

Getting the best of carbon bang for mangrove restoration buck

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Mangrove loss has reduced its carbon (C) sink function and ecosystem services. To effectively allocate climate finance for mangrove restoration, a thorough assessment of restoration potential is necessary. Here we show a net loss of ecosystem service value (ESV) of 29.2 billion USD (\$) due to land changes in mangroves from 1996 to 2019. The estimated mangrove ESV in 2019 amounts to \$894 billion yr⁻¹, mainly provided by regulating and provisioning services (57.4% and 19.7%). Over the next two decades, we project that the restoration of mangroves would necessitate an investment of \$40.0–52.1 billion, yielding net gains in ESV of \$231–725 billion. The global benefit-cost ratio (BCR) of mangrove restoration ranges from 6.35 to 15.0, demonstrating that such projects are highly cost-effective. Furthermore, an estimated of 19.4 Tg C can be sequestered in mangrove soils based on a 20-year mangrove restoration program, which can generate \$68.6–\$236 million via blue C trading. Our findings highlight the significant opportunities for blue C restoration projects to mitigate climate change and support livelihoods.

United Nations adopted 17 Sustainable Development Goals (SDGs) in 2015, with the intention of solving some of the planet's biggest challenges by 2030 and building a better and more sustainable future for everyone¹. Mangrove forests, as a highly productive blue carbon ecosystems (BCEs), are particularly important carbon (C) sinks, which is a critical way to reduce atmospheric carbon dioxide (CO₂) concentration and accomplish SDGs related to climate action and biodiversity conservation^{2–4}.

However, over the past two decades, mangrove have faced numerous threats, including sea level rise⁵, storm impacts⁶, erosion and progradation⁶, along-shore development⁷, and direct human activities⁸, which leads to substantial losses of global mangroves⁹. The following loss of C and ecosystem service have been recognized

worldwide, and substantial restoration efforts have been put into mangrove ecosystems^{10–12}. For example, China has achieved significant success in mangrove restoration, with an increase of 70% of the mangrove coverage from 2000 to 2018¹³. Mangrove restoration directly enhances soil organic carbon (SOC) sequestration and holds great potential for achieving various policy objectives related to biodiversity conservation, climate change mitigation, and sustainable development¹⁴. Therefore, mangrove restoration was reported to be a cost-effective practice¹¹.

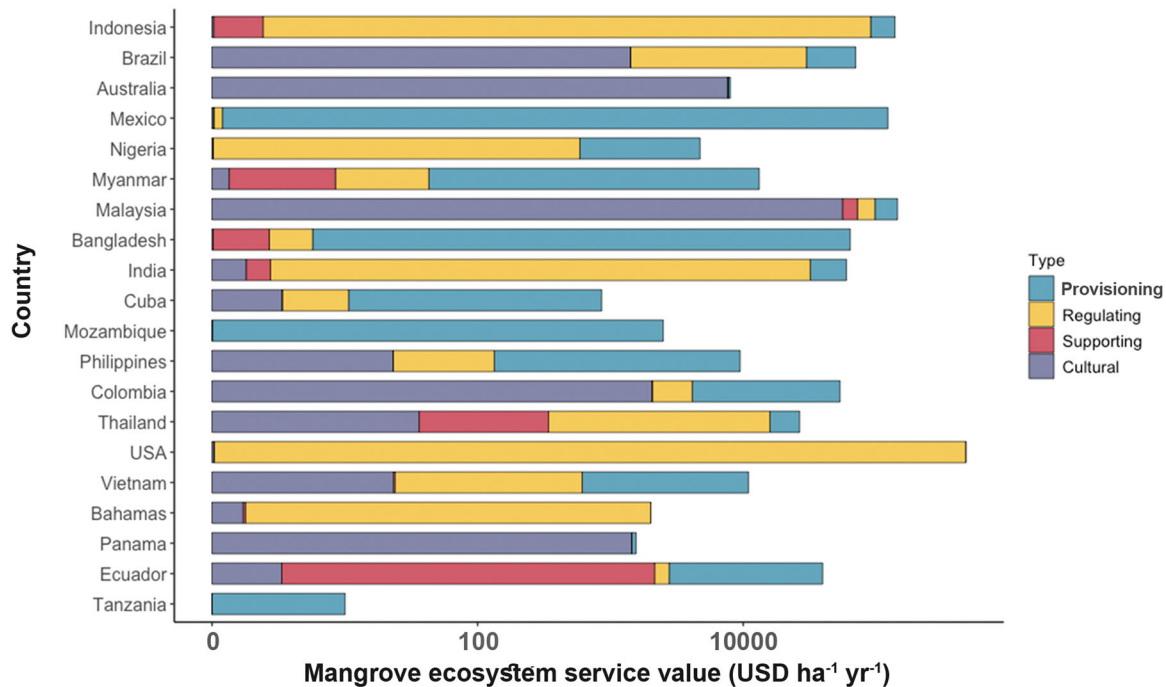
Aquaculture areas and tidal flats present suitable opportunities for mangrove restoration and are currently the primary locations where such efforts are undertaken¹⁵. While many studies have investigated the ecological drivers and outcomes of mangrove restoration,

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there is a research gap in addressing the associated economic benefits at country-level and specific mapping of potential mangrove restoration areas^{11,12}. Analyzing the investment and returns of mangrove restoration is crucial, as it provides compelling evidence for stakeholders and policymakers to support these efforts. Therefore, a comprehensive global analysis of the economic benefits of mangrove restoration is urgently needed to support blue C ecosystem services and promoting sustainable development.

