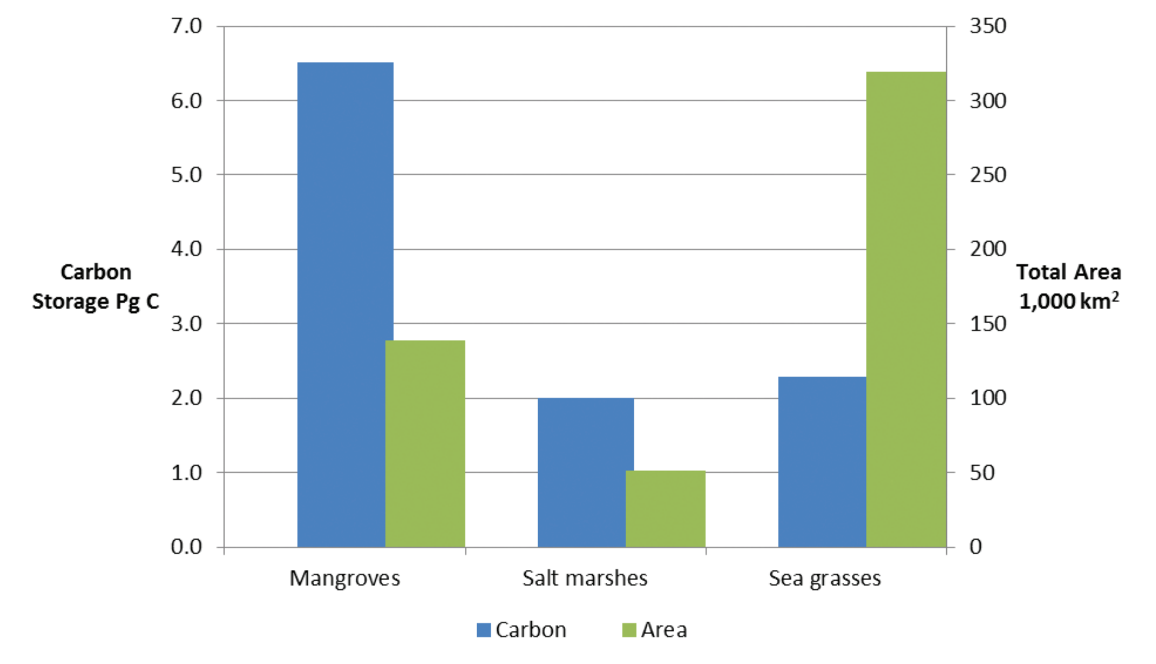

Figure 3 sums up the global coverage of blue carbon ecosystems, including 139,170 km² of mangroves, 319,000 km² of seagrasses, and roughly 51,000 km² of salt marshes. Adding up our estimates of carbon storage globally, we project that mangroves, salt marshes, and seagrasses together store about 11.25 Pg C (about 41.25 Pg CO_2e). Most of the blue carbon pool is in the soils, which contain more than 80% of the overall carbon stock.

Carbon Emissions Triggered by Coastal Development

Coastal Development Rates

Estimating emissions triggered by coastal development requires information on the rate of conversion of the blue carbon habitats and the amount of blue carbon habitat susceptible to conversion (Figure 1). To model the risk of mangrove conversion, we used country-level data on mangrove forest areas over time from the UN Food and Agriculture Organization (FAO).[42] Using the FAO data, which is provided by each country, we measured the net change in the mangrove area between 1990 and 2005 to estimate an average annual deforestation rate. Although most countries experienced a loss of mangroves, a few countries, such as Bangladesh, saw an increase in mangrove acres in 1990–2005.

According to our results, the annual mangrove loss between 1990 and 2005 was about 0.7%, on average, which is substantially greater than the recent rates of deforestation. For example, in South America, FAO estimates an annual loss of about 0.45% of the forest areas between 2005 and 2010. In Southeast Asia, another focal area for deforestation, the annual loss rate was about 0.23% during the same time period (FAO 2010).[43]

Unfortunately, no data are available on the local loss rates of salt marshes or seagrasses. We developed global estimates by extrapolating from the estimated mangrove loss rates to salt marsh and seagrass areas. Using the mangrove loss rate across other blue carbon ecosystems limits the generality of the results but is not completely arbitrary. Seagrass meadows often lie adjacent to mangroves, whose loss likely will degrade also the seagrass bed (see, e.g., Figure 1). Salt marshes are subject to similar land-use pressures as mangroves, though their much broader and different geographic range suggests specific caution when interpreting these estimates.

