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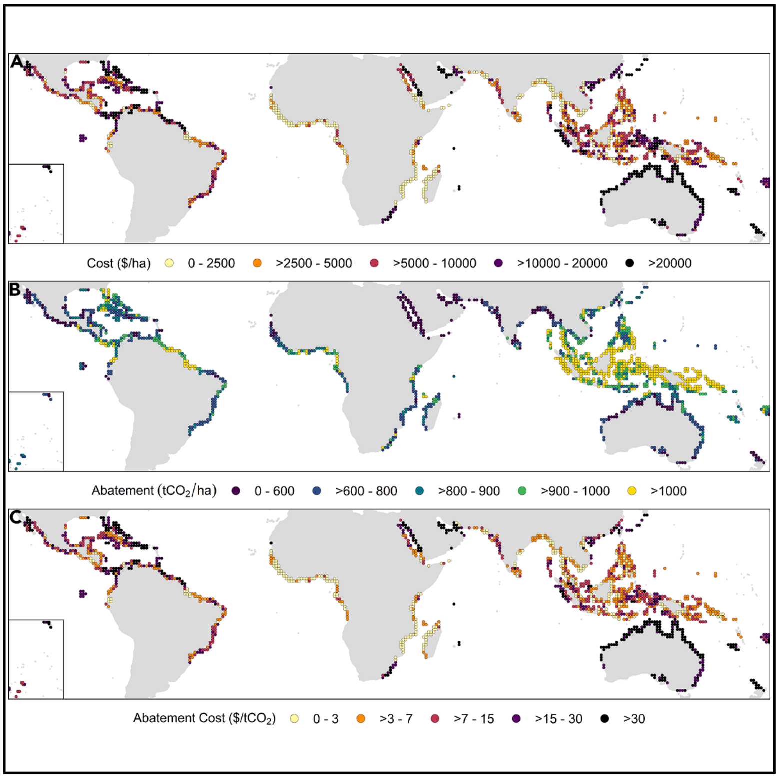
Implementation costs of restoring global mangrove forests

Graphical abstract



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In brief

Mangrove forests provide many ecosystem services, prompting a wave of recent mangrove restoration initiatives. Here, we estimate and map the implementation costs of restoring mangroves globally. This information can help mangrove restoration initiatives prioritize sites with low cost and high impact and provides an indication of the level of funding needed to achieve their ambitions.

Highlights

- We map low-cost, high-impact sites for mangrove restoration and climate mitigation
- Restoring 1.11 mha mangroves globally would remove 0.99 $GtCO_2$ and cost $10.9 billion
- 0.84 $GtCO_2$ (85%) of potential carbon sequestration would cost below $20 tCO_2^{-1}
- Greatest low-cost restoration potential: Indonesia, Brazil, Mexico, Myanmar, and India

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Implementation costs of restoring global mangrove forests

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SCIENCE FOR SOCIETY Mangroves' many ecosystem services have led to a wave of recent mangrove restoration initiatives. These include international conventions such as the Convention on Biological Diversity's Aichi Target 15 and Kunming-Montreal Global Biodiversity Framework Target 2; intergovernmental initiatives such as the United Nations Decade on Ecosystem Restoration and the Bonn Challenge; global conservation partnerships such as the Global Mangrove Alliance and Trillion Trees initiative; national commitments by numerous countries, including through their national climate change commitments (NDCs) to the United Nations Framework Convention on Climate Change Paris Agreement; and private-sector initiatives.
Our research supports such endeavors by estimating and mapping the global implementation costs of restoring mangroves. This information can help mangrove restoration initiatives prioritize where to restore and provides an indication of the level of funding needed to achieve their ambitions.

SUMMARY

Mangroves provide numerous ecosystem services and are increasingly recognized as a natural climate solution. As a result, multiple recent initiatives have set ambitious mangrove restoration targets. However, there has been little research estimating the costs of achieving such targets, either site by site or in aggregate. Here, we spatially model the costs of restoring mangroves globally based on reported implementation costs from 249 restoration projects in 25 countries. Using multiple regression analysis, we find that implementation costs decrease with project size, with project year, for aquaculture ponds, and in deltas and increase with national GDP per capita, for eroded sites, and on open coasts. Restoring mangroves across 1.10 million ha globally would remove 0.93 $GtCO_2$ at an implementation cost of \$10.73 billion in 2022 international dollars (an average of \$9,739 ha^{-1} or \$11.49 $tCO_2{}^{-1}$). Our global map of low-cost, high-impact sites can aid spatial prioritization of mangrove restoration and climate mitigation efforts.

INTRODUCTION

Mangroves provide many critical ecosystem services.[1,2] These coastal forests support the livelihoods and well-being of millions of coastal inhabitants through their provisioning services, such as fish, oysters, and honey; nurseries and breeding grounds for fisheries; and timber (both sustainably and unsustainably harvested).[3] The cultural services provided by mangroves include recreation and tourism, education and research, and generational historical value.[2,4] Their regulating services include enhancing coastal resilience to sea-level rise and extreme storms,[5–7] being havens for biodiversity,[8,9] regulating water quality,[10] and sequestering and storing large quantities of carbon.[11] Per unit area, mangrove forests and soil are estimated to contain around twice the carbon of temperate or tropical forests and 5–11 times the carbon of grasslands.[12] Mangroves are increasingly recognized as a natural climate solution along with other "blue carbon" ecosystems (e.g., seagrass meadows, tidal marshes, and tidal freshwater forested wetlands).[13]

Deforestation from the expansion of aquaculture, agriculture, urbanization, and coastal development has reduced overall mangrove cover and impeded natural ecosystem dynamics.[14] Although the exact extent of loss is unknown, an estimated 35% of global mangroves were lost in the 1980s and 1990s.[15] The global average per-annum loss rate slowed from an estimated 0.21% (1996–2010) to 0.04% (2010–2020); however, net mangrove area still decreased by 3.4% (524,500 ha) in the period between 1996 and 2020.[16]

In addition to coastal land-use stressors, climate change has affected mangrove distribution and extent, though the magnitude of its impact is uncertain.[17] Climate change may have contributed to some of the natural expansion (294,500 ha) of the spatial extent of mangroves, which exceeded natural retraction (173,100 ha) between 2000 and 2020.[17] However, it is unclear whether climate change is driving this phenomenon because of the complexity of predicting and attributing the effects of climate change on mangrove communities, given the numerous and changing biological, physical, and anthropogenic conditions under a rapidly changing climate.[3] While some areas have the potential to naturally regenerate, the extensive losses of mangrove ecosystems provide considerable scope for active restoration.[18]

Mangrove restoration and rehabilitation activities have been undertaken for decades, with varying interventions, scales of implementation, and rates of success.[19] In recognition of mangroves' environmental, social, and climate benefits, ambitious global targets to restore lost mangrove habitats are increasingly being championed.[20] Such efforts include national-level commitments (e.g., Indonesia's target to restore 600,000 ha by 2024[21]), intergovernmental initiatives (e.g., United Nations Decade on Ecosystem Restoration[22]), private sector engagements,[23] and global conservation partnerships, such as the Global Mangrove Alliance (e.g., to restore half of the restorable mangrove area by 2030[4]). While healthy mangrove forests provide numerous ecosystem services of interest to these global initiatives,[2] their carbon mitigation potential is a key incentive for mangrove conservation and restoration projects.[7,24] The majority of verified blue carbon projects include mangrove restoration,[25] underlining their role and attraction as natural climate solutions to combat climate change.

The cost of mangrove restoration has been inconsistently recorded and presented in the peer-reviewed literature.[26] Mangrove restoration costs have typically been summarized as global dollar-per-hectare averages or reported as a range spanning several orders of magnitude (e.g., $225 to $216,000 ha^{-1}).[27] Recent meta-studies have found global median restoration costs ranging from $1,269 ha^{-1} (in 2019) to $8,961 ha^{-1} (in 2010).[28–30] The cost of mangrove restoration is influenced by numerous factors, including biophysical, social, and political setting; the degree of degradation; the intensity of restoration activities; the total restored area; and the relative costs in different countries. Depending on the condition of the site, mangrove restoration can include a wide range of cost-driving activities, such as sediment trapping and coastal stabilization, hydrologic connectivity, natural regeneration, or (historically the most common approach) planting monocultures of seedlings or propagules.[31–33] Such cost drivers are not uniformly reported across projects, if at all.

