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The potential of Indonesian mangrove forests for global climate change mitigation

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Mangroves provide a wide range of ecosystem services, including nutrient cycling, soil formation, wood production, fish spawning grounds, ecotourism and carbon (C) storage[1]. High rates of tree and plant growth, coupled with anaerobic, water-logged soils that slow decomposition, result in large long-term C storage. Given their global significance as large sinks of C, preventing mangrove loss would be an effective climate change adaptation and mitigation strategy. It has been reported that C stocks in the Indo-Pacific region contain on average 1,023 MgC ha^{-1} (ref. 2). Here, we estimate that Indonesian mangrove C stocks are 1,083 ± 378 MgC ha^{-1}. Scaled up to the country-level mangrove extent of 2.9 Mha (ref. 3), Indonesia's mangroves contained on average 3.14 PgC. In three decades Indonesia has lost 40% of its mangroves[4], mainly as a result of aquaculture development[5]. This has resulted in annual emissions of 0.07–0.21 Pg CO_2e. Annual mangrove deforestation in Indonesia is only 6% of its total forest loss[6]; however, if this were halted, total emissions would be reduced by an amount equal to 10–31% of estimated annual emissions from land-use sectors at present. Conservation of carbon-rich mangroves in the Indonesian archipelago should be a high-priority component of strategies to mitigate climate change.

Globally, deforestation and conversion of mangroves has been shown to contribute 0.08–0.48 Pg CO_2e yr^{-1}, or 10% of the total global emissions from tropical deforestation, even though mangroves account for only about 0.7% of the world's tropical forest area[2]. C losses from mangrove conversion can be high not only because of losses from aboveground C pools but also belowground pools. Potential C losses from mangroves converted to shrimp ponds in the Dominican Republic were 661–1,135 MgC ha^{-1} (ref. 7).

In 1980, there were 4.2 Mha of mangrove forests along Indonesia's 95,000 km of coastline[3]. Over just 20 years mangrove forest cover had declined about 26%, to an estimated 3.1 Mha (ref. 8). In 2005, mangrove forest cover had further decreased to 2.9 Mha (ref. 3). On the basis of FAO data, cumulatively Indonesia has lost 30% of its mangrove forests between 1980 and 2005; this is equivalent to an annual deforestation rate of 1.24%. Recent estimates of Indonesia's mangrove cover suggest a total loss of 40% in the past three decades[4]. Aquaculture development was the main cause[5], after it expanded rapidly in 1997–2005 and resulted in an officially recorded active pond area of about 0.65 Mha (ref. 9). It was also reported that the revenue from shrimp export approached US$ 1.5 billion in 2013; almost 40% of the total revenues arising from the Indonesian fishery sector[10].

As most countries do not have sufficient information to include mangroves in their national reporting to the United Nations, it is important to generate country- or region-specific data on C stocks and emission factors from various land-use activities in mangroves. In the latest National Communication[11] to the United Nations Framework Convention on Climate Change (UNFCCC), Indonesia did not specifically include mangroves, because the IPCC Guidelines for wetlands greenhouse gas (GHG) inventories became available only in 2013 (ref. 12). Indonesia's mangroves are subject to tremendous development pressures despite the fact that sustainable mangrove management could contribute substantially to meeting the proposed national GHG emissions reduction target of 26–41% by 2020. If conservation actions were taken, emissions from mangrove conversion would be reduced[13]. However, to be a part of a land-based GHG emission reduction activity, information on C storage and its dynamics is necessary.

Mangrove ecosystem C stocks

We assessed ecosystem C stocks of 39 mangroves located in eight sites spanning longitudes of 105°–140° E (Supplementary Fig. 1 and Supplementary Table 1). The mangrove C stocks were partitioned by pools, including aboveground live and dead trees, belowground roots, downed wood, and soils stratified into meaningful depth layers[14]. Coupled with deforestation estimates this allowed us to use a stock change approach[15] to estimate emissions from land use, as well as mitigation potentials.