In this study, we tracked land changes in global mangrove ecosystems from 1996 to 2019. We incorporated 846 mangrove ecosystem service value (ESV) observations along with ESVs of 10 corresponding land use types during mangrove change to analyze net changes in ESV. By integrating these ecological parameters with economic factors, we were able to estimate the costs and potential returns of mangrove restoration initiatives. This study aims to assess the outcomes of mangrove change and the investment and benefits of

(a) Mangrove ESV types



(b) Mangrove ESV in 2019

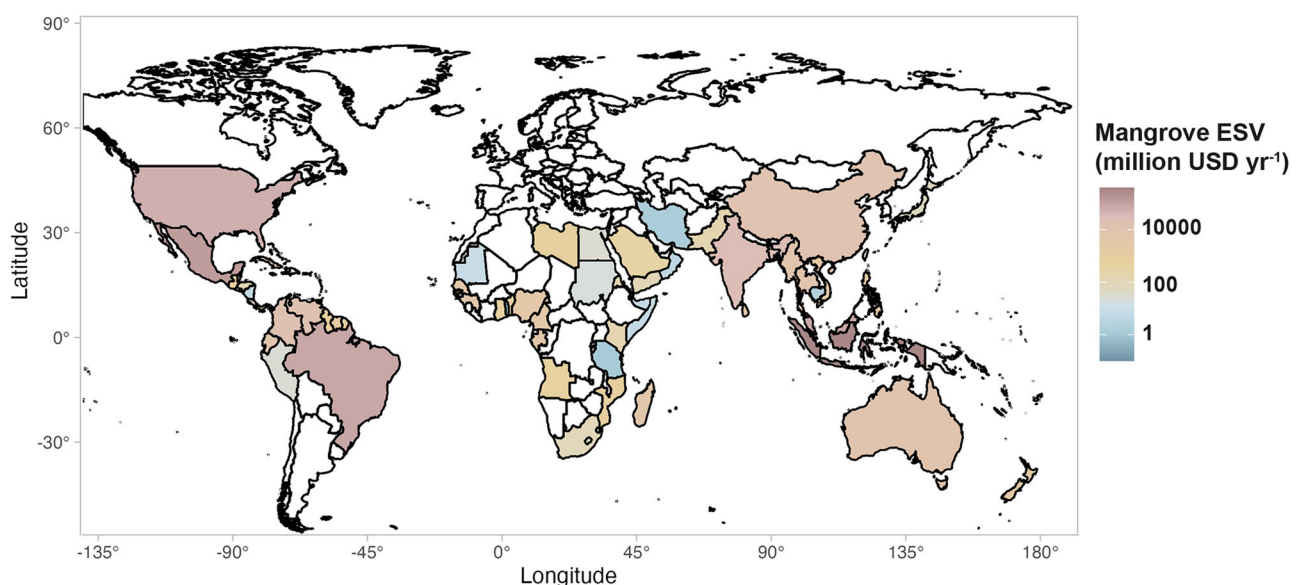


Fig. 1 | Different categories of mangrove ecosystem service value (ESV) in 2019. Four types (provisioning, regulating, supporting and cultural ESV) of the major (areal extent ranks the top 20) ESV data collecting country (a); and global mangrove

ESV in 2019 of each country (b); countries are ranked by its mangrove areal extent in 2019. **b** was generated using R package “maps” developed by Becker et al.³⁵. Source data are provided as a Source Data file.

Table 1 | Continental areal extent and percent of land changes during mangrove losses

Continent	Aquaculture (km ²)	Tidal flat (km ²)	Water (km ²)	Others (km ²)	Total (km ²)
Africa	13.7 (1.19%)	272 (23.6%)	850 (73.9%)	14.8 (1.29%)	1150
North America	106 (6.33%)	417 (24.9%)	1148 (68.2%)	8.07 (0.48%)	1679
South America	194 (13.8%)	414 (29.3%)	784 (55.6%)	17.8 (1.26%)	1410
Asia	1988 (38.9%)	963 (28.9%)	2130 (41.7%)	28.0 (0.55%)	5109
Oceania	1.49 (0.14%)	260 (25.2%)	701 (68.0%)	68.6 (6.65%)	1031
Global	2303 (22.2%)	2327 (22.4%)	5614 (54.1%)	137 (1.32%)	10381

Others refer to sum of urban area, agriculture, saltmarsh, tidal flat, forest, shrub, grass and bare land.

potential mangrove restoration by: (1) evaluating net changes in ESV caused by land changes in mangroves between 1996 and 2019; (2) identifying potential restoration areas for mangrove restoration; (3) performing a cost-benefit analysis of potential restoration activities; and (4) assessing the economic returns of mangrove restoration through blue carbon trading.

Results and discussion

Ecosystem service value change in mangrove ecosystems

Ecosystem service value (ESV) was divided into four main categories: provisioning, regulating, cultural and supporting. Regulating and cultural service were the main ecosystem service types, contributing 41.2% and 39.1% to the global ESV per unit area (Fig. 1a and Table S3). About 57.4% of the global mangrove ESV was provided by regulating services, followed by 19.7% by provisioning, 18.4% by cultural and 4.46% by supporting services (Table S4). One of the most talked about mangrove ecosystem services has been C sequestration due to the growing recognition of the effectiveness of mangroves in climate regulation through pulling carbon out of the atmosphere^{16,17}. Among 18 ESV subcategories, the contribution of climate regulating value to total ESV reached 12.9%, indicating the importance of mangrove C sequestration (Source data file).

Mangroves have suffered significant losses during the past two decades, with global areal extents decreasing from 152,604 km² in 1996 to 147,605 km² in 2019¹⁸. Lost mangroves were mainly turned into permanent water (54%, 5613 km²), tidal flats (22.4%, 2327 km²) and aquacultures (22.2%, 2302 km², Table 1). Global mangrove ESV was 894 billion USD (\$) year⁻¹ in 2019, with \$483, \$35.4, \$29.1, \$226, and \$121 billion year⁻¹, in Asia (mainly Southeast Asia), Africa, Oceania, North America, and South America, respectively (Fig. 1b, Tables S1 and S2). Top five countries with the greatest mangrove ESV was valued at \$320 billion year⁻¹ in Indonesia, \$124 billion year⁻¹ in Mexico, \$79.6 billion year⁻¹ in Brazil, \$75.9 billion year⁻¹ in Malaysia, and \$56.7 billion year⁻¹ in United States (Fig. 1b and Table S1). However, mangrove ESV was not necessarily corresponds to its areal extent but also decided by economic conditions¹¹.

Compared to 1996, mangrove ESV decreased by \$43.9 billion yr⁻¹, with the loss of mangrove ecosystem services at \$13.0 and \$29.2 billion yr⁻¹ in the Americas and Asia (Fig. 2a). Some countries gained mangrove ESV, such as Suriname (\$108 million yr⁻¹), Bangladesh (\$40.9 million yr⁻¹), French Guiana (\$34.8 million yr⁻¹), Cameroon (\$14.0 million yr⁻¹) and New Zealand (\$11.7 million yr⁻¹, Fig. 2a and Table S1). Specifically, the loss of mangroves would release considerable C into atmosphere, since climate regulating plays a significant role in mangrove ecosystem services.