Understanding how restoration costs vary by project attributes is more useful for restoration design and planning than single project-specific costs or generic global cost averages. A more refined understanding of restoration costs can help decision-makers and investors adequately anticipate requisite funding and potential returns on investment, thus contributing to achieving ambitious restoration targets. A better understanding of factors driving variation in mangrove restoration costs can also be used to produce maps of estimated site-level restoration costs and more accurate estimates of the cost of achieving global area restoration targets. When combined with spatial variation in carbon sequestration potential, this information can be used to estimate the cost of achieving climate mitigation targets, i.e., marginal abatement cost (MAC) curves. MAC curves for mangrove restoration can then be compared to interventions in other sectors in larger global synthesis analyses (e.g., Figure SPM.7 in IPCC AR6[34]) to inform global cost-effective emissions reductions strategies.

Here, we estimate the implementation cost of restoring mangrove forests on a site-by-site basis and in aggregate. We began by constructing the most comprehensive database to date on the implementation costs of mangrove restoration by integrating previous syntheses,[28–30,35] additional data reported in academic and gray literature, and project data collected through unstructured interviews. We modeled variations in project-level mangrove restoration cost as a function of project attributes that we hypothesized would influence costs (e.g., project size, project year, initial site condition, geomorphic class, and national GDP per capita). We then spatially extrapolated the explanatory model to produce a global map of estimated mangrove restoration costs. We aggregated these maps to generate global marginal area cost curves for mangrove restoration, which show the global cost of achieving any given area of mangrove restoration. We integrated the map of restoration costs with global maps of potential carbon stocks to produce MAC curves, showing the global cost of achieving any given level of carbon abatement from mangrove restoration. Finally, we compared the map of carbon abatement costs with global maps of biophysical suitability for restoration to identify areas with low carbon abatement cost and high suitability. By comparing the costs and benefits of restoration opportunities across space, we provide a science-based approach to identifying low-cost, high-impact sites for mangrove restoration and climate mitigation. This information can aid spatial prioritization of public restoration efforts (e.g., the Indonesian government's 600,000 ha mangrove restoration and enhanced protection target[36]), as well as maximizing the carbon market returns on private investments.

RESULTS

Restoration costs

We found a global median implementation cost across mangrove restoration projects of $8,143 ha^{-1} ($n$ = 249, $Q1$ = $1,434 ha^{-1}, $Q3$ = $47,935 ha^{-1}) in 2022 international dollars (Int$), with a wide range, from a minimum of $9 ha^{-1} up to a maximum of $714,693 ha^{-1} (Table S1). Restoration projects where the initial condition was aquaculture ponds had the lowest median cost, followed by viable afforestation sites, sites with

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Table 1. Summary statistics for project cost per hectare, disaggregated by project attributes

Variable	*n*	Min ($ ha^{-1})	Q1 ($ ha^{-1})	Median ($ ha^{-1})	Q3 ($ ha^{-1})	Max ($ ha^{-1})	Mean ($ ha^{-1})	SD ($ ha^{-1})
Total	249	9	1,434	8,143	47,935	714,693	42,730	87,305
Initial condition								
Viable afforestation areas	19	264	1,819	1,931	2,914	4,618	2,361	1,078
Aquaculture ponds	22	305	856	1,067	5,648	12,556	3,236	3,884
Deforested	96	9	661	8,758	38,105	377,163	35,493	65,568
Highly eroded	34	1,902	14,111	63,819	145,230	572,592	105,095	134,633
Hydrological restoration required	55	178	4,123	17,281	61,711	161,396	39,957	44,841
Undefined	23	609	1,712	6,222	16,333	714,693	58,498	160,411
Geographic class								
Delta	29	9	366	834	1,920	32,457	4,004	8,189
Estuary	43	296	9,172	47,935	85,051	294,191	57,516	60,229
Lagoon	16	366	2,418	4,688	7,993	151,606	18,963	40,073
Open coast	39	178	4,848	22,746	69,757	249,074	44,718	53,139
Undefined	122	71	1,472	6,395	37,226	714,693	49,205	112,722
Region								
Africa	2	1,058	4,201	7,343	10,486	13,628	7,343	8,888
Southeast Asia	73	71	663	1,385	6,397	161,396	7,409	22,333
South Asia	14	9	236	407	947	9,250	1,449	2,541
East Asia	2	316	21,279	42,242	63,205	84,168	42,242	59,293
Australia	4	6,408	8,813	13,620	27,641	57,684	22,833	23,708
Caribbean (incl. Puerto Rico)	12	5,622	10,694	24,327	35,331	94,120	29,339	25,475
Mexico and Central America	19	178	2,306	5,964	11,247	38,299	9,465	10,213
South America	39	1,586	1,956	4,356	21,785	249,074	23,573	45,401
Pacific Islands	3	2,800	9,761	16,723	42,891	69,059	29,527	34,936
United States	81	366	21,371	66,230	130,330	714,693	103,065	127,835

$ ha−1, cost per hectare.

deforestation only, and deforested sites where hydrologic restoration was needed, while sites that were deforested and highly eroded had the highest restoration cost (Table 1). Restoration projects located in deltas had the lowest median per-hectare cost of any geomorphic class, followed by projects on lagoons and open coasts. Sites in estuaries had the highest costs. The United States was the region with the highest median per-hectare restoration costs, while South Asia was the region with the lowest costs, followed by Southeast Asia.

Going beyond previous studies, we used multiple regression analysis to understand the contribution of project attributes to per-hectare implementation costs (Table 2). We found that the natural log of project area was significant and negatively correlated with costs, meaning that per-hectare costs declined with larger project size. Similarly, project year was significant and negatively correlated with project cost, meaning that costs have declined over time. Highly eroded sites had higher restoration costs than other initial site conditions, all else equal, while aquaculture ponds had lower costs. Additionally, sites on open coasts had higher restoration costs than other geomorphic classes, while sites located in deltas had lower restoration costs, all else equal. The natural log of GDP per capita was significant and positively correlated with project cost, meaning costs were higher in richer countries. Altogether, project area, project year, the site's initial condition, the site's geomorphic class, and national GDP per capita explained more than half of the variation in site-level restoration costs (R^2 = 0.58; Table 2).

Our analysis found that mangroves could be restored across 1.10 million hectares globally at an implementation cost of $10.73 billion in 2022 Int$ (an average of $9,739 ha^{-1}). This does not account for opportunity costs (i.e., the loss of potential economic returns from using lands that are restored and which would need to be paid if the land were to be purchased from private landowners), which could raise the total cost of mangrove restoration substantially. For example, opportunity costs were estimated to be 1.4 times that of implementation costs for terrestrial reforestation projects.[37] If the same ratio holds in mangrove settings, this would imply total implementation and opportunity costs of perhaps $25.8 billion in 2022 Int$ (an average of perhaps $23,400 ha^{-1}).

Estimated restoration costs across restorable areas vary over several orders of magnitude, from $27 to $253,300 ha^{-1} (Figure 1A). Regions with large concentrations of low per-hectare restoration costs included West Africa, East Africa, Madagascar, and Southeast Asia; regions with large concentrations of high per-hectare restoration costs included North America, the Caribbean, Australia, and New Zealand (Figure 1A).