The presence in a country of a significant amount of mangroves or other blue carbon habitat does not necessarily imply that this habitat is susceptible to conversion. For example, some mangrove areas are already protected. Using spatial data from the World Database on Protected Areas (WDPA), which is a joint initiative of the International Union for Conservation of Nature (IUCN) and the World Conservation Monitoring Centre of the UN Environmental Programme,[44] we estimate that about 4% of the world's total mangrove area is under some type of protection (IUCN conservation categories I–VI). Using these data, we net out the mangrove hectares that are already protected from our analysis.

Carbon Emissions After Land Conversion

Estimates of carbon emissions from mangrove deforestation depend on the depth of mangrove soils as well as the nature of the soil disturbance. Unfortunately, there is a paucity of measurement data on the effects of land conversion on carbon stored in coastal environments. For example, when estimating emissions from mangrove deforestation, Murray et al.[45] assume that all carbon in the first meter of mangrove soils is exposed to oxygen and gradually released into the atmosphere. Murray et al. further assume that 90% of soil carbon in the top 1 m is released into the atmosphere after 25 years. Donato et al.[46] posit that 50% of soil carbon in the top 30 cm of mangrove soils is released, and that in the soils beneath that, 17.5% of soil carbon is emitted. Both Donato et al. and Murray et al. assume that 75% of the carbon in mangrove biomass is released upon conversion.

We drew from the two studies just described, to project a range of potential emissions. First, consistent with most of the literature on mangrove soil carbon, we considered that mangrove conversion affects soil carbon down to 1 m. Second, and again consistent with previous studies, we predicted that 75% of carbon in the aboveground and belowground biomass is emitted. Third, we constructed a range of potential carbon emissions from the mangrove soils: With the Donato et al. approach, a total of 27.25% of the soil carbon in the top 1 m is released; with the Murray et al. set of assumptions, 90% of soil carbon in the top 1 m is released. We used those estimates as the low and the high, and the average of the two forms our middle estimate of the carbon that could be released from mangroves as a result of conversion.

Our emissions estimates indicate that mangrove loss currently releases about 35 million tons of carbon annually (Table 2). Using a CO_2 equivalent, this means that about 130 million tons of carbon dioxide is released into the atmosphere from mangrove loss. The estimated emissions from salt marshes and seagrasses (9.8 million and 10.6 million tons C yr^{-1}, respectively) are about one-third the mangrove emissions. Overall, we estimate that annually, roughly 200 million tons of carbon dioxide (55.6 million t C) is returned to the atmosphere from the loss of blue carbon habitat. More than 60% of the estimated emissions is from mangroves.

Geographically, Southeast Asia, western Africa, and Mexico are the areas with the highest carbon emissions. The three countries with the largest emissions from mangrove losses are Indonesia, with 10.6 million t C per year; Mexico, with 2.1 million t C per year; and Papua New Guinea, with more than 1.6 million t C per year. These three

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Mangrove, Costa Rica.

countries alone account for about 54% of all emissions from mangroves.

Economic Potential of Reducing Emissions From Mangrove Loss

We examined the economic potential of blue carbon conservation by developing estimates of the spatially explicit estimates of the marginal cost (dollars per ton CO_2) of preventing emissions from mangrove conversion.

Figure 4 graphically illustrates our spatial approach using a small concentration of mangroves (in yellow) on the island of Borneo in Indonesia. We divided the world surface area into a large number of regular quadrilaterals (grid cells), each with a side length of 5 minutes (about 9 km). For each grid cell where mangroves are found, we projected current carbon storage (tons C ha^{-1}), including carbon in above- and belowground biomass and in the soils, and accumulation (tons C ha^{-1} yr^{-1}) by mangroves. Combining these with data on mangrove area per grid cell (netting out protected hectares), we estimated the current carbon storage in the mangroves within each grid cell. Thereafter, we used the estimated mangrove deforestation rates (% loss yr^{-1}) for each country to project carbon emissions (tons CO_2 ha^{-1}) due to deforestation over a 25-year time horizon, assuming that the deforestation rates remain constant over time.