The net change of ESV in mangroves ecosystems was further estimated by combining land change types and their corresponding ESVs. Mangrove loss has led to \$29.2 billion net ESV loss per year, with the greatest net ESV loss in Indonesia, reaching \$17.5 billion year⁻¹. Countries such as Philippines, Bahamas, United States had a net ESV gain of \$301, \$114 and \$110 million year⁻¹ (Fig. 2b and Table S5). Interestingly, some countries gained ESV despite losing mangroves. This can be attributed to other land-use types, such as permanent

water bodies, providing substantial ESV—sometimes even exceeding that of mangroves. For example, permanent water can provide ESV reaching \$24,622 ha⁻¹ year⁻¹ in Vietnam, compared with the \$10,946 ha⁻¹ year⁻¹ provided by mangroves, as 79% of the mangroves were turned into water. Another reason is that even when mangrove provides the greatest ESV among all land use types, the extent of ESV change is different during mangrove gains and losses. For instance, 89% of the lost mangroves in United States were turned into water, while 73% of the gained mangroves were from saltmarshes and tidal flats. The ESV provided by water was almost the same as that provided by mangroves (\$240,285 ha⁻¹ year⁻¹ compared with \$240,314 ha⁻¹ year⁻¹), while much lower ESV was provided by saltmarshes and tidal flats (\$26,027 ha⁻¹ year⁻¹ and \$38,689 ha⁻¹ year⁻¹). Therefore, net changes in ESV depend on the dynamics of mangrove conversion and the differences in ESV between mangroves and other land-use types. However, certain ecosystem services provided by mangroves – such as coastal protection and supporting coastal life circles – are irreplaceable^{3,4,19}. Hence, ESV alone is not the sole criterion to evaluate the ecological risks of mangrove losses, changes in ecosystem service types should be considered.

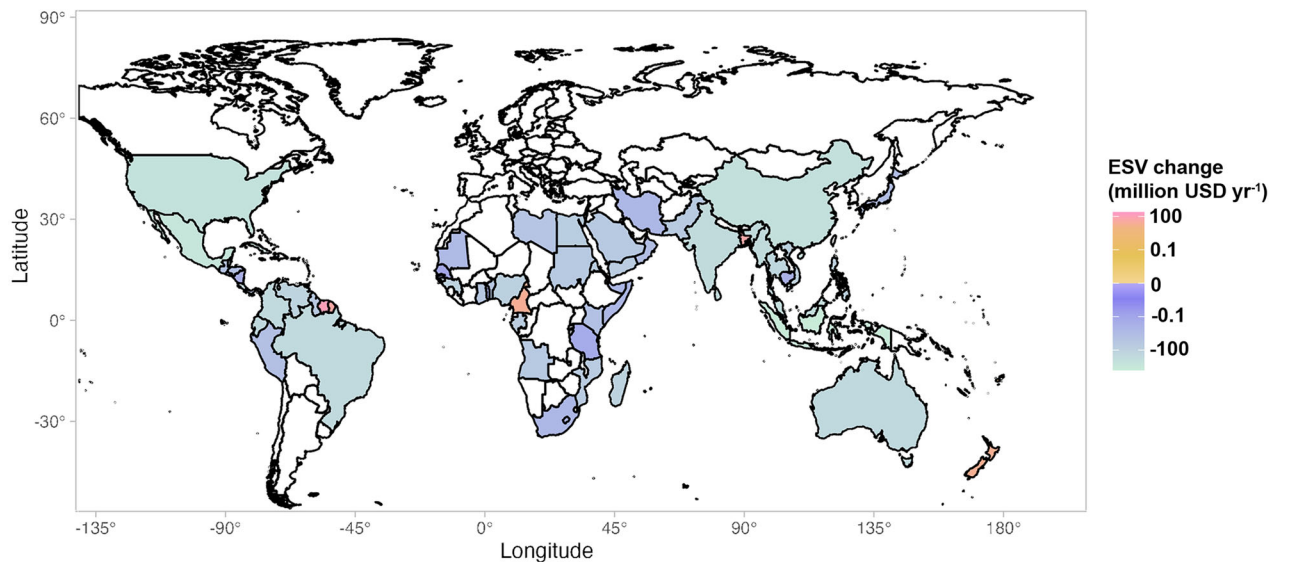
Cost-benefit analysis of mangrove restoration

We assumed that mangrove restoration mainly occurs in aquacultures and tidal flats that converted from former mangroves to ensure a suitable growing environment^{14,20,21}. We conducted a cost-benefit analysis across multiple time frames (10, 20, 30 and 40 years) and social discount rate (8%, 4.5%, and -2%), and reported results in the main text based on a 20-year time frame.

Globally, mangrove restoration on aquacultures costs \$13.1–17.1 billion at different social discount rate. Asia incurs the highest cost (\$11.1–\$14.5 billion), given its widespread aquaculture industry (Figure S1a and Table S6). Restoration costs in South America, Africa, and Oceania were \$0.66–\$0.86 billion, \$0.11–\$0.14 billion, \$0.11–\$0.14 billion, respectively (Fig. 3a, Figure S1a and Table S6). The cost of mangrove restoration on tidal flats is most costly in the Americas (\$13.1–\$17.1 billion), where the previous mangroves were most converted into tidal flats, followed by Asia (\$9.41–\$12.3 billion) (Figure S1b and Table S6). The global cost for mangrove restoration on tidal flats is \$26.9–\$35.0 billion, and restoring both aquaculture and tidal flats raises the global cost to \$40.0–\$52.1 billion, with Asia and the Americas bearing the majority of the expense (\$20.5–\$26.7 billion and \$15.0–\$19.5 billion, respectively) (Fig. 3a and Table S6).