We estimated that a per-hectare payment for restoration of $1,000 ha^{-1} would exceed implementation costs of restoration for 375,600 ha (34%) of restoration globally. A hypothetical

Table 2. Results of multiple regression models

	Model 1	Model 2
Dependent variable	cost per hectare ($ ha^{-1})	log $ ha^{-1}
Project area (ha)	−0.3201 (−0.681)	–
Log project area (ha)	–	−0.10096** (−2.358)
Project year	−1,289** (−2.577)	−0.03042*** (−2.883)
Initial condition (0/1)		
Viable afforestation areas	5,804 (0.237)	−0.60498 (−1.136)
Aquaculture ponds	−5,744 (−0.226)	−1.63495*** (−2.929)
Deforested only	24,830 (1.135)	−0.2747 (−0.55)
Deforested and eroded	89,830*** (3.5)	1.32692** (2.31)
Deforested with hydroalteration required	14,620 (0.647)	0.26161 (0.509)
Geomorphic class (0/1)		
Delta	−30,620 (−1.638)	−1.47293*** (−3.484)
Estuary	−36,250*** (−2.657)	−0.15167 (−0.515)
Lagoon	−19,230 (−0.952)	−0.39342 (−0.919)
Open coast	2,399 (0.156)	0.80964** (2.408)
GDP per capita ($)	1.334*** (4.634)	–
Log GDP per capita ($)	–	0.8553*** (4.934)
Intercept	2,583,000** (2.579)	62.11736*** (2.969)
n	186	186
R^2	0.37	0.58

Model 2 is preferred. t values are in parentheses.
***Significance at 1%, **significance at 5%, and *significance at 10%.

per-hectare payment for restoration of $10,000 ha^{-1} would exceed implementation costs of restoration for 849,000 ha (77%) of restoration (Figure 2A). The highest mangrove restoration potential of 379,000 ha globally below an implementation cost of $10,000 ha^{-1} is in areas where mangroves were lost to commodities, e.g., aquaculture ponds (Figure 2B). The same payment would exceed implementation costs for just 170,000 ha of highly eroded sites, 167,000 ha for deforested sites requiring hydrologic restoration, and 133,000 ha for deforested-only sites. By geomorphic class, deltas showed the highest mangrove restoration potential, at 429,200 ha below an implementation cost of $10,000 ha^{-1}. Open coast, estuary, and lagoon restoration followed with 159,600, 148,300, and 112,000 ha, respectively (Figure 2C). By country, Indonesia has the highest mangrove restoration potential, with 204,100 ha below an implementation cost of $10,000 ha^{-1}, followed by Brazil, Mexico, Myanmar, India, Cuba, Mozambique, Nigeria, Bangladesh, and the Philippines (Figure 2D). A table of restoration potential below per-hectare implementation costs between $1 and $50,000 for all initial conditions, geomorphic classes, and countries is provided in the supplemental information.

Carbon abatement

Restoring mangroves across 1.10 million ha globally could remove up to 0.93 $GtCO_2$ from the atmosphere below an implementation cost of $10.73 billion (an average of $11.49 tCO_2^{-1}). Combining the per-hectare cost maps above (Figure 1A) with maps of potential restorable and securable carbon stocks from Worthington et al.[18] (Figure 1B) indicates areas where restoration is estimated to be most cost effective in terms of carbon abatement. West Africa, East Africa, Madagascar, and Southeast Asia have large concentrations of areas with low abatement costs ($ tCO_2^{-1}), while areas with high abatement costs are widespread across North America, the Caribbean, the Middle East, Australia, New Zealand, and East Asia (Figure 1C).

The cumulative carbon sequestration potential of global mangrove restoration below a given carbon price globally is presented in MAC curves (Figure 3). At a global scale, a carbon price of $20 tCO_2^{-1} would exceed implementation costs of restoration for 0.78 $GtCO_2$ (84%) of carbon sequestration. A lower carbon price of $10 tCO_2^{-1} would exceed costs for 0.70 $GtCO_2$ (75%) of carbon sequestration, while $50 tCO_2^{-1} would exceed costs for 0.89 $GtCO_2$ (95%) of carbon sequestration. These costs are slightly higher than in a previous study,[38] which found that carbon prices between $4.5 and $18 would be adequate to support the restoration of 90% of deforested mangroves globally. Aquaculture ponds are the initial site condition with the highest mangrove carbon sequestration potential of 0.34 $GtCO_2$ below a hypothetical carbon price of $20 tCO_2^{-1}. The same carbon price would yield just 0.16 $GtCO_2$ for highly eroded sites, while deforested-only sites and deforested sites requiring hydrologic restoration could achieve 0.15 and 0.13 $GtCO_2$, respectively. By geomorphic class, deltas showed the highest mangrove carbon sequestration potential at 0.37 $GtCO_2$ below a carbon price of $20 tCO_2^{-1}. Open coast, estuary, and lagoon restoration followed with 0.17, 0.16, and 0.08 $GtCO_2$, respectively. By country, Indonesia has the highest mangrove carbon abatement potential, with 0.24 $GtCO_2$ below a carbon price of $20 tCO_2^{-1}. The other top 10 countries achieve lower total sequestration potential at the same price, ranging from 0.076 $GtCO_2$ (Brazil) to 0.02 $GtCO_2$ (Viet Nam). A table of carbon abatement potential at carbon prices between $1 and $500 for all initial conditions, geomorphic classes, and countries is provided in the supplemental information.

We further compared areas' carbon abatement cost with a relative index of their biophysical suitability for restoration.[18] Southeast Asia, West Africa, East Africa, Madagascar, and Brazil have many areas with low abatement cost and high biophysical suitability for restoration (Figure 4A). Conversely, New Zealand and many Caribbean, Middle Eastern, and Australian areas combine high restoration costs with low biophysical suitability for restoration. At a national scale, the 20 countries with the largest restorable area (>∼100 km^2), which together represent over 80% of the global restorable area, exhibit markedly different combinations of high- and low-cost and high- and low-suitability areas (Figure 4B). Countries in Southeast Asia (Indonesia, Myanmar, the Philippines, Viet Nam, Malaysia, and Papua New Guinea) as well as Brazil are dominated by areas with low abatement cost and high suitability for restoration. In contrast, Australia and the Bahamas generally have areas of high suitability for restoration but with higher carbon abatement costs.

DISCUSSION

Mangrove restoration has received a wave of momentum from intergovernmental initiatives, non-governmental partnerships

