a combination of strategic and applied research, including simulation experiments, modelling and ecosystem-based approaches is essential. These estimates will improve the accuracy in carbon accounting with implications for greenhouse gas mitigation and carbon sequestration.

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COMMENTARY

Carbon storage potential of mangroves – are we missing the boat?

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Increasing soil carbon stocks and protecting carbon-rich soils are crucial for achieving the Paris climate targets. Mangrove forests are the potential carbon sinks for mitigating the growing greenhouse gas emissions due to their highest carbon storage capacity per unit area compared to terrestrial forests. Furthermore, restricted global distribution of mangroves testifies their role in climate change mitigation as most effective at the national level rather than on a global scale. Nevertheless, lack of reliable estimates, insufficient data, discrepancy in the available data, increasing degradation rates and failure of conservation endeavours signify that we are missing the carbon storage potential of mangrove soil. So, here we emphasize the imperative need of country-wise site-specific precise estimates and an understanding of the spatial distribution of mangrove soil carbon stocks to recognize the actual climate mitigation potential of the mangroves as well as strengthen the conservation measures for the sustainability of mangroves.

Despite the small geographical extent of mangroves (0.1% of the earth's continental surface), they are considered as potential carbon sinks and proposed as a low-cost effective option for mitigating greenhouse gas (GHG) emissions and climate change, due to their much greater carbon storage potential per unit area[1]. However, there is no robust estimate for carbon stocks of global mangroves. According to a recent estimate[2], carbon sequestration in the mangroves amounts to 14.2 Tg C yr^{-1}, with an average sequestration rate of 171 ± 17.1 g C m^{-2} yr^{-1} and average soil accretion rate of 5.8 mm yr^{-1}. In recent times, efforts have been made to assess the carbon stocks of global mangroves; however, uncertainty still exists. For instance, the available estimates[1–6] of total global carbon stocks of mangroves are 20, 10, 4.03, 13.1, 11.2 and 4.4 Pg C respectively. The estimated mean mangrove carbon stocks per unit area are 761.4 ± 45.5, 956, 511 and 885 Mg C ha^{-1} which are higher than those of other forest ecosystems[2,4,7–9].

Unlike other tropical forests, for which the bulk of carbon storage is in the biomass, mangrove carbon is primarily stored in soil[1,5,10,11]. The estimated average soil carbon concentration of global mangroves is also highly variable. For instance, Jardine and Siikamäki[12] reported the global mangrove soil carbon stock as 5.00 ± 0.94 Pg C, whereas Atwood *et al.*[6] and Sanderman *et al.*[13] have reported values of 2.6 and 6.4 Pg C respectively, for the top metre of soil. Similarly, estimates of soil carbon stock per unit area also vary. Donato *et al.*[1] reported the average mangrove soil organic carbon as 864 Mg C ha^{-1}, whereas Alongi[4], Jardine and Siikamäki[12], Atwood *et al.*[6] and Sanderman *et al.*[13] have reported values of ~700, 369 ± 6.8 (range 272–703), 283 ± 193 (range 72–936) and 361 ± 136 Mg C ha^{-1} (range 86–729 Mg C ha^{-1}) respectively. Previous estimates of global mangrove soil organic carbon have relied solely on climate-based models[11] or mean country-level statistics[6,14], and more recently, on remote sensing[13]. The differences in carbon stock values among these studies have often been attributed to discrepancies in the estimation of the extent of global mangrove cover[15].

Recently, Rovai *et al.*[16] have estimated a total global budget of 2.26 Pg C in mangrove soils based on coastal environmental setting framework, and noted that mangrove soil organic carbon stocks have been underestimated by up to 44% and overestimated by up to 86% in carbonate and deltaic settings respectively, in earlier studies. Twilley *et al.*[17] have also estimated the global mangrove soil organic carbon budget as 2.3 Pg C, and found that the mangrove soil organic carbon stocks vary markedly across different types of coastal environmental settings, increasing from the river-dominated to tide/wave-dominated to carbonate coastlines. They noted that C storage in the deltaic settings has been overestimated, while soil organic carbon stocks in carbonate settings have been underestimated by up to 50%. Walcker *et al.*[10] reported that the carbon sink capacity declines with ecosystem age, and global projections of the above- and belowground reservoirs of carbon stock need to be accounted for mangrove age structures, which result from historical changes in coastal morphology. This variation in the estimation of carbon stock of mangroves has been attributed to the severe limitation of country-wise data and use of global mean values of earlier studies for estimating carbon stocks of countries that lack data[16].

