Mangrove blue carbon strategies for climate change mitigation are most effective at the national scale

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Carbon fixed by vegetated coastal ecosystems (blue carbon) can mitigate anthropogenic CO2 emissions, though its effectiveness differs with the spatial scale of interest. A literature review compiling carbon sequestration rates within key ecosystems confirms that blue carbon ecosystems are the most efficient natural carbon sinks at the plot scale, though some overlooked biogeochemical processes may lead to overestimation. Moreover, the limited spatial extent of coastal habitats minimizes their potential at the global scale, only buffering 0.42% of the global fossil fuel carbon emissions in 2014. Still, blue carbon plays a role for countries with moderate fossil fuel emissions and extensive coastlines. In 2014, mangroves mitigated greater than 1% of national fossil fuel emissions for countries such as Bangladesh, Colombia and Nigeria. Considering that the Paris Agreement is based on nationally determined contributions, we propose that mangrove blue carbon may contribute to climate change mitigation at this scale in some instances alongside other blue carbon ecosystems.

1. Introduction

Parties ratifying the Paris Agreement have pledged to ‘achieve a balance between anthropogenic emissions by sources and removals by sinks by 2100’ [1]. Considering the high competition between land-uses and the lag time before economies become fossil fuel-independent, conservation and expansion of ecosystems with high carbon sequestration potential are one option to contribute to this commitment. In this study, we defined carbon sequestration as the ability of an ecosystem to assimilate and store in biomass, sediments or water more carbon than what is being released to the atmosphere through respiration.

Blue carbon ecosystems (saltmarshes, seagrasses and mangroves) are characterized by their disproportionately large organic carbon (OC) storage, even at the mature stage, primarily within sediments over millennia [2]. As such, blue carbon has received international attention as a climate change mitigation tool owing to its high carbon sequestration and storage capacity at the plot scale [3]. However, a complete assessment of blue carbon potential requires to assess their contribution at larger scales to align with policy-makers’ requirements.

In this study, we ask: ‘at what scale is blue carbon a suitable climate change mitigation tool?’ We investigate this by (i) verifying whether blue carbon ecosystems are the highest carbon sinks at the plot scale; (ii) determining the contribution of blue carbon at the global scale; and (iii) considering blue carbon at the national scale, where it may be relevant in terms of nationally determined contributions (NDC) towards the Paris Agreement.
2. Methods

A literature review was conducted to compile estimates of (i) carbon sequestration and (ii) areal extent of 14 terrestrial and coastal ecosystems, adapted from the Ecoregions of the World [4]. A literature search using the Scopus and Web of Science database was conducted using two search strings: (i) ecosystem name AND 'carbon' AND 'review' AND ('sequestration' OR 'burial' OR 'accumulation' OR 'storage' OR 'sink' OR 'pool'); and (ii) ecosystem name AND ('global cover' OR 'global map' OR 'atlas'), sorted by relevancy. Papers were critically appraised to only select studies which provided estimates from multiple sites or at the global scale. Reviews of reviews (e.g. [3]) were excluded. Carbon sequestration estimates and uncertainties were extracted at the plot (gC m⁻² yr⁻¹) or global scale (TgC yr⁻¹) based on the unit available and were converted using the areal extent (km²) estimates. A sensitivity analysis which integrated the varying estimates between papers and the range of values from the two variables (carbon sequestration and areal extent) was conducted. Values are presented as the mean ± min max, according to the sensitivity analysis.

Owing to limited spatial data available for saltmarshes and seagrasses, national fossil fuel emissions were compared only to national mangrove carbon sequestration using the following equation:

\[
\text{mangroves mitigation potential (%) } = \frac{S_{\text{mangroves}} - E_{\text{mangroves}}}{E_{\text{fossil fuel}}} \times 100,
\]

where \(S_{\text{mangroves}}\) is the national carbon sequestration from mangroves based on the average plot estimate (gC m⁻² yr⁻¹) [5,6] multiplied by the national mangrove areal extent (km²) [7]; \(E_{\text{mangroves}}\) is the national carbon emissions from the national carbon emissions (TgC yr⁻¹) from mangrove deforestation consistently estimated between countries [7,8]; \(E_{\text{fossil fuel}}\) is the national fossil fuel emissions (TgC yr⁻¹) [9]. This assessment was made for 2014 as it is the latest year with full national fossil fuel and mangrove area estimates. Further details regarding methods are provided in the electronic supplementary material.