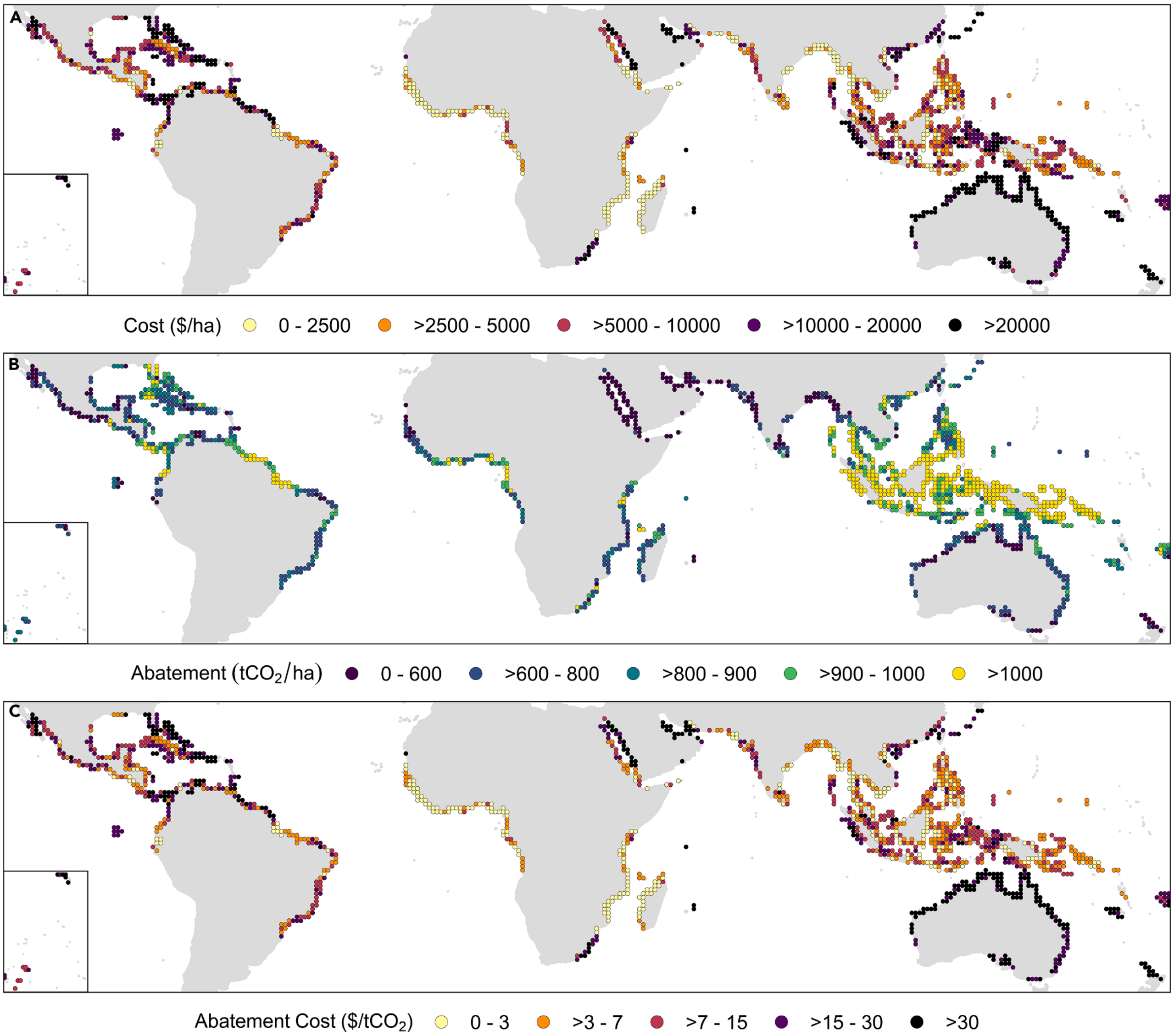

Figure 1. Global maps of restoration cost, carbon abatement potential, and abatement across potential global mangrove restoration sites
(A) Restoration cost ($ ha^{-1}), (B) carbon abatement potential (tCO_2 ha^{-1}), and (C) abatement cost ($ tCO_2^{-1}). Data were summarized to 1° cells using the area-weighted mean across areas of potential mangrove restoration in each cell.

and consortia, and national governments. These ambitious targets have been well summarized[39] and include Convention on Biological Diversity Aichi Target 15, to restore at least 15% of degraded ecosystems by 2020[40]; Kunming-Montreal Global Biodiversity Framework Target 2, to restore 30% by 2030[41]; the Bonn Challenge aim to restore 60 million hectares of degraded and deforested land to productive, functional, and biodiversity-friendly landscapes[42]; the Trillion Trees by 2025 initiative[43]; the Global Mangrove Alliance's target to restore half (409,200 ha) of global mangroves by 2030[4]; and the inclusion of coastal wetland and restoration within the climate change commitments (nationally determined contributions or NDCs) of numerous countries.[44] However, there has been little research to date on the site-by-site and aggregate costs of mangrove restoration. This knowledge gap, along with other factors, has contributed to many large-scale initiatives struggling to achieve their aspirational targets.[39] The costs and cost-effective abatement potential that we have estimated and mapped here can better inform how and where such targets can be achieved. They also provide an indication of the level of resources needed to achieve mangrove restoration ambitions.

Geographically, Southeast Asia accounts for 35% of restoration potential by area, 41% of restoration abatement potential, and 45% of abatement potential below $20/$tCO_2$ (Table 3), as its per-tCO_2 costs are lower than those of higher-GDP countries. Indonesia has the largest carbon abatement potential through mangrove restoration, at 0.26 $GtCO_2$ across 246,700 ha. This is three times as much as the 0.089 $GtCO_2$ estimate assessed for restoring the 600,000 ha national target.[45] However, an analysis of mangrove restoration potential in Indonesia

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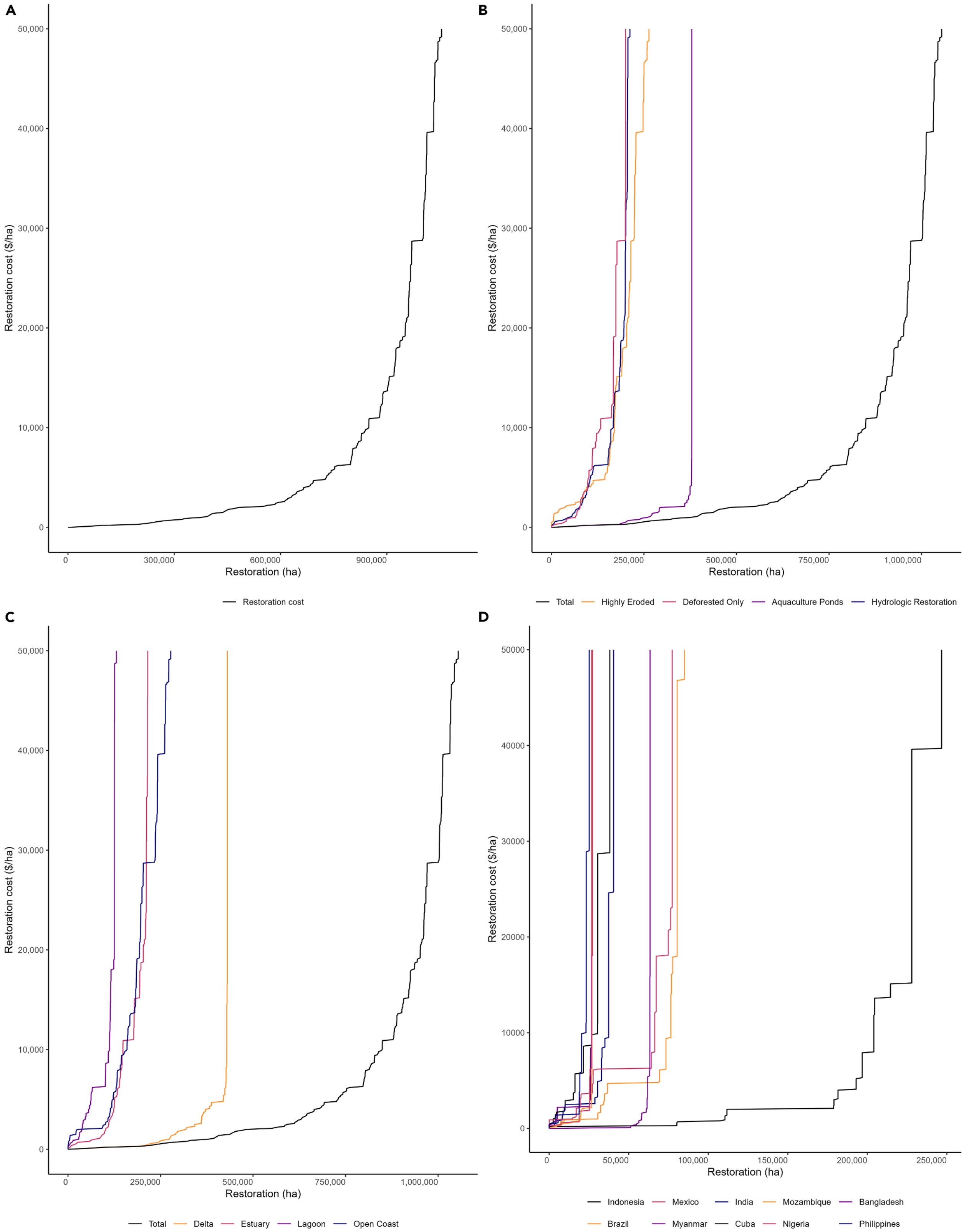

Figure 2. Marginal area cost curves
(A) Global, (B) by initial site condition, (C) by geomorphic class, and (D) for the top 10 countries by mangrove restoration potential.