We found that the average C of the plant/biomass pools was 211 ± 135 MgC ha^{-1}, with the lowest values found for plots located in Cilacap, Java (9 ± 10 MgC ha^{-1}) and the highest values found for plots located in Bintuni, West Papua (367 ± 80 MgC ha^{-1}; Supplementary Table 2). The average values reported here were similar to those of the primary mangrove forests dominated by *Rhizophora apiculata* in Malaysia (216 MgC ha^{-1}) and *Bruguiera gymnorrhiza* in Indonesia[16] (205 MgC ha^{-1}). Among the sampled mangroves, we found significant variations in soil bulk density (BD) and

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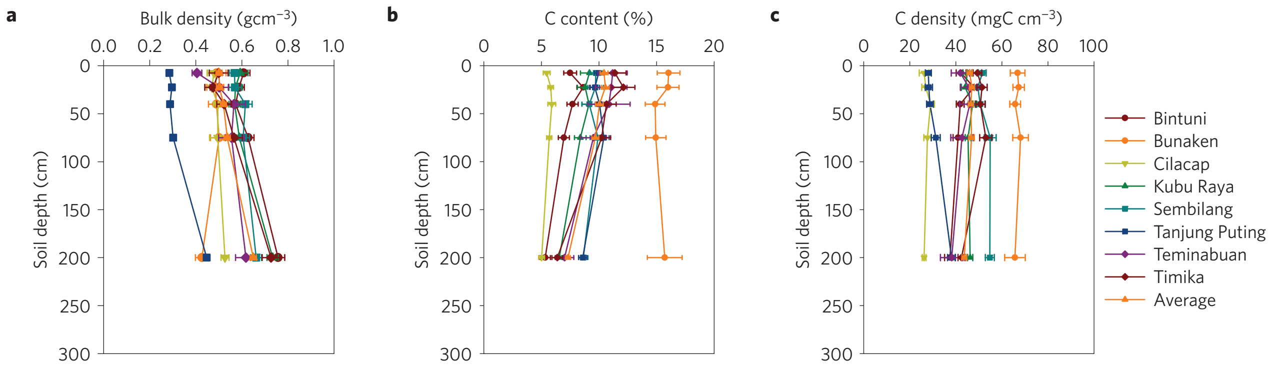

Figure 1 | Averaged values of soil properties. Soil bulk density (**a**), soil carbon content (**b**) and soil carbon density (**c**) of mangroves by depth from eight regions of Indonesia. Horizontal bars signify the standard error.

soil C content, and therefore soil C density and soil C pools (Fig. 1 and Supplementary Table 2). Differences in C stocks among sites were analysed using analysis of variance (Supplementary Table 3).

In general, soil BD at all sites (except Cilacap) significantly increased with depth ($\chi^2(4) = 76.199$, $p = 0.001$; Supplementary Table 3). We found that soil BD across sites and depths ranged from $0.28 \pm 0.04\,\mathrm{g\,cm^{-3}}$ at the 0–15 cm depth in Tanjung Puting to $0.76 \pm 0.03\,\mathrm{g\,cm^{-3}}$ at the 100–200 cm depth in Bintuni. The mean soil BD was $0.56 \pm 0.15\,\mathrm{g\,cm^{-3}}$. Soil C concentration tended to decrease with depth, although in some sites (Sembilang, Cilacap, Bunaken and Teminabuan) the differences were not significant. When data are pooled, the total mean C concentration of the top 100 cm of soil was 10.45% and highly significantly different ($\chi^2(4) = 64.673$, $p = 0.001$) than deeper soil layers (100–300 cm) with a mean C concentration of 7.30%. It is clear that C-rich soil exists at depths of 3 m or greater in these ecosystems. Soil C density did not differ significantly ($\chi^2(4) = 5.011$, $p = 0.286$) with depth within any site. The mean C density of soil depths from all sites combined was remarkably similar, ranging from 43.65 ± 1.03 to $46.95 \pm 1.08\,\mathrm{mg\,C\,cm^{-3}}$ (Fig. 1). We estimated that the mean soil C stocks were $849 \pm 323\,\mathrm{MgC\,ha^{-1}}$, with a range from $572 \pm 200\,\mathrm{MgC\,ha^{-1}}$ at the Cilacap site to $1{,}059 \pm 189\,\mathrm{MgC\,ha^{-1}}$ at the Tanjung Puting site.

The mean mangrove ecosystem C stock, which represents the total quantity of C stored in all components, was $1{,}083 \pm 378\,\mathrm{MgC\,ha^{-1}}$ (Fig. 2 and Supplementary Table 2). Uncertainty propagation (95% confidence interval) indicated that Indonesia's mangrove C stocks ranged between $442\,\mathrm{MgC\,ha^{-1}}$ and $1{,}567\,\mathrm{MgC\,ha^{-1}}$ in the areas studied. With an extent of 2.9 Mha in 2005, we estimated that Indonesian mangroves store as much as 3.14 ± 1.10 PgC, with a range between 1.28 and 4.54 PgC.