If mangrove restoration is conducted on all the suitable aquacultures and tidal flats, global ESV gains range from \$254 to \$783 billion with a net ESV gain of \$231 to \$724 billion. Asia accounts for most of the net ESV gains (\$186–\$575 billion, Table S7). Surprisingly, there was a net ESV loss in Oceania and Africa during mangrove restoration, mainly because the relatively high ESV for tidal flats (\$38,106 ha⁻¹ year⁻¹) and aquacultures (\$9,588 ha⁻¹ year⁻¹) compared to mangroves (\$7,994 ha⁻¹ year⁻¹ in Australia), which is similarly observed in Tanzania (Table S7). The global benefit-cost ration (BCR) of mangrove restorations over the next 20 years is 6.35–15.0. Mangrove restoration had the highest returns in Asia (average: 9.36–22.1), while got lower returns but still a

(a) Mangrove ESV change



(b) Net ESV change

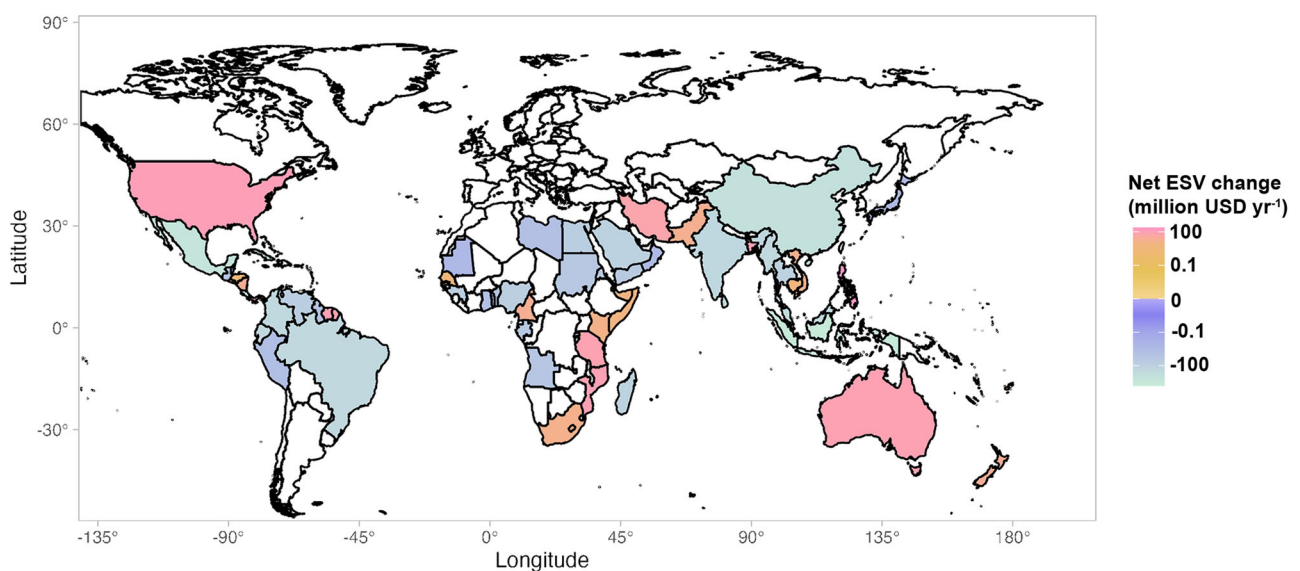


Fig. 2 | Ecosystem service value (ESV) changes in mangrove ecosystems. Mangrove ESV change (a), and net ESV change in mangrove ecosystems due to land use shifts (b); where the warm tone color refers to the increase ESV while the cool tone

color refers to the loss of ESV. This figure was generated using R package ‘maps’ developed by Becker et al.³⁵. Source data are provided as a Source Data file.

cost-effective ecological management in Oceania (1.21–2.86) and Africa (1.22–2.88, Table S8). Countries such as India, Ecuador, Thailand, has extremely high BCR, reaching more than 100, followed by Bangladesh, Colombia, China, Vietnam, Costa Rica, American Samoa and Indonesia, with their BCR over 20 (Fig. 4a).

When accounting for the hidden cost of losing ESV from aquaculture and tidal flats, the net BCR was then calculated by subtracting the ESV of aquaculture (including fishery revenue) and tidal flats on the basis of the restored mangrove ESV. The global average net BCR is 5.78–13.9, with India, Ecuador, Thailand, Bangladesh, China, Colombia, Costa Rica, Vietnam and Indonesia generating substantial net ESV gains (net BCR: 21.7–137, Fig. 4b). The BCR improves over longer restoration periods since initial investments like planting and engineering are fixed, and only ongoing management costs are added annually (Table S8).

While the global average BCR and net BCR suggest that mangrove restoration is highly beneficial, this trend does not apply universally. Countries like India, Ecuador, Thailand which has extremely high BCR and leveled up the global average, while 22 countries had BCR of less than 1, with 49 countries which had no observations of any ESV and cost, had BCR of 2.21 calculated by mean values (Fig. 4 and Table S8). Overall, mangrove restoration is a cost-effective but not very profitable ecosystem management for some regions and countries. If net BCR is used to evaluate feasibility, results are less encouraging: 23% of countries have BCRs less than 1, and 34% of the countries can gain net benefits (Fig. 4). For countries with developed fisheries such as Indonesia, Myanmar and Vietnam, building integrated mangrove aquaculture systems (IMAS)^{22–24} by maintaining partial ESV provided by aquacultures is a good practice to further improve the BCR.