Then we estimated the cost of avoiding emissions or the opportunity cost per hectare within the grid-cell based on three pieces of information (Figure 5). First, if a hectare of mangroves is protected, then the present value of all future economic returns from the hectare is lost. While there are many potential uses for the hectare if it is developed, our calculations use the potential agricultural net revenue ($ ha^{-1}). The second and third components capture the fees associated with the one-time set-up cost of protecting the hectare and the annual costs associated with maintaining the protection.

Finally, for each grid cell, we project the cost avoided emissions ($ ton^{-1} CO_2) by dividing the opportunity cost of mangrove conservation by the estimated avoided emissions (amount of carbon in the offset). We conducted the estimation process in each of the altogether roughly 25,000 grid cells where mangroves are located.[47]

With the grid cell level estimates of the cost of avoided emissions, we estimated global and regional marginal cost curves (supply curves) of avoided

Figure 4. Illustration of the spatial assessment framework for mangroves.

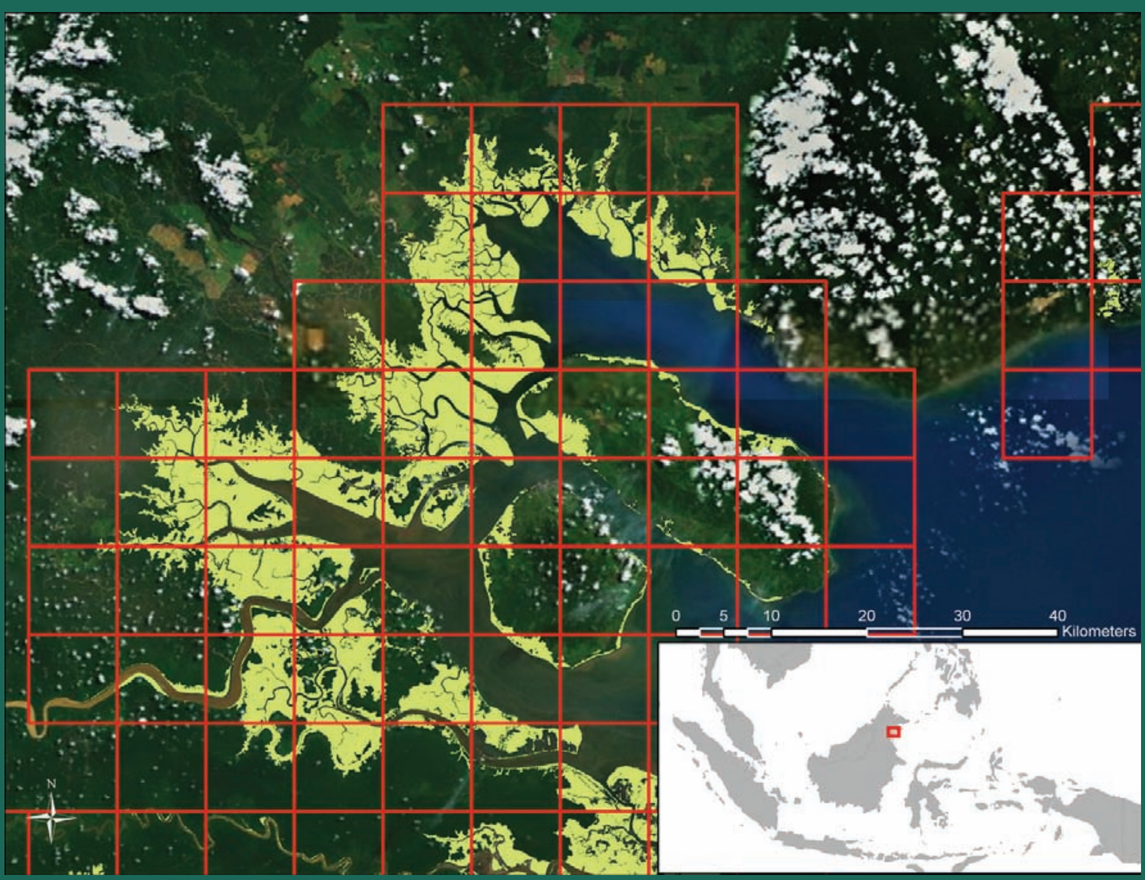


Figure 5. Opportunity cost assessment.