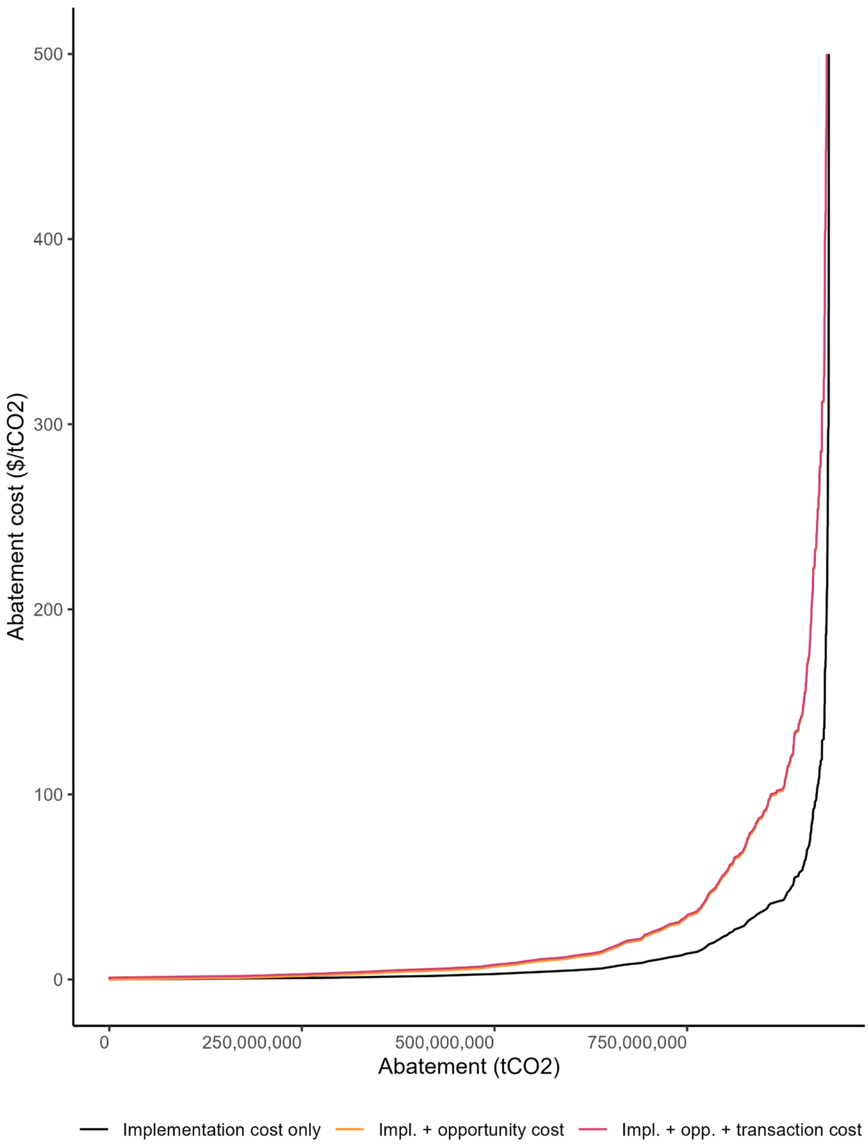

Figure 3. Marginal abatement cost curves
Implementation cost was generated as described in the methods. Opportunity cost was assumed to be 1.4× the implementation cost based on the average for terrestrial reforestation projects.[37] Transaction cost was illustratively assumed to be $1/t$CO_2$.

asserted that restoration may be feasible in only about 200,000 ha at a cost between $0.29 billion and $1.74 billion (equivalent to $1,450–$8,700 ha^{-1}),[46] indicating that a significant amount of investment will be necessary. Indeed, those estimates are corroborated by the results of this study, in which we have estimated a total cost of $1.4 billion across 246,700 ha, with per-hectare restoration costs ranging from $209 to $39,620 ha^{-1} depending on the site's initial condition and geomorphic class.

Altogether, restoring mangrove forests globally has the potential to remove up to 0.93 GtCO_2. This is considerably larger than a previous estimate of global abatement potential through mangrove restoration of 0.08–0.32 GtCO_2.[38] However, this value is still comparatively small relative to previously assessed annual removal potential in other biomes, such as 0.52–0.98 GtCO_2 year^{-1} from terrestrial reforestation in 138 low- and middle-income countries[37]; 0.39–0.75 GtCO_2 year^{-1} from afforestation globally[47]; 0.15–1.5 GtCO_2 year^{-1} from reforestation and afforestation globally[48,49]; or 1.4 GtCO_2 year^{-1} from the restoration of the 20% most cost-effective natural climate solutions for forests and wetlands.[50]

Terrestrial restoration offers greater cost-effective mitigation potential as well, due to the much larger available area. For example, below an implementation cost of $20 t$CO_2{}^{-1}$, terrestrial tropical reforestation (2020–2050) could increase carbon removal by 5.7–24.2 GtCO_2,[37,51] while we find that mangrove restoration could achieve 0.78 GtCO_2 of carbon removal at the same price. Improved protection, management, and restoration of ecosystems could deliver 6.56 GtCO_2 year^{-1} across tropical regions (2030–2050) at cost-effective prices of less than $100 t$CO_2{}^{-1}$.[52]

Protecting existing mangroves is even more cost effective than mangrove restoration. One study estimated that 82,000 km^2 of mangroves globally in 2017 were estimated to contain 4.23 GtC and that conserving these forests would avoid the emission of between 3.88 and 5.51 GtCO_2.[38] Most potential emissions from conserving mangroves could be avoided below a price of less than $10 t$CO_2{}^{-1}$ (in 2005 dollars and adjusted to $14.74 in 2022).[53,54] This aligns with other findings that a carbon price between $3 and $13 t$CO_2{}^{-1}$ could avoid emissions of 90% of the estimated 15.51 GtCO_2 carbon currently held in existing mangrove forests.[38] In contrast, we find that a carbon price of $10 t$CO_2{}^{-1}$ applied to mangrove restoration could sequester 0.70 GtCO_2 (75%) globally. That study[38] also found that Indonesia and Brazil have the largest share of mangrove conservation area, which could be achieved with prices of $3–$11 t$CO_2{}^{-1}$, but that most countries could support conservation with $6–$10 t$CO_2{}^{-1}$.[38] Another study[55] found that a carbon price of $5–$9.4 t$CO_2{}^{-1}$ would be adequate for financial sustainability of 1.1–1.3 Mha of mangrove conservation over 30 years and contribute up to 29.8 MtCO_2 year^{-1}.

Carbon market implications

Investments from the private sector through carbon markets can be leveraged to connect financial resources to mangrove restoration projects. Blue carbon has gained increasing attention from

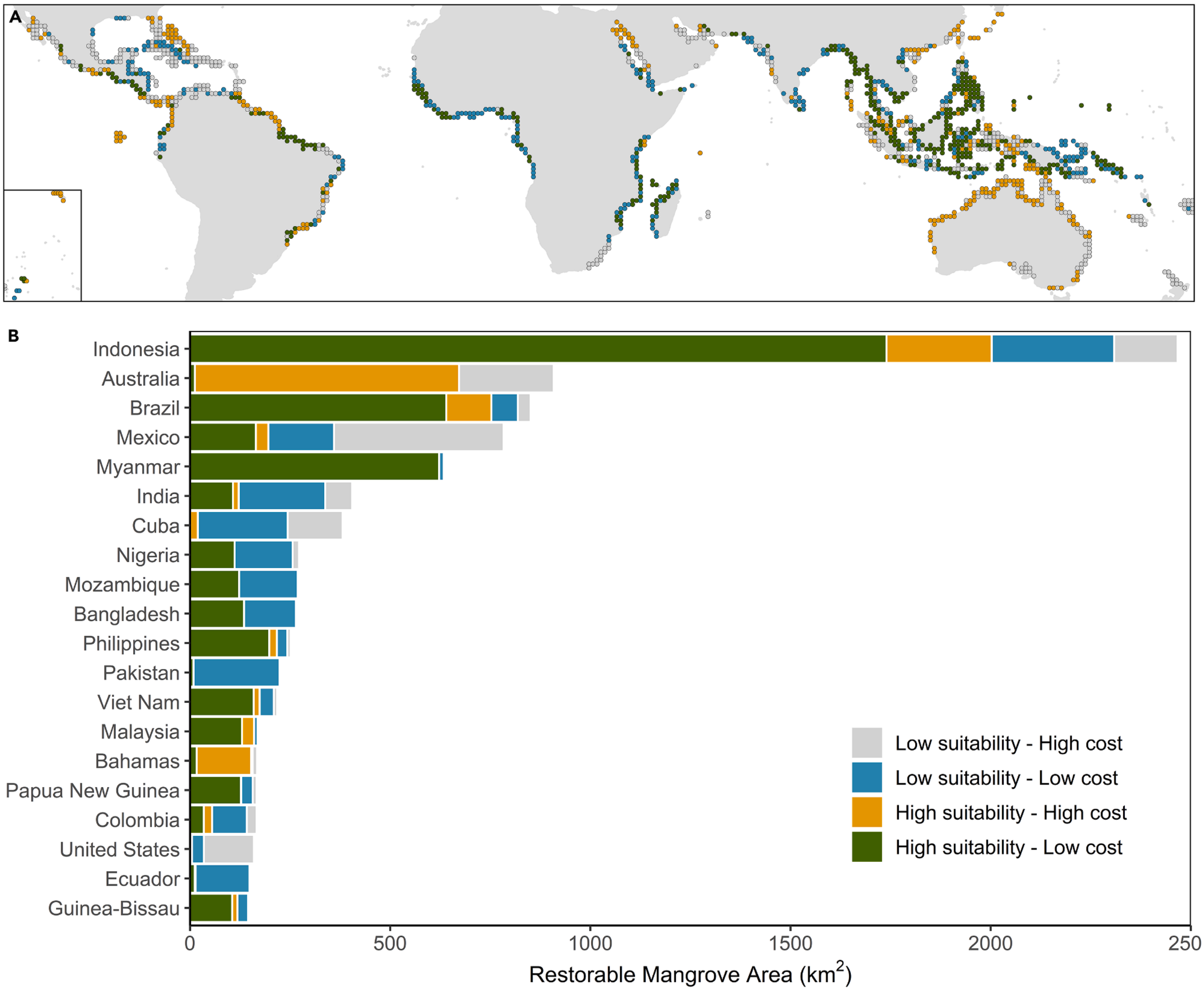

Figure 4. Overlay of abatement cost and biophysical suitability for restoration

(A) Mapped across the global extent of potential mangrove restoration and (B) summed by area for the 20 countries with the greatest area of potential mangrove restoration. Abatement cost was calculated using the area-weighted mean within each 1° cell. Cells were categorized as having "high" or "low" value for each metric relative to the median value.