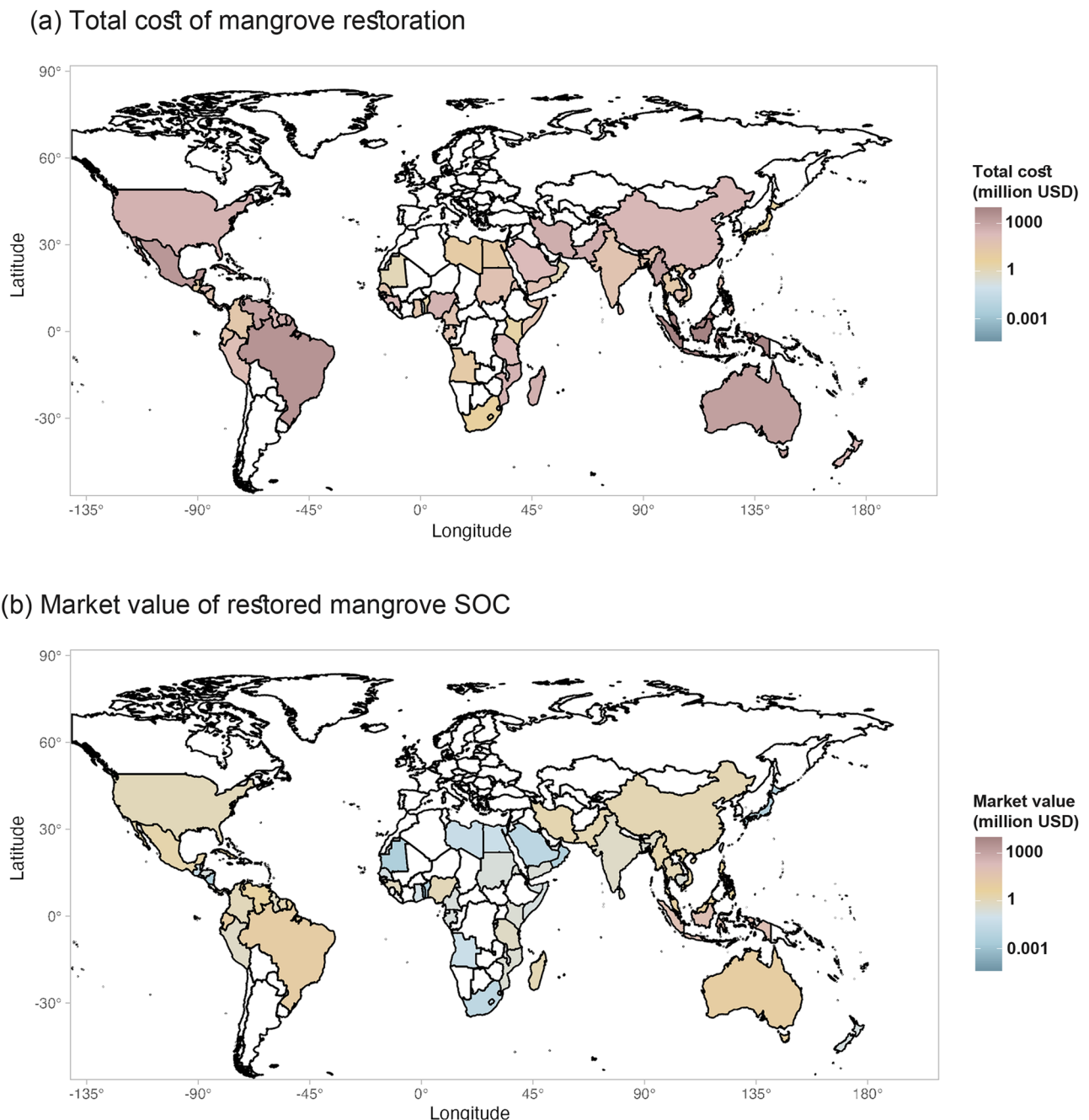


Fig. 3 | The cost and economic returns of mangrove restoration. The total cost of mangrove restoration at the 4.5% social discount rate (a) and the market value of selling the mangrove soil organic carbon (SOC) during mangrove restoration based

on the carbon price of 9.4 USD CO₂e per ton on a 20-year time frame at the 4.5% social discount rate (b). This figure was generated using R package ‘maps’ developed by Becker et al.³⁵. Source data are provided as a Source Data file.

Blue carbon trading in mangrove restoration

As a highly productive BCEs, mangrove soils have great ability of C sequestration. By compiling 324 observations of mangrove C accumulation rate (CAR), we were able to estimate the amount of C sequestered in mangrove soils through mangrove restoration programs. Globally, an annual increase of 1.35 Tg SOC stock is expected from mangrove restoration, with 19.4 Tg SOC stock gained based on a 20-year time scale (supposing newly restored mangrove started to provide ecosystem services from the 5th year and an annual decay rate of 0.1²⁵, Table S9). Countries with large potential mangrove restoration areas would witness substantial increase in SOC stocks, such as Indonesia (11.4 Tg), Brazil (1.04 Tg), Malaysia (0.88 Tg), Ecuador 0.86 Tg) and Philippines (0.41 Tg).

The economic return on investment of mangrove restoration was analyzed using blue C marketing as a proxy based on the market price of its climate mitigation potential (CMG). The annual increase of 4.95 million tCO₂e from 1.35 Tg of SOC stock would yield \$68.6–\$236 million and \$129–\$444 million, based on global blue C prices of \$5 and \$9.4 per tCO₂e, respectively (Fig. 3b, Tables S9 and S10). Asia would see the highest economic returns (\$41.6–\$219 million), followed by the Americas (\$20.7–\$133.8 million), Oceania (\$3.82–\$24.7 million), and Africa (\$2.51–\$16.3 million) (Table S10). Key contributors to global CMP and economic gains include Indonesia, Brazil, Malaysia, Ecuador, the Philippines, the Bahamas, and Australia, collectively accounting for 80% of the global CMP and generating substantial returns (Tables S9 and S10).

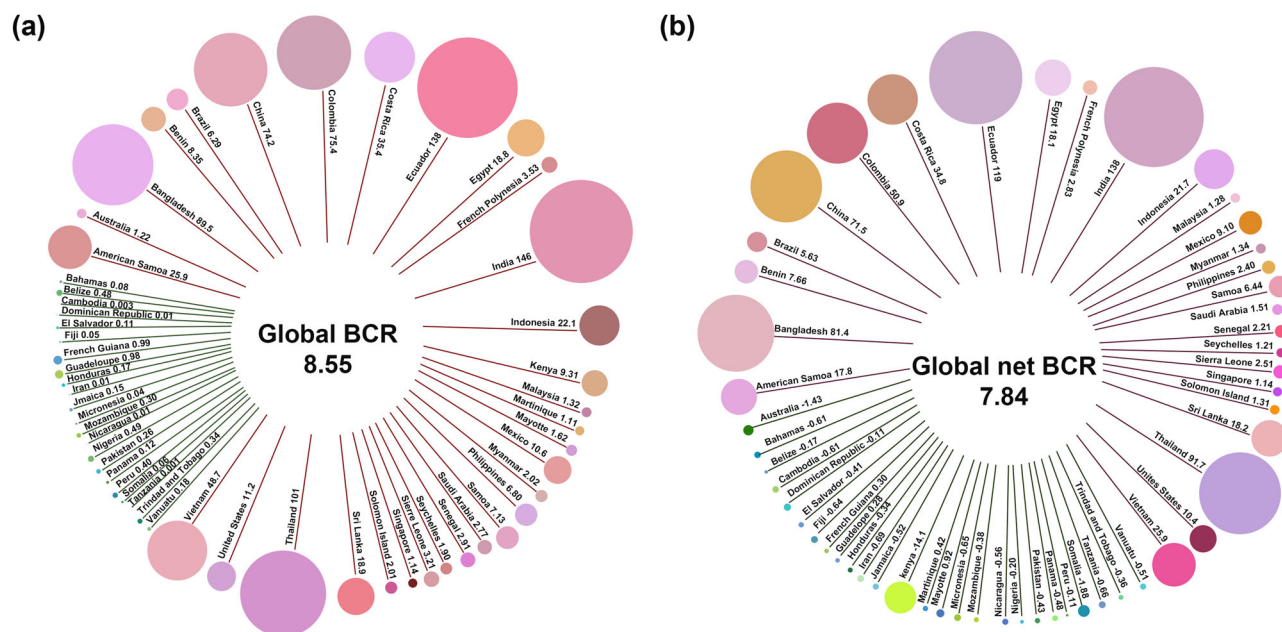


Fig. 4 | Country-level cost-benefit analysis of mangrove restoration. The benefit cost rate (BCR) (a) and net BCR (b) when conducting mangrove restoration on a 20-year time frame at 4.5% social discount rate of all the data collecting countries. Countries that are not shown in this figure means no mangrove cost data and