3. Results and discussion

(a) Blue carbon is the highest carbon sink at the plot scale

Blue carbon ecosystems are the highest carbon sinks per plot (figure 1a). Carbon sequestration in saltmarshes is on average 242 ± 26 gC m⁻² yr⁻¹ [10], followed by mangroves (168 ± 36 gC m⁻² yr⁻¹ [5,6]) and seagrasses (83 gC m⁻² yr⁻¹ [2]). Tropical, boreal and temperate forests, even at their mature stage, are also important carbon sinks per plot with 40 ± 20 gC m⁻² yr⁻¹, 44 ± 7 gC m⁻² yr⁻¹ and 22.5 ± 12 gC m⁻² yr⁻¹, respectively (figure 1a) [11,12]. Full data and references are presented in the electronic supplementary material, table S1.
In comparison to terrestrial ecosystems, blue carbon ecosystems disproportionally accumulate OC because of their specific sediment conditions and land–ocean interface position [2]. Blue carbon is predominantly stored in waterlogged sediment rather than in biomass (figure 2), which prevents risks of sudden carbon loss, particularly from fire. Moreover, this allows a steady carbon accumulation even when the ecosystem reaches its mature stage. Still, sequestration could be overestimated as some previously overlooked processes suggest carbon losses. For instance, blue carbon sequestration is generally estimated from sediment accumulation and OC content [5], which assumes that these two parameters are stable over time. However, sediment mixing via bioturbation, OC remineralization and porewater discharge (figure 2) continuously deteriorate OC stocks [21,22]. Blue carbon may also be overestimated because some allochthonous OC trapped is refractory and not subject to remineralization [23], not reflecting additional burial. Finally, blue carbon often emphasizes OC sequestration, though dissolved inorganic carbon is also important as it can be directly re-emitted to the atmosphere as CO₂ ([6]; figure 2) and can influence calcium carbonate cycling, and consequently the coastal carbon budget in an unclear direction [24]. Thus, future blue carbon budgets at the plot scale should include these variables to constrain carbon sequestration estimates.

(b) Blue carbon accounts for less than 2% of the land carbon sink

Although blue carbon ecosystems are the highest natural carbon sinks at the plot scale, their contribution is limited at the global scale (figure 1c) because they are restrained to low-energy coastlines. Globally, 30.7% of the atmospheric CO₂ assimilated by terrestrial ecosystems is absorbed by tropical forests, owing to their extensive area (figure 1b) and relatively high rates of carbon sequestration. This represents a potential storage of 915 ± 460 TgC yr⁻¹. In comparison, seagrasses, mangroves and saltmarshes store only 14.7 ± 5.1 TgC yr⁻¹, 13.7 ± 11 TgC yr⁻¹ and 10.1 ± 2.85 TgC yr⁻¹, respectively (figure 1). globally, blue carbon represents approximately 1.3% (38.5 ± 19 TgC yr⁻¹) of land sequestration while covering less than 0.4% of the land. This makes blue carbon ecosystems disproportionately efficient carbon sinks (notwithstanding our generally poor knowledge of their extent [25]), though they remain of limited significance globally. For example, blue carbon only mitigated 0.42% of global fossil fuel CO₂ emission in 2014, estimated at 9264 TgC yr⁻¹ [9].