Based on the available literature, it is also evident that there can be significant variability in the soil carbon stocks across different mangrove forests[12] and also within the same mangrove forest[18,19]. For instance, Kuffman *et al.*[19] have reported the increasing trend of soil organic carbon from the seaward to the landward side, and Weiss *et al.*[20] have reported high soil organic carbon stocks in the natural marine mangroves than estuarine mangroves. Similarly, mangroves of the sub-humid or arid regions have much lower soil carbon stock than that of the humid region[21]. Furthermore, it has been reported that the mixed mangrove stands have 20% higher soil C stocks per unit area than the monotypic stands[6,22], and carbon accumulation within the conserved environments is up to fourfold higher than that of the degraded or deforested environments, but threefold lower than those impacted by domestic or aquaculture effluents, and twofold lower than those impacted by storms and flooding[22]. The mean total carbon stocks of mangroves per unit area between the regions also vary (highest in the Asia-Pacific (1094 Mg C ha^{-1}) followed by Latin America (939 Mg C ha^{-1}), West–Central Africa (799 Mg C ha^{-1}) and Arabian/Oman Gulf (217 Mg C ha^{-1}))[9]. Thus, carbon storage capacity of mangroves is site-dependent and hence global generalization will be of little value.

It has also been reported that the controls on soil carbon stocks are diverse, involving both climatic[5,12,23,24] and local edaphic factors[25–28] that act in a complex manner. Furthermore, recently, Rosentreter *et al.*[29] have highlighted the production of CH_4, during the process of carbon burial by methanogenic archaea in the anoxic sediments of mangroves. They have estimated that the CH_4 evasion rate (96.5–1049.8 mmol m^{-2} day^{-1}) has the potential to partially offset the blue carbon burial rates in mangrove sediments on an average by 20%, and emphasized the need for considering the mangrove sediments and water CH_4 emissions for future blue-carbon assessments. However, at present, the available information on CH_4 emission of global mangroves is scarce[29]. Despite the discrepancy in the estimates, certainly soil carbon stock per unit area of mangrove forest is higher than the other forest ecosystems in all the studies. However, the restricted global distribution and severe lack of country-wise data testify the role of mangroves in climate change mitigation as most effective at the national level rather than on a global scale[30]. Increasing soil carbon stocks and protecting carbon-rich soils are crucial for achieving the Paris climate targets[31]. So, it is vital to estimate and understand the spatial distribution of mangrove soil carbon stocks across mangrove nations to recognize the actual climate mitigation potential of this ecosystem so as to strengthen the conservation measures.

Indeed, the potential role of mangroves as carbon sinks can be known only when the rate of mangrove destruction and degradation by habitat conversion is halted significantly. Despite the three decades of conservation and rehabilitation efforts, land conversion for aquaculture and agriculture remains a major threat and mangroves experience an annual loss of 0.16–0.39% (ref. 32). In addition, increasing anthropogenic activities[33–35] and frequency of extreme natural calamities[36–40] caused by global climate change also threaten the survival and productivity of mangroves. According to a recent estimate[13], the annual soil carbon emission by mangrove degradation is 2.0–8.1 Tg C yr^{-1} and during the period between 2000 and 2015, due to land-use conversion, mangrove soils have witnessed the loss of 30.4–122 Tg C. More private land acquisition (which includes mangroves), legal protection and expanded mangrove rehabilitation by mono-specific plantation are the three widely used measures for mangrove management. In addition, recently, Lewis *et al.*[41] have proposed the fourth parallel approach, viz. early detection and pre-emptive rehabilitation, to prevent the complete loss of plant community structure and ecological function by long-term monitoring of changes in hydrological and ecological status of mangroves. However, globally, current management and policy-making efforts have not been fully successful in ensuring the conservation and sustainable use of mangrove resources[42]. If the current rate of degradation continues, the world may become devoid of mangroves in the 22nd century[43]. If all of the world's mangrove forests are destroyed and assuming that 95% of all mangrove carbon is oxidized to CO_2, the loss would be 30.2 Pg CO_2 equivalents, which is equal to 6.5 years of carbon emissions from the global forest loss[2,44]. So, as of now, it is evident that we are missing the carbon storage potential of mangroves due to want of sufficient data, discrepancy in the available data, lesser success of conservation endeavours and increasing rate of mangrove degradation. To sustain the ecosystem services of mangroves, country-wise, site-specific, long-term ecosystem-based conservation and management measures should be taken as an immediate step along with the existing conservation endeavours, suitably strengthened and amended site-wise, if needed.

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