mangrove ESV data were collected and can use the global average value as references. Warm tone colors refer to the BCR or net BCR over 1, and cool tone colors refers to BCR or net BCR less than 1. Source data are provided as a Source Data file.

Despite economic benefits ranging from \$68.6 to \$444 million over a 20-year period, blue C trading alone may not break even. Zeng et al.²⁶ reported a quite high net present values (NPVs) for mangrove restoration by including both biomass and soil C. Besides that, different approaches were used to analyze the additional SOC stock. In this study, we used the CAR to estimate the annual soil C sequestration when conducting restoration, while Zeng, et al.²⁶ used the annual deforestation rate to estimate the C loss if no restoration were conducted. Our methods can give a more accurate analysis of sediment C sequestration.

The primary goal of this study is to present comprehensive data on mangrove restoration rather than to promote its economic benefits. The motivation of mangrove restoration should be the protection of natural resources and sustainable development instead of the pursuit of greater profits. It is all very well to be able to commercialize mangrove restoration and reap huge ecological and economic profits, but this should not be the only standard to evaluate the feasibility of mangrove restoration. The main goal of these practices is to share scientific knowledge and technology, research capacity development and transfer of marine technology. Besides that, C trading was included to better support mangrove restoration initiatives by linking respective communities to international markets. International funding mechanisms, such as the Green Climate Fund could support large-scale mangrove restoration projects by forming collaboration between local authorities, experts and farmers to perform mangrove restoration and boost the income of farmers, fisherfolks, and other rural business, such as bee-keeping and honey production. Furthermore, Climate-resilient housing and community-based disaster risk management, vulnerability assessments and planning process are also being scaled up to ensure the long-term growing benefits. (<https://www.greenclimate.fund>).

Limitations

Although mangrove autochthonous organic carbon (OC) is the main contributor to OC in mangrove sediments, allochthonous marine and/or terrestrial OC also accounts for a considerable proportion²⁷. When considering blue C trading based on CMP, not all newly accumulated C in mangrove sediments are newly generated, part of them were found to be allochthonous 'old C', whose CMP were double counted.

Secondly, ESVs were calculated by adding all types of ESVs in certain ecosystems, but since some countries lack complete data on all 18 ESV categories, missing values were considered as zero. Therefore, ESVs might be underestimated due to insufficient research efforts, and the BCR is thus quite conservative in this study. We further conducted a sensitivity analysis by filling missing values of 18 ESV subcategories using the global average value adjusted to local socio-economic values and reported the most ideal scenario for mangrove restoration (global BCR:13.8–32.6; global net BCR:13.2–31.9, Table S11, Source data file). We recognize the complexities in securing funding, negotiating with governments and local communities, executing restoration activities, and managing post-restoration maintenance. In our cost calculations, we included expenses for engineering, planting, labor, management, and maintenance but excluded the costs of securing funding due to a lack of consistent reporting across over 100 countries, preventing accurate estimates. Furthermore, mangrove restoration are at risk of replantation failure²¹, rising sea levels, and socioeconomic emergency, which should be carefully evaluated before conducting mangrove restoration.

Methods

Data collection

To analyze the net ecosystem service value (ESV) change during land use shifts in mangrove ecosystems from 1996 to 2019, we collected ESVs of coastal ecosystems (saltmarshes and tidal flats) and other terrestrial ecosystems. ESV of mangroves, saltmarshes, tidal flats, forests, shrubs, grasslands, agriculture and water were extracted from Ecosystem Service Valuation Database (ESVD: <https://www.esvd.info/ourdatabase>). Since evaluating mangrove ESV is very crucial for this study, we further added additional data to it by searching *Web of Science* using combinations of keywords "mangrove ecosystem service", "mangrove ecosystem service value" and "mangrove ESV". Since ESVs of aquacultures and urban areas were not included in ESVD datasets, we got those data by searching *Web of Science* using combinations of keywords "aquaculture ecosystems service*", "aquaculture ESV", "urban area ecosystems service*", "urban area ESV", "ecosystem service" land change", "ecosystem service" land cover change" and "ecosystem service" LULC". There were 871 observations of mangrove ESV (689 from

ESVD and 182 from our collected datasets), 146 observations of salt-marsh ESV, 63 observations of tidal flat ESV, 3280 observations of water ESV, 967 observations for forest ESV, 104 observations of shrub ESV, 50 observations of grassland ESV, 983 observations of agriculture ESV, 94 observations of aquaculture ESV (most of them were reported as fishery revenue), 44 observations of urban area ESV. For bare lands, we use value of 405 2020 USD ha⁻¹ yr⁻¹ from Costanza, et al.²⁸.

We constructed a comprehensive global mangrove carbon accumulation rate (CAR) database to evaluate the mangrove C sequestration ability during mangrove restoration, collecting as many experiments that fulfilled our criteria as possible. The basic CAR data was from Wang, et al.⁴. We searched the *Web of Science*, *China Knowledge Resource Integrated Database* using combinations of keywords “mangrove carbon”, “mangrove C* accumulation”, “mangrove SOC accumulation”, “mangrove C* accretion” that were published after 2021. The database should meet the following requirements: (1) the work must have been published in peer-reviewed publications; (2) the study must have been a field study in natural conditions without artificial manipulation. Where studies made available both soil accretion rate (SAR) and C density, the CAR was calculated as:

$$\text{CAR}(\text{g Cm}^{-2} \text{y}^{-1}) = \text{C density}(\text{g cm}^{-3}) \times \text{SAR}(\text{mm y}^{-1}) \times 10^3 \quad (1)$$

The final database has 314 CAR observations, where 213 observations were extracted from Wang, et al.⁴, 111 observations were additionally added by searching Web of Science. The geostatistical principle assumes vegetation distribution gradually changes with environmental factors²⁹. Therefore, we assumed that the mangrove CAR of a sampling site might have the highest similarity to the nearest sampling point. Combining the mangrove mapping in 2019 with Kriging interpolation, mangrove total CAR was analyzed in Google Earth Engine (GEE). Then, the country-level average CAR was calculated as follows:

$$\text{CAR}_{\text{meanX}} = \frac{\text{CAR}_{\text{totalX}}}{\text{Area}_X} \quad (2)$$

where $\text{CAR}_{\text{meanX}}$ is the average CAR of a country, $\text{CAR}_{\text{totalX}}$ is the total C accumulated per year in a country, Area_X is the mangrove distribution area of a country. The purpose of this step rather than directly calculating the mean values of these CAR observations is to include the spatial variety of mangrove CAR and filling the missing values for countries as much as possible.