The lowest ecosystem C stocks ($593 \pm 210\,\mathrm{MgC\,ha^{-1}}$) were found in Cilacap. The lower C stock at this site is probably a reflection of exploitation for more than 70 years in this densely populated area[17]. In contrast, the mangroves of the sparsely populated Bintuni region had the highest mean C stocks of $1{,}397 \pm 191\,\mathrm{MgC\,ha^{-1}}$. Our estimate of Indonesian mangrove C stocks are several times higher than those of tropical forests growing on mineral soil—for example, C stocks of upland forests in Sumatra, Indonesia were estimated to be $254\,\mathrm{MgC\,ha^{-1}}$ (ref. 18). In one of few studies to directly compare the C stocks of upland forests and mangroves, it was repoted that average C stocks of mangroves were 830–$1{,}218\,\mathrm{MgC\,ha^{-1}}$ (ref. 2), whereas the C stocks of non-mangrove neotropical forests were reported to range from 141 to $571\,\mathrm{MgC\,ha^{-1}}$ (ref. 19).

Although there was variation in how ecosystem C stocks were partitioned across sites, the majority (78%) of C was stored in the soils. Smaller pools of C were stored in living trees and roots or biomass (20%), and in dead or downed wood (2%). This finding is similar to many other mangrove ecosystems worldwide[2,7,20,21].

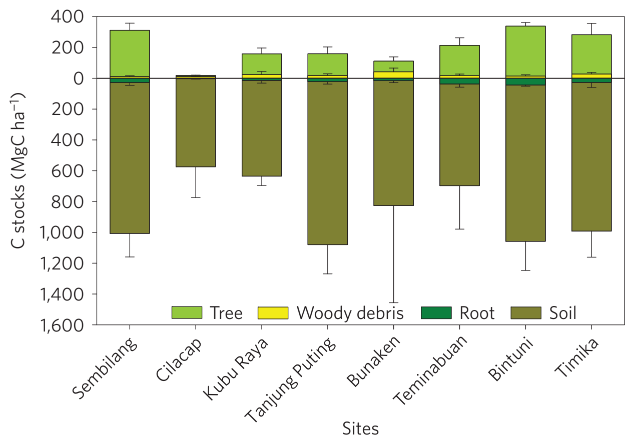

Figure 2 | Ecosystem C stocks of mangroves partitioned into dominant pools from eight regions of Indonesia. Vertical bars signify the standard error.

Climate change mitigation potential

The Indonesian mangrove deforestation rate from 1980 to 2005 was $52{,}000\,\mathrm{ha\,yr^{-1}}$ (ref. 3). Although covering less than 2% of the forest area[22], this was 6% of the $0.84\,\mathrm{Mha\,yr^{-1}}$ annual forest loss reported for Indonesia[6]. With a total C storage of 3.14 PgC, Indonesian mangroves have significant potential to contribute to climate change mitigation efforts. Assuming that the fate of soil carbon following land-use change in Indonesia were to be similar to that measured in abandoned shrimp ponds in the Dominican Republic[7], emissions from land use were estimated to be 0.07–$0.21\,\mathrm{Pg\,CO_2e\,yr^{-1}}$, or an average estimate of $0.19\,\mathrm{Pg\,CO_2e\,yr^{-1}}$. Total emissions from the Indonesian land-use sector were estimated to be $0.7\,\mathrm{Pg\,CO_2e\,yr^{-1}}$ (ref. 11). This suggests that avoiding mangrove deforestation would reduce emissions by an amount equal to 10–31% of estimated annual land-use emissions at present.

Having regional and global estimates of C stocks and emission factors helped the progress of managing coastal blue carbon[2,13,23]. However, generating country-specific estimates derived from the extensive measurements demonstrated here is an improvement for the next important step for informed decisions on climate change mitigation, restoration of degraded mangroves, and fishery practices.