(c) Blue carbon can contribute to the Paris agreement at the national scale

While blue carbon ecosystems are less relevant globally, they may be influential at national scales. Our conservative estimation of national mangrove sequestration potential (table 1) shows that they can contribute to mitigating emissions if mangrove deforestation remains low. For instance, mangroves buffered greater than 1% of the national carbon emissions for countries such as Nigeria (top 40th fossil fuel emitter), Colombia (43rd), Bangladesh, (45th), Ecuador (62nd) and Cuba (70th). Conversely, in countries with high mangrove deforestation rates, the carbon storage potential of remaining undisturbed mangroves was less than the carbon emissions generated by mangrove deforestation (e.g. Malaysia, Myanmar; table 1). These countries may not contribute to emissions mitigation right now but show huge potential if conservation can prevent further emissions from their loss and encourage future carbon sequestration through restoration [8]. Hence, blue carbon mitigation at the national scale is well aligned with the Paris Agreement and associated NDCs for some nations.

(d) Severe data limitations in assessing the role of blue carbon

Data limitations are inevitable, considering the multiple scales used in this study. These limitations highlight the
Table 1. Comparative analysis of carbon sequestration from mangroves ($S_{\text{mangroves}}$), carbon emissions from mangrove deforestation ($E_{\text{mangroves}}$), and carbon emissions from fossil fuels ($E_{\text{fossil fuel}}$) at the national scale in 2014 for the top 20 mangrove-holding countries. (Data in brackets present the min and max values from our sensitivity analysis.)