Land changes in mangrove ecosystems

The global mangrove distribution in 1996 and 2019 were extracted from Global Mangrove Watch¹⁸. Tidal flats distribution of the corresponding year were from Murray, et al.⁷. Saltmarsh distribution were generated by subtracting the above-mentioned mangrove and tidal flats distribution from global tidal wetland mapping⁹. Aquaculture mapping were generated by visual interpretation using high resolution data on Google Earth. Other land use types were categorized into forests, shrubs, grasslands, agricultures, bare lands, urban areas and permanent water according to “Land cover classification gridded maps from 1992 to present derived from satellite observations” on Copernicus platform (<https://cds.climate.copernicus.eu/cdsapp#!/dataset/satellite-land-cover?tab=overview>). Therefore, land use types were classified into 11 classes in this study.

Ecosystems service value and its changes in global mangroves

ESV data from extracted from the ESVD website (<https://www.esvd.info>) were standardized into 2020 USD in the TEEB database³⁰. ESV data collected by ourselves (mangroves, aquacultures and urban areas) were also standardized into 2020 USD by using the official exchange rates to convert the economic estimates reported in the original studies into the official local currency. These values were then

adjusted to 2020 local currency using official gross domestic product (GDP) deflators. Finally, the purchase power parity (PPP) conversion factors were used to convert the values to 2020 USD¹¹. Mangrove ESV was divided into four main categories and 18 subcategories (provisioning: food, medicinal resources, raw materials and water; regulating: air quality regulating, climate regulating, erosion prevention, moderation of extreme events, regulation of water flows waste treatments; cultural: aesthetic information, existence and bequest values, information for cognitive development, inspiration for culture, art and design, opportunities for recreation and tourism; supporting: maintenance of genetic diversity, maintenance of life cycles, maintenance of soil fertility). Mangrove ESV categories were compared at country-level and calculated as follows:

$$\text{ESV}_{\text{categoryN}} = \sum_{i=1}^n \text{ESV}_{\text{mean_subN_i}} \quad (3)$$

where $\text{ESV}_{\text{categoryN}}$ is certain mangrove ESV categories, such as regulating, n is the number of ESV subcategories, $\text{ESV}_{\text{mean_subN_i}}$ is the corresponding ESV subcategories under that ESV category. It should be noted that, not all ESV subcategories were reported in one study. The missing values were treated as 0.

Country-level mangrove total ESV were calculated as follows:

$$\text{ESV}_{\text{total_sub}} = \sum_{i=1}^{18} \text{ESV}_{\text{mean_i}} \quad (4)$$

$$\text{ESV}_{\text{total_others}} = \sum_{i=1}^x \text{ESV}_{\text{total_i}} \quad (5)$$

$$\text{ESV}_{\text{total}} = \frac{\text{ESV}_{\text{total_sub}} + \text{ESV}_{\text{total_others}}}{n + 1} \quad (6)$$

where $\text{ESV}_{\text{total_sub}}$ is sum of mean values of each ESV categories in each country, $\text{ESV}_{\text{mean_i}}$ is mean values of certain ESV categories in each country, $\text{ESV}_{\text{total_others}}$ is the sum of studies that directly reported the total mangrove ESV, $\text{ESV}_{\text{total_i}}$ is the total mangrove ESV in that study, n is numbers of studies that directly reported the total ESV. $\text{ESV}_{\text{total}}$ is the final country-level mangrove total ESV. Values of different mangrove ESV types and its contribution to the total mangrove ESV per year in each country were calculated as follows:

$$\text{ESV}_{\text{cateN_countryX}} = \text{ESV}_{\text{categoryN}} \times \text{Area} \quad (7)$$

$$\text{Contribution}_{\text{categoryN}} = \frac{\text{ESV}_{\text{categoryN}}}{\text{ESV}_{\text{Total}}} \quad (8)$$

where $\text{ESV}_{\text{cateN_countryX}}$ is the ESV of certain categories per year in each country, Area is the mangrove distribution area, $\text{Contribution}_{\text{categoryN}}$ is the relative contribution of certain ESV categories in each country. The contribution of ESV categories at global scale is weighted as follows:

$$\text{ESV}_{\text{cateN_global}} = \sum_{i=1}^m \text{ESV}_{\text{cateN_countryX}} \quad (9)$$

$$\text{ESV}_{\text{Total_global}} = \sum_{i=1}^4 \text{ESV}_{\text{cateN_global}} \quad (10)$$

$$\text{Contribution}_{\text{cateN_global}} = \frac{\text{ESV}_{\text{cateN_global}}}{\text{ESV}_{\text{Total_global}}} \quad (11)$$

where ESV_{cateN_global} is the global value of certain ESV categories per year, m is the number of countries with ESV observations, ESV_{Total_global} is the global total ESV per year, $Contribution_{cateN_global}$ is the contribution of certain ESV categories at global level. For countries that did not have their own observations of ESV, mean values of the total ESV were used. Specifically, considering the unbalanced developing status worldwide, before calculating mean values, total ESV in each country were standardized into the total ESV in United States, and then the mean values were transformed into their local total ESV. For example, using ESV in country A and B to calculate the mean ESV and transformed into ESV in country C which had no ESV observations:

$$ESV_{mean} = \frac{ESV_A + ESV_B}{2} \quad (12)$$

$$ESV_C = \frac{ESV_{mean} \times PPP_C}{Exchange\ rate\ C} \quad (13)$$

where ESV_A is the observation value of ESV in country A and was standardized into 2020 USD, ESV_B is the observation value of ESV in country B and was standardized into 2020 USD, ESV_{mean} is the mean ESV values based on ESVs of country A and B, Exchange rate C is the official exchange rate between country C and United States, PPP_C is the PPP of country C, and ESV_C is estimation of ESV in country C.