private sector companies seeking to offset their carbon emissions that otherwise could not be reduced through decarbonization or production efficiencies.[25] We find that 0.93 GtCO_2 could potentially be sequestered through mangrove restoration. Combined with the 20% of global mangroves (~2.6 million ha) that could qualify for avoided deforestation carbon credits (33.8 ± 5.1 MtCO_2e year^{-1}), potentially generating $1.1 billion per year according to Zeng et al.,[55] this suggests ample potential for generating blue carbon credits. However, an accurate calculation of blue carbon market potential would need to account for issues of carbon permanence associated with development risks, climate change stressors such as sea-level rise, and increased cyclone activity, all of which can have a substantial impact on the volume of mangrove blue carbon that is ultimately feasible[56] and which we do not consider here.

Despite this potential, only 8 validated and 16 potential mangrove blue carbon projects had been developed as of 2022.[25] Additionally, determining blue carbon crediting prices for these and future projects remains challenging, especially when restoration implementation, opportunity, and maintenance costs lack consistency or transparency. This uncertainty, in combination with the few blue carbon projects available, presents a high level of financial risk for investors.[25] Being able to estimate restoration implementation costs, as demonstrated in this study, provides a science-based approach for informing part of the supply side of blue carbon markets and may decrease real or perceived risks by investors.

While the investment potential should not be overlooked, blue carbon revenue alone is unlikely to fully fund mangrove restoration.[39] Indonesia, for example, has used blue carbon as the impetus to strengthen its climate commitments, but other ecological and social benefits must also be considered in addition to potential emissions reductions.[57] Additional revenue streams, such as multiple-use systems that integrate mangroves

Table 3. Composition of restoration projects, restorable area, abatement potential, and abatement potential below \$20/tCO_2, by initial condition, geographic class, and region

Variable	Restoration projects	Restorable area (ha)	Abatement potential (tCO_2)	Abatement potential below \$20/tCO_2 (tCO_2)
Total	249 (100%)	1,132,527 (100%)	934,199,787 (100%)	784,768,065 (100%)
Initial condition				
Viable afforestation areas	19 (7%)	–	–	–
Aquaculture ponds	22 (9%)	373,433 (34%)	343,871,329 (37%)	343,839,823 (44%)
Deforested	96 (39%)	198,909 (18%)	162,258,007 (17%)	134,135,120 (17%)
Highly eroded	34 (14%)	304,044 (28%)	260,857,467 (28%)	161,736,159 (21%)
Hydrological restoration required	55 (22%)	206,951 (19%)	167,212,984 (18%)	145,056,962 (18%)
Undefined/other	23 (9%)	18,603 (2%)	0 (0%)	0 (0%)
Geographic class				
Delta	29 (12%)	439,363 (39%)	370,293,389 (40%)	370,280,843 (47%)
Estuary	43 (17%)	240,839 (21%)	191,362,723 (20%)	158,761,216 (20%)
Lagoon	16 (6%)	136,327 (12%)	95,160,802 (10%)	82,840,112 (11%)
Open coast	39 (16%)	315,998 (28%)	277,382,872 (30%)	172,885,895 (22%)
Undefined	122 (49%)	0 (0%)	0 (0%)	0 (0%)
Region				
Africa	2 (1%)	143,643 (13%)	103,298,400 (11%)	102,283,976 (13%)
Southeast Asia	73 (29%)	398,084 (35%)	380,811,388 (41%)	355,854,658 (45%)
South Asia	14 (6%)	99,331 (9%)	59,807,759 (6%)	56,727,844 (7%)
East Asia	2 (1%)	8,498 (1%)	6,109,068 (1%)	3,135,286 (0%)
Australia	4 (2%)	90,974 (8%)	61,962,050 (7%)	16,740,153 (2%)
Caribbean (incl. Puerto Rico)	12 (5%)	65,755 (6%)	51,635,767 (6%)	31,562,482 (4%)
Mexico and Central America	19 (8%)	111,130 (10%)	73,825,486 (8%)	62,469,825 (8%)
South America	39 (16%)	160,421 (14%)	151,035,806 (16%)	125,389,880 (16%)
Pacific Islands	3 (1%)	25,638 (2%)	25,170,263 (3%)	22,783,898 (3%)
United States	81 (33%)	17,020 (2%)	16,567,137 (2%)	7,043,837 (1%)
Middle East	0 (0%)	12,031 (1%)	3,976,664 (0%)	776,226 (0%)

into aquaculture ponds, are attractive but offer fewer biodiversity and ecosystem service benefits due to habitat fragmentation.[39] Innovative approaches such as the Climate Smart Shrimp Fund, where the sustainable intensification of shrimp aquaculture in a portion of a low-productivity farm can fund restoration on the remainder of the farm,[58] should be considered to deliver environmental and climate benefits, while maintaining landholder incomes and providing ongoing financial resources for restoration and maintenance.

Conclusion

We have estimated the implementation costs of restoring mangroves across 1.10 million hectares of potentially restorable areas globally to be \$10.73 billion in 2022 Int\$ (perhaps \$26 billion including opportunity costs). This figure is modest relative to other global goals. The average estimated implementation cost of \$11.49 tCO_2^{-1} (perhaps \$27.58 tCO_2^{-1} including opportunity costs) is competitive with current carbon market prices and is well below the social cost of carbon dioxide emissions, even before considering the other ecological and economic values that restored mangrove ecosystems provide.

A wave of restoration targets by governmental, non-governmental, and private sector institutions, along with current momentum in the carbon market, suggests this is an opportune time to implement mangrove restoration projects globally. Even so, the long-term success of restoration projects will need to incorporate many other socioeconomic metrics in addition to propagules planted and area restored.[59] Restoration projects should be implemented in ways that are science informed, socially just, and in agreement with local stakeholder communities who rely on mangrove resources, which will take substantial time and resources, often beyond short donor timescales.[19,59,60] To ensure that mangrove restoration projects successfully deliver long-term climate mitigation and other ecosystem services, projects should consider and address social, governance, and political barriers (e.g., land tenure, community engagement, etc.) as well as biophysical considerations (e.g., location, species, etc.) and communications challenges (e.g., accessibility of resources, non-standardized reporting, underreporting of failures, etc.).[19] Furthermore, the effects of climate change on mangrove restoration sites should be considered.[24] Determining the response and resilience of coastal mangroves to multiple stressors affected by climate change (e.g., sea level rise, storm intensity, temperature and precipitation fluctuations, sediment budgets and nutrient loading, etc.) remains a challenge[61] but should be accounted for by practitioners and policymakers to maximize the success of potential restoration projects into the future.