To put this into the global perspective, on the basis of our estimates, Indonesian mangrove loss contributed 42% of the global emissions from the destruction of coastal ecosystems, including marshes, mangroves and sea grasses, which have been estimated to release 0.15–$1.02\,\mathrm{Pg\,CO_2e}$ annually[23]. It was also estimated that the global blue carbon emissions were equivalent to 3–19% of all

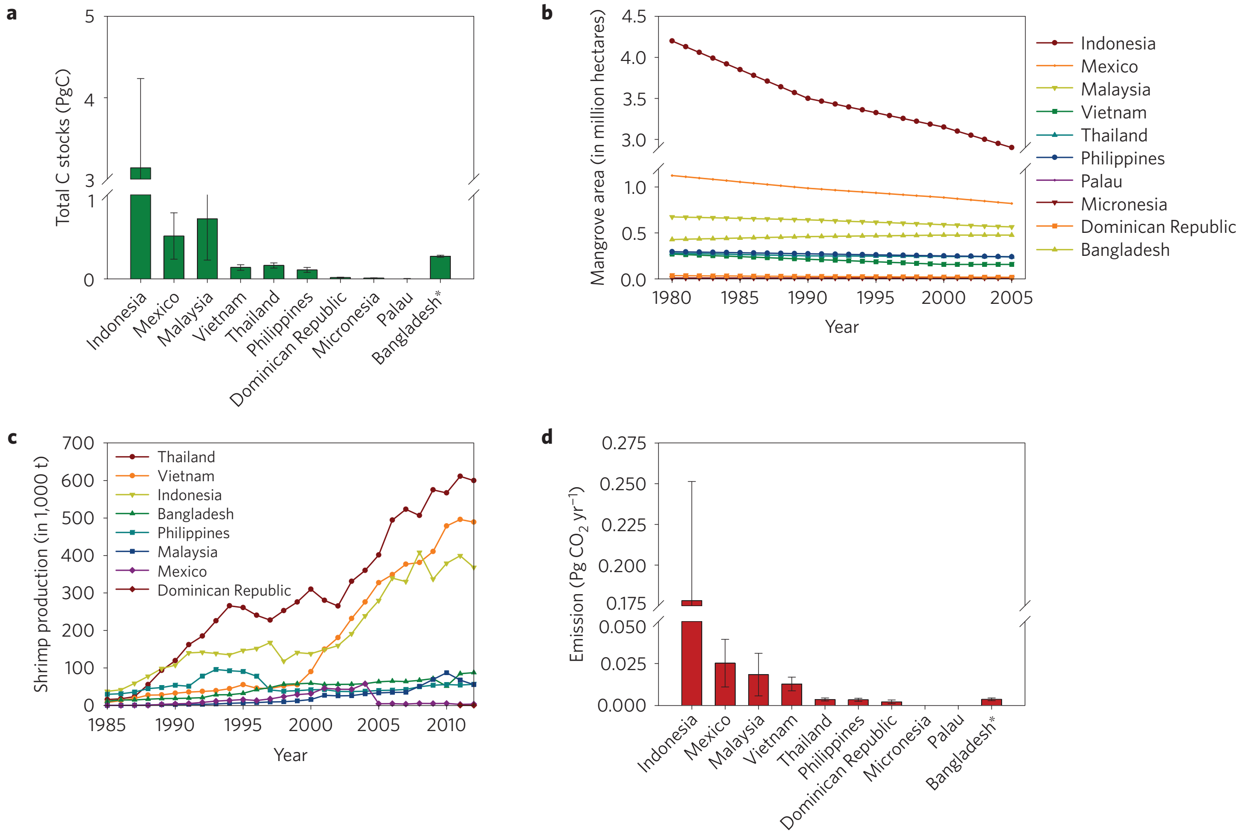

Figure 3 | Mangrove carbon dynamics in 10 selected countries. a, Total C stocks, obtained by multiplying ecosystem C stocks (from Table 1) by the most recent mangrove area. **b**, Mangrove area changes, obtained from FAO-Forest Resource Assessments in 1980, 1990, 2000, and 2005. **c**, Shrimp production. **d**, C emissions, obtained by multiplying mangrove deforestation and ecosystem C stocks. Vertical bars signify the standard error. *Afforestation is occurring (increasing area and C stocks).

Table 1 | Ecosystem C stocks, area, deforestation rate, and total C stocks in mangroves of ten selected countries.