The change in mangrove ecosystem service value was calculated as follows:

$$ESV_{change} = ESV_{mangrove} - ESV_{others} \quad (14)$$

where ESV_{change} is the net ESV change, $ESV_{mangrove}$ is the ecosystem service value of the previously existing mangrove, and ESV_{others} is the ecosystem value change of the converted land use (saltmarshes, tidal flats, forests, shrublands, grasslands, agricultures, water, aquacultures, urban areas and bare land). ESV_{others} was calculated as the $ESV_{mangrove}$ mentioned above.

Cost-benefit analysis

Mangrove restoration on tidal flats and aquacultures is the most common practice in mangrove restoration^{14,20,21}. We considered the tidal flats and aquacultures converted from mangroves were suitable for replanting mangroves because the hydrology conditions were not greatly disrupted¹⁵. Therefore, the potential mangrove restoration areas were mangrove-converted aquaculture and tidal flats. The cost of mangrove restoration includes five criteria: plantation cost, engineering cost, labor cost, transportation cost, and maintenance cost. Considering the large variance in socio-economic conditions across countries and regions, all cost was transformed into 2020 USD using local currency and purchasing power parity, similar as the $ESVs^{11}$. Mangrove ESV of restored mangroves was considered as the economic benefits of mangrove restoration.

The economic benefits of restoration were estimated decennially from 10 to 40 years at social discount rates of -2%, 4.5%, and 8%, where the negative value reflects the possibility that conditions will deteriorate in the future due to ecological degradation and resource depletion³¹. The net-present annual total economic benefit is estimated starting in the 5th year by summing up the estimated values for mangrove ESV. The total cost of mangroves is the sum of plantation, engineering, labor, transportation, and maintenance cost and with an annual management cost component of up to 2.5% of the capital cost³¹. The benefit-cost ratio (BCR) of mangrove restoration was then calculated follows¹¹:

$$BCR = \frac{PV[Benefits]}{PV[Costs]} = \frac{\sum_{t=5}^T B_{total} / (1+r)^t}{C_{total} + \sum_{t=1}^T C_{management} / (1+r)^t} \quad (15)$$

Where PV is the present value; t is the year of calculation, B is the total economic benefits; C is the costs (including total initial cost and management cost); and r is the discount rate. When conducting mangrove restoration, aquacultures and tidal flats were transformed into mangroves, while their ESVs were replaced by mangrove ESV. When calculating BCR, benefits were considered as restored mangrove ESV, while the hidden costs, the loss of aquaculture and tidal flat ESV were neglected. Therefore, we proposed 'net BCR' to evaluate the net benefit considering the ESV loss of aquaculture and tidal flats.

Blue carbon trading

We further evaluate the economic return of mangrove restoration by blue C trading. The blue C price is based on its climate mitigation potential (CMP), which was calculated by applying a conversion factor (3.67) to the SOC stock³². Specifically, SOC stock is the accumulated SOC stock each year, calculated by the CAR. We also considered the annual decay rate of 0.1 to SOC specific to mangrove forests²⁵.

$$SOC\ stock_{acc} = CAR \times 0.01 \quad (16)$$

$$CMP = SOC\ stock_{acc} \times D \times (1 - decay\ rate) \quad (17)$$

where $SOC\ stock_{acc}$ is the accumulated SOC stock per year ($Mg\ C\ ha^{-1}\ y^{-1}$), CAR is the carbon accumulating rate ($g\ C\ m^{-2}\ y^{-1}$), CMP is the climate mitigation potential, D is the conversion factor (3.67).

We estimated the economic return of mangrove restoration using the present values (PVs) as the proxy based on the following simplifying assumptions from previous studies: (1) a constant blue C price of $5\ t^{-1}CO_2e$ USD and $9.4\ t^{-1}CO_2e$ USD for the first five years, roughly matching the average C price of all avoided deforestation projects recorded by Forest Trends' Ecosystem Marketplace reports between 2006-2018³³; (2) After the first five years of mangrove restoration started providing ecosystem service (the 10th year of mangrove restoration), we assumed a 5% price appreciation for the following years over a 10 to 40-year restoration time frame³⁴; (3) the social discount rate of -2%, 4.5% and 8% were applied. Therefore, the PV were calculated as follows:

$$V_{total} = CMP \times market\ price \quad (18)$$

$$PV[Financial] = \frac{\sum_{t=5}^T V_{total}}{(1+r)^t} + \frac{\sum_{t=10}^T (1+5\%)^{(t-9)} \times V_{total}}{(1+r)^t} \quad (19)$$

where V_{total} is the total market value of the mangrove SOC and $PV[Financial]$ is the accumulated economic gains of mangrove restoration at a 10 to 40-year time frame.

Sensitivity analysis

Mangrove ESVs were divided into 18 subcategories as above-mentioned, but most of these studies did not cover all of them. For example, the ESVD database only provide the "existence, bequest value" and "Food provision" of mangroves in Australia. We believe that mangroves can provide more types of ecosystem services in Australia and other countries than recorded. Therefore, the ESV gain and BCR might be underestimated. We further conducted a sensitivity analysis to show the maximum ESV gain and BCR that can be achieved by fulfilling the all 18 ESV subcategories with the global mean value. These mean values were further adjusted to match the local socio-economic conditions according to PPP and local exchange rate. These maximum values show the most ideal scenario for mangrove restoration, however, might be hard to achieve because mangroves cannot provide all types of ecosystem service at one location.

Data availability

The source data used for estimation of ecosystem service value change, costs and benefits of mangrove restoration and blue carbon trading have been deposited in Data Center of South China National Botanical Garden, CAS and Figshare (https://figshare.com/articles/dataset/Country-level_mangrove_restoration_costs_and_benefits/28169759?file=51556409). Source data are provided with this paper.

Code availability

All custom code that has been used in this study is available from authors by request.

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Author contributions

J.Z. and F.W. conceived and designed the study. J.Z. collected the data and conducted the analysis, J.Z. and F.W. prepared and wrote the draft. Z.L., J.Z. (Jing Zhou), G.Q., Y.B., C.S., P.M., J.Y. and X.H. helped revising the draft.

Competing interests

The authors declare no competing interests.

Additional information

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