Other land uses for blue carbon habitats

(Opportunity cost per hectare) = (Present value of economic returns from most profitable land use) + (One-time set-up cost of protection) + (Present value of annual costs of protection)

carbon emissions. These estimates (Figure 6) depict the minimum cost per ton (marginal cost) of avoiding different amounts of CO_2 emissions from mangroves. We constructed the supply curves 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 (or regional) projected annual mangrove loss.

Because the degree of emissions triggered by land conversions in a particular location is only partially understood, we developed low and high estimates of potential offset supply to correspond to the range of approaches taken by recent studies.[48] 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.

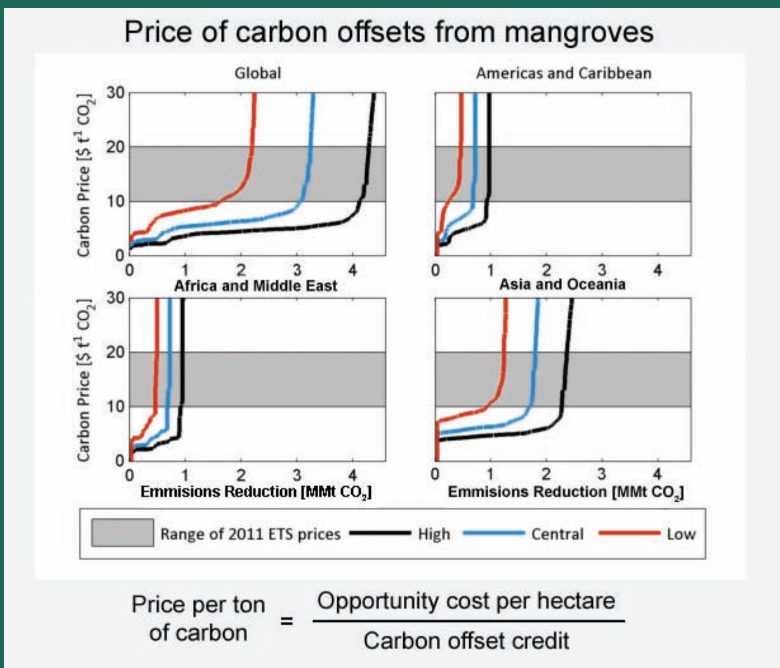
According to our results, preventing mangrove loss has the potential of reducing global emissions for a cost of roughly \$4 to \$10 ton^{-1} CO_2 (Figure 6). Dividing the world's mangroves into three regions by longitude, the Asia and Oceania region has the largest potential emissions offset supply, comprising roughly two-thirds of the potential global offset availability. The other two regions—Americas and Caribbean and Africa and Middle East—each supply approximately half of the remaining world supply (Figure 6).

The overall economic attractiveness of avoiding greenhouse gas (GHG) emissions from mangroves depends on how costly it is relative to reducing emissions from other sources, such as industrial sources. To examine this question, we contrast our results with the recent estimates of the social cost of CO_2 emissions and the long-term range of emissions allowance prices in the EU Emissions Trading System (ETS), which is the world's largest emissions allowance trading system. While the EU ETS does not allow for carbon offsets from avoided deforestation, its credit prices reflect well for other options for reducing CO_2 emissions, such as decreasing emissions from industrial and energy sectors.

Our projection that the majority of available carbon offsets could be generated at less than \$10 ton^{-1} CO_2 (in 2005 U.S. dollars) is below the estimated social cost of carbon emissions and comparable to the recent EU ETS allowance prices. Recent estimates of damage cost caused by CO_2 emissions ("social cost of carbon") include \$19 by the U.S. government;[49] \$12 by Nordhaus;[50] and \$96 by Stern,[51] with all estimates in dollars (2005 U.S. dollars) ton–1 CO_2. The EU ETS allowance prices have remained in the long term between roughly \$10 and \$20 ton^{-1} CO_2, albeit significantly dipping in the current economic downturn. The economic recession has dampened demand for and increased the supply of allowances, thereby, hitting the allowance prices by downward pressure from two directions. Regardless, both of the preceding comparisons suggest that investing in reduced emissions from mangrove loss could be economically reasonable.