METHODS

Project-level restoration costs

We assembled the most comprehensive database of project-level mangrove restoration costs to date. First, we compiled observations from existing published datasets. We began with datasets from Mangrove Data[62] (n = 88) from Bayraktarov et al.,[30] along with an updated Database[63] (n = 4) from Bayraktarov et al.,[35] the supplementary material[64] (n = 55) from Taillardat et al.,[29] and the Database[65] (n = 39) from Su et al.[28] Cost data from the same primary source were included only once to avoid duplication, resulting in n = 103 data points. We then conducted a systematic review of peer-reviewed and gray literature for reports on mangrove restoration costs. We conducted the search in English using Google Scholar, SCOPUS, the SpringerLink database, and the University of California, Santa Barbara, library database using the following inclusion criteria: mangrove*, restoration*, or rehabilitation* in the title and cost* in the title, abstract, or keywords. This resulted in n = 118 additional data points. Finally, we conducted our own unstructured interviews of practitioners and implementers of mangrove restoration projects to obtain a further n = 34 cost data points. This resulted in a database of n = 249 observations.

For each project in the database, we either obtained implementation costs per hectare directly as reported or calculated them by dividing reported total project costs by reported project area. Reporting by projects on disaggregated restoration activities and their costs was not standardized and varied considerably across projects. Activities reported by projects variously included site preparation, nursery construction and operation, propagule collection and planting, hydrologic alteration, land moving, physical labor, transportation, and maintenance.

We converted all costs to 2022 Int$ to account for inflation over time and differences in purchasing power across countries, following De Groot et al.[66] That is, we inflated contemporary costs in local currency to 2022 costs in local currency using an inflation calculator[67] and then converted 2022 costs in local currency to 2022 Int$ using a purchasing power parity (PPP) conversion factor.[68]

We next compiled data on variables that we hypothesized could plausibly influence the cost of restoration. For each observation in the database (n = 249), we recorded the project area, cost year, initial site condition, site geomorphic class, and country of the project.

Project area can plausibly influence the cost of restoration if there are economies of scale, i.e., if per-hectare costs diminish over larger areas. This could be the case if some portion of a project's labor costs, material costs, or start-up costs is fixed, for example. Only a subset of projects in the database reported project area (n = 200). Project areas were reported to be as small as 0.0001 ha and as large as 120,000 ha (Table S1).

Project year refers to the year in which project activities concluded, i.e., after activities and costs had been documented. Project year can influence the cost of restoration if costs systematically diminish with time. This could be the case due to falling costs of materials or if techniques for mangrove restoration improve over time through global knowledge sharing. Project dates ranged from 1977 to 2021 (Table S1).

The condition of a restoration site can influence the cost of restoration by determining the type and amount of work required. We categorized observations into one of five initial site conditions (deforested only, deforested with hydrologic restoration required, deforested and highly eroded, aquaculture ponds, and viable afforestation areas), either using direct statements in the project description or by assigning a category based on reported restoration activities. "Deforested only" included sites where mangroves had been cleared or damaged (e.g., from storms), but the physical landscape had not been significantly changed. Such sites may be more conducive to restoration, with fewer additional activities needed. "Hydrologic restoration required" indicated that the physical landscape was largely intact after deforestation of mangroves but lacked the proper hydrologic flow necessary for mangrove growth. Such sites often require the creation of tidal channels and appropriate topography to manage salinity, facilitate tidal flushing, and drain stagnant waters.[27,69,70] "Highly eroded" sites experienced erosion after deforestation due to a lack of vegetation. These sites typically required the construction of physical barriers to protect mangrove seedlings from wave and wind energy, including sediment traps, dams, or bamboo fencing.[71] Such interventions contribute to sediment accrual that can progressively reverse erosion. "Aquaculture ponds" refer to areas that were used or recently used for aquaculture. Such sites required breaking or removing pond walls and dikes and improving hydrologic connectivity.[72] "Viable afforestation areas" describes areas that, unlike other conditions, were not covered in mangroves as of 1996. However, due to sediment accumulation, such sites developed as viable areas for mangrove growth, which may require only planting activities to supplement natural regeneration. We characterize this type of initial condition as distinct from planting mangrove seedlings on tidal mud flats or seagrass meadows, which can result in habitat conversion conflicts and often have lower blue carbon benefits[73] and higher failure rates. We categorized the initial site condition as "undefined" when project-specific details could not be confirmed (n = 26).

Similar to site condition, a site's geomorphic class can affect the cost of restoration by determining the type and amount of work required. We assigned sites to a geomorphic class (delta, estuary, lagoon, or open coast) based on an updated version of Worthington et al.[74] using reported coordinates, a site map, or a description. We categorized the geomorphic class site as "undefined" when project-specific details could not be confirmed (n = 128).

National income level (GDP per capita) can influence the cost of restoration through the cost of labor, equipment, seedlings, and so forth. GDP per capita has been found to be a strong predictor of implementation costs in terrestrial reforestation projects.[29] We obtained the GDP per capita that aligned with the country of each project site.[75] We then converted GDP per capita in the project year to 2022 Int$ as described above for project costs. Restoration project sites spanned 25 countries and territories with a range of GDP per capita in the project year from $1,616 to $70,171 per capita in 2022 Int$. While nearly all of the projects in the dataset reported country of project, a small number of projects (n = 6) reported only a region (e.g., "Caribbean") or reported values without a country. These projects were included in our database, but not in our analysis.

The cost of restoration is plausibly influenced by other variables as well, such as those included in an index of areas' biophysical suitability for restoration, discussed below. However, because precise geolocations were unavailable for most projects, we could not compile site-level variables other than initial condition and geomorphic class, and thus they were omitted from the analysis.

Relative to the global area of potential mangrove restoration, the distribution of restoration projects included in our database overrepresented sites that were deforested only and sites in the United States and underrepresented sites that were deforested and highly eroded; sites in aquaculture ponds, deltas, and open coasts; and sites in Africa and Australia (Table 3).

Multiple regression model

We modeled the cost per hectare of mangrove restoration projects, $Cost_i$, as a function of explanatory variables using a multiple regression model, Equation 1:

$$\ln(Cost_i) = \beta_0 + \beta_1 \ln(Area_i) + \beta_2 Year_i + Condition_i^{'}\beta_3 + Class_i^{'}\beta_4 + \beta_5 GDP_i + \epsilon_i. \quad \text{(Equation 1)}$$

Here, $Area_i$ is project area and $Year_i$ is project year. $Condition_i$ is the initial site condition relative to sites with unreported condition; $Class_i$ is the geomorphic class relative to sites with unreported class. GDP_i is the national GDP per capita of the country in which the project is located in the project year. We did not include an explanatory variable related to geographic region because there were very few observations in several regions, e.g., East Asia ($n = 2$), Africa ($n = 2$), the Pacific islands ($n = 3$), Australia ($n = 4$), and the Middle East ($n = 0$). Data from more projects from these less-represented regions would improve model outputs. Regression analyses were performed using R version 4.4.0.

Pairwise correlations between explanatory variables (Figure S1) all had absolute values less than 0.45, indicating that multicollinearity is not a concern. Because initial site condition, site geomorphology, and national GDP per capita are not influenced by project costs, we are not concerned about endogeneity with respect to these variables. It is conceivable that higher project costs could have led to smaller project areas or later project years. Such endogeneity, if present, would have resulted in the negative coefficient on project area being underestimated (biased away from zero) and the negative coefficient on project year being overestimated (biased toward zero). It is beyond the scope of this research to address such potential endogeneity concerns, e.g., by using instrumental variables. Furthermore, there was potential for selection bias if sites that were selected for restoration had lower expected costs than a typical site elsewhere for reasons not captured by the explanatory variables, resulting in predicted costs being underestimated.

Model 1 of the multiple regression included cost ($ ha^{-1}) as the dependent variable, with project area, project year, initial site condition, geomorphic class, and national GDP per capita as explanatory variables (Table 2, column A). In model 2, we log-transformed the dependent variable so that all cost-per-hectare output values below would be positive (Equation 1; Table 2, column B). This increased the coefficient of determination from $R^2 = 0.37$ to $R^2 = 0.58$ and improved the mean absolute percentage error (MAPE) from 2,174 to 319. Plotting the observed restoration costs versus the modeled outputs from the multiple regression provides a visual illustration of goodness of fit (Figure S2).