Country	Ecosystem C stocks			Area (ha)		Annual deforestation rate*		Total C stocks (Pg)
	n	(MgC ha^{-1})	Reference	1980	2005	(ha)	(%)	
Indonesia	39	1,082.55 ± 377.85	This study	4,200,000	2,900,000	52,000	1.24	3.14
Mexico	7	621.85 ± 336.79	19	1,124,000	820,000	12,160	1.08	0.51
Malaysia	3	1,267.00 ± 872.72	28	674,000	565,000	4,360	0.65	0.72
Bangladesh	2	565.60 ± 26.16	2	428,000	476,000	(1,920)	(0.45)	0.27
Thailand	3	662.33 ± 126.59	28	280,000	240,000	1,600	0.57	0.16
Philippines	3	441.76 ± 120.76	29	295,000	240,000	2,200	0.75	0.11
Vietnam	15	862.95 ± 210.09	†	269,150	157,000	4,486	1.67	0.13
Dominican Republic	9	922.11 ± 274.56	7	34,400	16,800	704	2.05	0.02
Micronesia	3	1,063.88 ± 283.68	20	8,500	8,500	0	0	0.01
Palau	3	719.73 ± 309.38	20	4,700	4,700	0	0	0.003

n = number of plots. Numbers in brackets indicate afforestation. *Area and deforestation rates are from ref. 3. †Nam, V. N. *et al.*, manuscript in preparation.

GHG emissions from global deforestation, and resulted in economic damages of US$ 6–42 billion per year at a price of US$ 41 per ton of CO_2 (ref. 23). Following earlier study, the economically viable abatement cost was less than US$ 10 per ton of CO_2 (ref. 24), Indonesia could potentially gain substantial social benefits from avoiding mangrove conversion.

Provided that the cost structure, including that of project development costs, are well defined, the net benefits from avoiding mangrove deforestation and conversion may be established. Nevertheless, climate change mitigation by preventing the existing C from being released can be bundled with adaptation measures for coastal protection of rising sea levels. Mitigation and adaptation strategies also promote the benefits of ecosystem services by improving community nutrition and livelihoods from near-shore capture fisheries.

Indonesia's shrimp industries, which are mainly large scale, generate revenue of US$ 1.5 billion annually[9,10]. The increased production is associated with an expansion in 1997–2005, which then levelled off at an average area of around 650,000 ha (Supplementary Table 5). To provide a global context of mangrove C dynamics (ecosystem C stocks, deforestation rates and total C stocks) of this study and the major driver of mangrove conversion, we compiled published data from nine other countries (Table 1). Along this line we plotted the calculated total national mangrove

C stocks, as shown in Fig. 3a, and compared the decreasing trends of mangrove area (Fig. 3b) with shrimp production[25] (Fig. 3c) and emissions of CO_2 (Fig. 3d).

Thailand, Vietnam, and Indonesia are the top three countries for shrimp export. Indonesia has the largest total C stocks (3.14 Pg) and the highest deforestation rate (52,000 ha yr^{-1}) among these countries, which could be closely associated with shrimp pond expansion and shrimp production trends over the past three decades. In contrast, Thailand has a low deforestation rate yet had the highest shrimp production on Earth. This is because the Thai shrimp industry relied on intensified high-input systems[26]. In addition, one third of Thailand's mangroves were destroyed before 1980 (ref. 27). On the other hand, in Vietnam, although its mangrove area is relatively small, its high deforestation rate of 1.67% (Table 1) led Vietnam to overtake Indonesia in shrimp production in 2002 (Fig. 3c)[25]. Countries such as Bangladesh and Malaysia may have protected their mangroves and did not pursue conversions, whereas the Philippines and the Dominican Republic have lost over half of their mangrove cover from 1985 to 2005 (ref. 3) to be able to support the shrimp industry or other land uses.

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Author contributions

D.M. conceived and designed the study, collected field data, performed data analyses and led the writing of the paper. J.P. collected field data, performed data analyses and contributed to writing. J.B.K. also conceived and designed the study, collected field data and contributed to analysis and writing. M.W.W. collected field data and contributed to writing. S.D.S. contributed to data collection, data analysis and writing. D.C.D. contributed to data collection and writing. S.M. collected field data and contributed to writing. H.K. collected field data and contributed to writing. S.T. collected field data and contributed to writing. S.K. contributed to data collection and writing.

Additional information

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Competing financial interests

The authors declare no competing financial interests.