The assessment required to construct the supply curves is rife with challenges with data and assumptions required. However, 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. An exception is when we approximated the opportunity cost for Indonesia and Thailand based solely on local estimates of potential returns

Figure 6. Marginal cost of avoided emissions from mangroves (from Siikamäki et al.[41]).



from oil palm plantations[52] and shrimp aquaculture.[53] 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.

Governance Considerations and Blue Carbon Offsets

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 countries 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 was beyond the scope of our analysis. However, we used the World Bank[54] index on governance effectiveness to shed light on the potential impact of such considerations on the supply of carbon offsets.

We considered two cases that limit the potential supply of offsets to countries in the top 50th or 90th percentile of the governance index. The effect of this restriction is both to reduce the supply of carbon offsets (less carbon available) and to increase the price per ton. While 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. While they represent only a small share of potential offset supply, offsets from 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.

Blue Carbon in Climate Change Mitigation Policy Frameworks

International Frameworks

Blue carbon has yet to establish a notable presence in international negotiations, though parties to the United Nations Framework Convention on Climate Change (UNFCCC) have acknowledged the potential benefits of maintaining stored carbon in blue carbon ecosystems. Since its introduction to official proceedings of the UNFCCC in 2005, REDD has been a prominent aspect of international climate negotiations. The UNFCCC negotiations in Cancun in December 2010 formally established many important aspects of REDD+, including basic guiding principles, a distinct scope for eligible activities, and initial frameworks for payment mechanisms.[55]

The similarities between blue carbon credits, especially for mangroves, and REDD credits suggest that including blue carbon in REDD structures may be a viable path forward. A coalition of marine-focused organizations and researchers has called on UNFCCC to include blue carbon in its deliberations.[56] Similarly, a group of scientists and organizations called the International Blue Carbon Policy Working Group made recommendations to develop financial incentives to reduce emissions from coastal ecosystems and to include mangroves in national REDD+ strategies and actions.[57]

Bottom-up efforts from these groups have increased the exposure of blue carbon issues enough to catch the attention of some non-Annex 1 countries. As a result, the issue of conducting more research on blue carbon and including it in systematic observations of important ecosystems was brought before the Subsidiary Body for Scientific and Technological Advice (SBSTA) during the UNFCCC intersessional meetings in Bonn in June 2011.[58] Papua New Guinea introduced blue carbon into the agenda and, with the Coalition of Rainforest Nations, advocated for its inclusion. Although most parties approved more research on the topic, there was strong opposition from Bolivia and Venezuela, both of which feared that blue carbon would generate new market mechanisms that will not adequately protect natural systems. The parties could not reach an agreement, and lacking consensus, blue carbon was not included as a subject for further research. It is apparent, however, that understanding of blue carbon is not sufficiently mature to warrant a separate mechanism.

Incorporating blue carbon into REDD+ structures may be a viable though currently limited option. Based on their height, density, and land cover, some mangroves are classified as forests, depending on the definition established by specific countries. These qualified mangroves would eligible to be included in national REDD+ plans, which all participating countries that receive funding are required to develop.

Mangrove forests share most of the same challenges facing terrestrial REDD+: establishing the clear additionality of projects, ensuring the permanence of credits, identifying specific drivers of deforestation, and developing robust measurement and verification standards.[59] Understanding the volume that mangrove losses contribute to overall deforestation in a REDD+ nation presents an additional obstacle because that information will be critical in establishing baselines by which the performance of each country is measured. Further, the amount of carbon stored in the soil of mangroves proves a particularly important challenge because the basic accounting standards address only the top 30 cm of soil or are based on emissions rates.[60] Neither approach is comprehensive enough to count all the carbon stores in mangrove systems. Standards that would fully capture the carbon sequestration by extending the soil depth are more expensive and difficult to implement.

While the inclusion of mangroves in REDD+ faces obstacles, the other major blue carbon habitats, seagrasses and salt marshes, are not eligible in the current REDD+. To include them, REDD+ programs would have to expand beyond forestry into other land-use types. Such expansions have been discussed in negotiations, but the parties have decided to focus on forestry for the time being. Therefore, seagrasses and salt marshes may remain on the sidelines until REDD+ programs have more on-the-ground experience and monitoring techniques advance.

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Cut tree trunk in a mangrove on the coast of Brazil.