Map of restoration costs

We mapped mangrove restoration costs ($ ha^{-1}) globally by extrapolating the explanatory model of project-level costs described above across a global map of potential mangrove restoration areas circa 2020.[18] In this global restoration map, the global extent of mangrove loss from 1996 to 2020[15] was subdivided into 4,052 geomorphic units, i.e., patches of mangroves grouped based on their proximity to macroscale coastal features.[18] Each unit contained information on the country, geomorphic class, restoration potential (ha), additional carbon that could be secured through restoration (tC ha^{-1}), and fraction of mangrove loss attributed to each of five drivers (commodities, non-productive conversion, human settlements, shoreline erosion, and extreme weather events)[72] using a weighted distance approach (see Worthington et al.[18] for details). For each geomorphic unit, we matched the "loss drivers" from Goldberg et al.[76] to corresponding "initial conditions" in our cost model using the five restoration archetypes shown in Table S2, in which the restoration activities represent a selection of commonly applied activities required to restore mangroves for each of the initial site conditions. Urban land uses were excluded, leaving a potentially restorable footprint. Unlike in Worthington et al.,[18] we did not exclude eroded areas from potential restoration, resulting in a larger global potentially restorable area than in that study. We assumed a universal project size of 14 ha corresponding to observed median project size (Table S1) and a universal project start date of 2025.

Marginal area cost curves and abatement cost curves

We constructed marginal area cost curves by rank-ordering sites from lowest to highest per-hectare restoration cost and then summing the area of mangrove restoration potential across sites with a restoration cost at or below a given cost. This method followed a similar study for terrestrial reforestation.[37]

We then constructed MAC curves by incorporating abatement cost ($ tCO_2^{-1}). Carbon abatement can refer to either a reduction (or prevention) of carbon emissions or the removal of atmospheric carbon through sequestration.[77] We use the latter definition in this study. For each geomorphic unit, we calculated abatement cost ($ tCO_2^{-1}) by dividing restoration cost ($ ha^{-1}) by the average total carbon (tC ha^{-1}) that could be "restored" and "secured" through mangrove restoration relative to a scenario in which mangroves are not restored. Restored carbon is realized by regrowing carbon in aboveground biomass (AGB) and soil carbon (SOC) stocks over a 40-year time horizon. It is calculated as the difference between the current extant stocks and the ratio of carbon in restored areas compared to the natural level. Meanwhile, the "secured" carbon is realized by preventing further losses to extant AGB and SOC stocks, assuming that all carbon in unrestored areas would eventually be lost in the absence of mangrove restoration.[18] We then divided this total carbon value by the atomic ratio of carbon dioxide to carbon (3.67 tCO_2 tC^{-1}) to obtain potential carbon abatement (tCO_2 ha^{-1}). Potential carbon abatement from mangrove restoration is consistently high in parts of Southeast Asia, West-Central Africa, and the north coast of South America[18] (Figure 1B). As with marginal area curves, we generated MAC curves by first ordering units from lowest to highest abatement cost and then summed the potential abatement for all sites with an abatement cost at or below a given cost.

For both marginal area cost curves and MAC curves, we included only areas of potential mangrove *restoration*, i.e., where mangroves had been lost between 1996 and 2020. We did not include areas of potential mangrove *afforestation*, including sites where mangroves once existed but where loss occurred before 1996. Thus, we underestimated the total potential for increasing global mangrove area and the climate mitigation potential from doing so.

Uncertainty analysis

We analyzed the sensitivity of our global area cost curve and global MAC curve to two types of uncertainty. First, we simulated the effects of a systematic error, in which all cost estimates were erroneous in the same direction (±0.5 and ±1 standard deviation). Second, we introduced site-specific random errors in cost estimates, conducting a Monte Carlo analysis (n = 300) by randomly drawing a cost estimate for each site from its prediction interval. Then cost curves were constructed as described above, summing the area or abatement for all sites below a given cost (Figure S3). Note that 5^{th} and 95^{th} percentile curves from the Monte Carlo analysis did not produce confidence intervals that bounded the area cost curve and abatement cost curve; rather, introducing site-specific random errors caused these curves to have higher quantities at low costs and lower quantities at high costs.

Comparison with biophysical suitability for restoration

We compared sites' abatement costs and biophysical suitability for reforestation by overlaying our map of abatement costs with a global map of areas' biophysical suitability for restoration. Biophysical suitability was obtained from Worthington et al.[18,78] for 3,635 individual landscape-scale mangrove restoration units, expressed as a continuous index (0–100). This index was created using geospatial modeling of data on eight mostly biophysical variables (land-use change, tidal range, antecedent sea-level rise, future sea-level rise, hydrological disturbance, patch size and number, patch connectivity, and timing of the loss) weighted using the Delphi method with a panel of experts.[18] For both abatement cost and biophysical suitability for restoration, we divided areas into high and low relative to the median value for each metric and then categorized areas into quadrants (high-high, high-low, low-high, and low-low).

Caveats and limitations

Restoration projects generally reported only the initial implementation costs of the restoration project and did not report on the opportunity costs or purchasing costs of restoring land, transaction costs of participating in carbon markets, or costs of monitoring and evaluation. This may have been due in part to many restoration projects being funded through grants, which makes transaction costs difficult to determine or report on and which have finite timelines and limited resources for ongoing maintenance. In only a few cases were maintenance costs disaggregated. In some cases, maintenance costs were anticipated to be higher in the first 4 years due to protection and replanting.[79,80] Other studies provided projected maintenance costs equivalent to dollars per person days over 18 months,[81] by area without specifying a timeline,[82] or as a fixed cost at year 2 and beyond.[83] In one case, implementation costs and ongoing monitoring and maintenance costs were recorded over a 10-year period (1993–2003) for five sites across the Philippines.[84]

Data were not available on project success in the years following implementation activities, including ecological and social function. Thus, project success beyond a few years following implementation activities, including ecological and social function, was not considered in our study. Factors influencing such outcomes are discussed in other studies.[85] As noted above, a lack of ongoing funding may inhibit the long-term evaluation of how successful restoration projects were.

There was potential for selection bias, if sites that were selected for restoration had lower expected costs than a typical site elsewhere, or reporting bias, if projects that reported their costs had lower costs than a typical project elsewhere. Additionally, although we attempted to construct a comprehensive database, the publications and data that we included might have had unobserved reasons for being discovered for inclusion and thus may not be representative of all restoration types, geographies, or interventions. For example, there could have been a bias toward publications and reports that were written in English and made available online. It is known that a reliance on English language sources can bias meta-analyses in ecology and conservation.[86] The total amount of data in non-English languages where mangrove restoration projects occurred is unknown.

Directions for future research and information collection

Our study suggests several productive directions for future research. Our global cost maps can be combined with other relevant spatial layers to prioritize sites for mangrove restoration. The construction of a coastal opportunity cost layer that is derived from common coastal economies (e.g., aquaculture, fishing, maritime infrastructure, urban settlements, or tourism) rather than agriculture and pasture[38] would be valuable. Future studies that explore the relationship between restoration spending and restoration effectiveness, i.e., whether better-resourced projects were more successful in restoring mangrove area over the long term, would be valuable as well. Spatially comparing the effects of climate change (e.g., sea-level rise, storm surge, etc.) with rates of mangrove growth can help identify restoration areas that are more or less vulnerable to inundation and erosion.

Mangrove restoration projects can facilitate future studies of the determinants of restoration costs by collecting and reporting more cost information disaggregated by year or by component activities. They can also collect and report geolocated information on project boundaries, which would enable researchers to spatially match project locations to local geographical, social, and economic conditions, as well as remotely sensed information on tree cover or other project outcomes. Resources such as the Mangrove Restoration Tracker Tool[87] aim to facilitate the collection and reporting of project information for more transparency and utility.

RESOURCE AVAILABILITY

Lead contact

Requests for further information and resources should be directed to and will be fulfilled by the lead contact, Jonah Busch (jonahmbusch@gmail.com).

Materials availability

This study did not generate new unique materials.

Data and code availability

The original contributions presented in the study are available as supporting datasets in Zenodo: https://doi.org/10.5281/zenodo.15330806. These include the database of project costs, attribute table of restorable areas, replication code, marginal area curves, and MAC curves. Further inquiries may be directed to the lead contact.

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AUTHOR CONTRIBUTIONS

G.M.G., D.H.K., J.H., and J.B. conceived the idea of the study. G.M.G., C.S.G., and S.T. conducted the literature review and unstructured interviews to collect project data. G.M.G., T.A.W., and J.B. conducted the analysis. G.M.G. and J. B. wrote the manuscript. All authors contributed toward data collection, analysis, and manuscript editing.

DECLARATION OF INTERESTS

The authors declare no competing interests.

SUPPLEMENTAL INFORMATION

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