Bilateral Agreements

Another, perhaps more promising, vehicle for valuing and preserving blue carbon is bilateral deforestation agreements. For example, in 2010, Norway agreed to support Indonesia's REDD efforts with up to US$1 billion, some of which will be used to develop a national REDD strategy.[61] The rest will be distributed based on Indonesia's performance in delivering actual, verifiable emissions reductions. This arrangement will continue regardless of the status of UNFCCC negotiations.

The advantage of a bilateral arrangement is that it can more easily include many kinds of land-use practices. For example, the Norway–Indonesia partnership covers not only forests but also peatlands, which store substantial amounts of carbon in their soils. Indonesia has the most extensive blue carbon resources in the world and could take a major step toward protecting those resources by including blue carbon in its national strategy. Similarly, if other countries follow in the footsteps of Norway and Indonesia, they will be able to develop national strategies that are compatible with, but more extensive than, the UNFCCC guidelines. Blue carbon could be identified as a priority if the participating countries decide to do so.

Regional and State Programs

Although the international community has not yet established a comprehensive carbon market, several regional and state-level programs in Europe and the United States are in operation. Many incorporate the use of carbon offsets from land use and natural systems, including avoided deforestation. These programs may eventually provide another way to include blue carbon in climate mitigation efforts, but the current rules governing which offsets are allowable make it unlikely they will include blue carbon in the short term.

The largest and most comprehensive cap-and-trade system is the European Union Emissions Trading System, which has been in operation since 2005. With 30 participating countries, it covers close to 40% of the CO_2 emissions from the EU.[62] It accepts offsets in the form of Clean Development Mechanism (CDM) or Joint Implementation (JI) credits, excluding land use and nuclear power. The European Commission investigated including land-use offsets in the third phase of the ETS but had serious reservations about several issues, including reliability of monitoring, the reporting and verification systems, and the permanence of credits.[63] As a result, land-use credits will not be included in ETS until possibly after 2020. However, in the same assessment, the European Commission highlights the need for prompt international action to generate economic incentives to promote forest conservation and avoid emissions due to deforestation. In the long term, the assessment identifies the inclusion of deforestation in carbon markets as a goal.

Wikimedia Commons/Jan Derk

White-spotted puffers are often found in seagrass areas, like this one in Dahab, Egypt.

In the context of CDM, while the CDM methodology was accepted for mangrove restoration in June 2011, no methodologies exist for avoided destruction of mangroves, nor have any been developed to cover seagrasses and salt marshes (UNFCCC 2011).[64]

In the United States, the sub-national-scale program with the most potential for blue carbon is California's Global Warming Solutions Act, also known as Assembly Bill (AB) 32. The act aims to reduce California's emissions to 1990 levels by 2020 through a combination of regulations and cap-and-trade markets. Offsets are included in the market, and a number of offset design methodologies, including one for avoided deforestation, have been developed for the system.

Mangroves could potentially qualify as a credit for Reduced Emissions from Deforestation (RED) under AB 32. *Forest* is defined broadly enough to include some mangroves. Currently, RED credits must be located in the United States, however, and this severely limits the area of mangroves eligible for inclusion. California has signed agreements with Chiapas (on the Pacific coast of Mexico, where mangroves occur) and Acre (in inland Brazil) to develop offset programs, but those programs are still years away from providing credits. Another barrier to blue carbon's inclusion is California's current methodology, which does not consider soil carbon and thus makes it far more difficult for mangroves to compete with the other potential sources of credits. Moreover, the protocols do not include salt marshes or seagrasses at all.

The other regional cap-and-trade system in the United States, the Regional Greenhouse Gas Initiative (RGGI), allows afforestation offset credits, but the project must be located within one of the member states.[65] All RGGI states are located in the U.S. Northeast and have no mangroves—the only blue carbon habitat eligible for afforestation under the program.


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Heathcote River Estuary Salt Marsh in Christchurch, New Zealand.

Discussion

Whether blue carbon can and should be considered in the context of climate policy depends, in part, on whether carbon storage and sequestration in coastal environments are sufficient from an emissions standpoint. Our results suggest that especially on a per-hectare basis, carbon storage in blue carbon ecosystems is relatively large, especially for mangroves and salt marshes and in comparison to other terrestrial ecosystems. Therefore, although, for example, mangroves only occupy a tiny share of Earth's surface, the total volume of carbon they hold is substantial. Given the current rates of conversion, which in some areas of the world are extraordinarily high, much of this carbon pool in mangrove ecosystems is likely to be released into the atmosphere unless additional conservation efforts are undertaken.

We have evaluated for mangroves whether the carbon benefits from mangrove conservation outweigh the cost of their provision. While 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.

Preserving mangroves may often be warranted simply on their carbon storage, but coastal conservation also brings other benefits, such as protecting biodiversity, securing economic returns to fisheries, and providing greater food security to coastal communities dependent on protein from the sea. Such benefits add further justification to protecting mangroves.

Considerable progress has been made in recent years on international efforts to combat climate change, yet major challenges remain. Regulating land management related to greenhouse gas emissions only complicates the vast political difficulties in formulating a comprehensive and effective global climate policy framework. Recent advances in understanding how deforestation affects the global carbon cycle are significant, but much more remains to be done before emissions from deforestation can be effectively regulated.

One specific concern regarding blue carbon conservation is host-country governance. Countries with mangroves, for example, differ considerably in their political, economic, and social risks of doing long-term conservation projects. Implementing conservation programs may in some cases require considerable investments in management and institutional change above and beyond the opportunity cost of avoided land conversion. Countries or areas with problematic management and institutional environments might also be effectively excluded from the potential offset market because of the risks and costs of doing business in them. We found, for example, that setting a minimum requirement for governmental effectiveness could drastically reduce the volume of offsets and potentially take whole regions—particularly Africa and the Middle East—off the market.

Several important areas for future work remain. For example, robust information on the opportunity costs of protecting coastal environments is lacking and needs further attention. In some locations, researchers will need to consider the economic returns from aquaculture, especially within the Asia Pacific region. In other locations, the deviation between agricultural returns and land prices can be driven by urban and tourism development. These development pressures can result in higher prices for land than we considered in our study.

Another key area of future research involves predicting the emissions profile from blue carbon ecosystems after land conversion or other disturbance. The current literature offers only very limited guidance[66] and much more needs to be done so that emissions from blue carbon ecosystems can be more accurately estimated. For example, available assessments of blue carbon emissions, including this one, posit that each type of land conversion in a given location has a uniform emissions profile. In reality, emissions will likely differ between, say, conversion to agriculture and development for urban uses. Emissions profiles of different forms of agriculture or mariculture may also differ, and further information would help in estimating emissions and in configuring land-use changes, if otherwise unavoidable, to minimize emissions.

Another area for future research involves blue carbon ecosystems' overall economic value. Mangroves are known to deliver considerable benefits to fisheries by providing juvenile and adult fish populations with nursery habitat, food, and protection from predation. Mangroves and coral reefs are widely acknowledged to have an interactive relationship for fish migration and reproduction.[67] Several studies show that many fish species occur in both habitats,[68] and there is increasing evidence that coral reefs close to mangroves are considerably more productive fisheries than reefs in mangrove-poor areas. In some areas seagrass meadows are situated near coral reefs and mangroves, thereby providing further connectivity of those areas and supporting fish species dependent on reefs and mangroves.[69] Our assessment did not consider these benefits, but future work should consider how blue carbon conservation programs can be configured to most effectively incorporate these ecosystems' beneficial effects on fisheries.

Finally, although protecting blue carbon may help somewhat mitigate climate change; climate change will unquestionably affect blue carbon environments. The effects of climate change, including air and sea-water temperature, sea level, ocean chemistry, ocean circulation, climate variability, and weather patterns, on coastal and marine ecosystems are exceedingly complex.[70] Projecting their implications on coastal carbon storage is therefore also complex, albeit needed. For example, the effects of sea-level rise on mangroves will depend on how the area of potential mangrove habitat changes and how effectively mangroves adapt to the changing habitat. If the newly inundated areas are suitable and accessible for mangroves, then as effective colonizers they could relatively successfully adapt to the sea-level rise by overtaking potential new habitats. On the other hand, the suitability of new coastal habitats to mangroves and other species will surely vary by local conditions. The sheer complexity of the effects of sea-level rise on coastal environments is vast, let alone that of considering them in the context of the overall effects of climate change.

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