<table>
<thead>
<tr>
<th>countries</th>
<th>mangrove surface area in 2014 (km²)</th>
<th>$S_{\text{mangroves}}$ in 2014 (TgC yr⁻¹)</th>
<th>mangrove surface area loss between 2013 to 2014 (km² yr⁻¹)</th>
<th>$E_{\text{mangroves}}$ and 2014 ⁴⁻⁻⁴⁻⁻⁻ (TgC yr⁻¹)</th>
<th>$S_{\text{mangroves}} - E_{\text{mangroves}}$ (TgC yr⁻¹)</th>
<th>$E_{\text{fossil fuel}}$ in 2014 (TgC yr⁻¹)</th>
<th>mangroves mitigation potential (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indonesia</td>
<td>23 143</td>
<td>3.77 [2.85; 4.49]</td>
<td>59.72</td>
<td>3.26</td>
<td>0.51 [−0.42; 1.23]</td>
<td>126.6</td>
<td>0.4 [−0.3; 1.0]</td>
</tr>
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<td>Brazil</td>
<td>7663</td>
<td>1.25 [0.94; 1.49]</td>
<td>3.99</td>
<td>0.20</td>
<td>1.05 [0.74; 1.28]</td>
<td>144.5</td>
<td>0.7 [0.5; 0.9]</td>
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<td>Malaysia</td>
<td>4691</td>
<td>0.76 [0.58; 0.91]</td>
<td>19.90</td>
<td>1.09</td>
<td>−0.33 [−0.51; −0.18]</td>
<td>66.22</td>
<td>−0.5 [−0.8; −0.3]</td>
</tr>
<tr>
<td>Papua N.G.</td>
<td>4169</td>
<td>0.68 [0.51; 0.81]</td>
<td>1.55</td>
<td>0.08</td>
<td>0.60 [0.48; 0.73]</td>
<td>1.72</td>
<td>34.9 [25.0; 42.4]</td>
</tr>
<tr>
<td>Australia</td>
<td>3314</td>
<td>0.54 [0.41; 0.64]</td>
<td>0.85</td>
<td>0.04</td>
<td>0.50 [0.37; 0.60]</td>
<td>98.52</td>
<td>0.5 [0.4; 0.6]</td>
</tr>
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<td>Mexico</td>
<td>2985</td>
<td>0.49 [0.37; 0.58]</td>
<td>2.55</td>
<td>0.13</td>
<td>0.36 [0.24; 0.45]</td>
<td>131.0</td>
<td>0.3 [0.2; 0.3]</td>
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<tr>
<td>Niger</td>
<td>2653</td>
<td>0.43 [0.33; 0.51]</td>
<td>0.26</td>
<td>0.01</td>
<td>0.42 [0.31; 0.50]</td>
<td>26.26</td>
<td>1.6 [1.2; 1.9]</td>
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<tr>
<td>Myanmar</td>
<td>2508</td>
<td>0.41 [0.31; 0.49]</td>
<td>21.24</td>
<td>0.99</td>
<td>−0.58 [−0.68; −0.50]</td>
<td>5.90</td>
<td>−9.8 [−11.5; −8.5]</td>
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<td>Venezuela</td>
<td>2401</td>
<td>0.39 [0.30; 0.47]</td>
<td>0.89</td>
<td>0.04</td>
<td>0.35 [0.25; 0.42]</td>
<td>50.51</td>
<td>0.7 [0.5; 0.8]</td>
</tr>
<tr>
<td>Philippines</td>
<td>2060</td>
<td>0.34 [0.25; 0.40]</td>
<td>2.18</td>
<td>0.11</td>
<td>0.23 [0.14; 0.29]</td>
<td>28.81</td>
<td>0.8 [0.5; 1.0]</td>
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<tr>
<td>Thailand</td>
<td>1876</td>
<td>0.31 [0.23; 0.36]</td>
<td>4.19</td>
<td>0.20</td>
<td>0.10 [0.03; 0.16]</td>
<td>86.23</td>
<td>0.1 [0.0; 0.2]</td>
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<td>Colombia</td>
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<td>0.27 [0.21; 0.32]</td>
<td>0.18</td>
<td>0.01</td>
<td>0.26 [0.20; 0.32]</td>
<td>22.93</td>
<td>1.1 [0.9; 1.4]</td>
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<tr>
<td>Cuba</td>
<td>1624</td>
<td>0.26 [0.20; 0.32]</td>
<td>2.56</td>
<td>0.13</td>
<td>0.14 [0.07; 0.19]</td>
<td>9.50</td>
<td>1.5 [0.7; 2.0]</td>
</tr>
<tr>
<td>USA</td>
<td>1553</td>
<td>0.25 [0.19; 0.30]</td>
<td>4.04</td>
<td>0.19</td>
<td>0.06 [0.00; 0.11]</td>
<td>1432</td>
<td>0.0 [0.0; 0.0]</td>
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<tr>
<td>Bangladesh</td>
<td>1773</td>
<td>0.29 [0.22; 0.34]</td>
<td>0.08</td>
<td>0.00</td>
<td>0.29 [0.21; 0.34]</td>
<td>19.96</td>
<td>1.5 [1.1; 1.7]</td>
</tr>
<tr>
<td>Panama</td>
<td>1323</td>
<td>0.22 [0.16; 0.26]</td>
<td>0.35</td>
<td>0.02</td>
<td>0.20 [0.14; 0.24]</td>
<td>2.40</td>
<td>8.3 [5.8; 10.0]</td>
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<td>Mozambique</td>
<td>1233</td>
<td>0.20 [0.15; 0.24]</td>
<td>0.22</td>
<td>0.02</td>
<td>0.19 [0.14; 0.23]</td>
<td>2.30</td>
<td>8.3 [6.1; 10.0]</td>
</tr>
<tr>
<td>Cameroon</td>
<td>1112</td>
<td>0.18 [0.14; 0.22]</td>
<td>0.45</td>
<td>0.02</td>
<td>0.16 [0.11; 0.19]</td>
<td>1.91</td>
<td>8.4 [5.8; 9.9]</td>
</tr>
<tr>
<td>Gabon</td>
<td>1081</td>
<td>0.18 [0.13; 0.21]</td>
<td>0.37</td>
<td>0.02</td>
<td>0.16 [0.11; 0.19]</td>
<td>1.42</td>
<td>11.3 [7.7; 13.4]</td>
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<tr>
<td>Ecuador</td>
<td>935</td>
<td>0.15 [0.12; 0.18]</td>
<td>0.15</td>
<td>0.01</td>
<td>0.14 [0.11; 0.17]</td>
<td>11.98</td>
<td>1.2 [0.9; 1.4]</td>
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<tr>
<td>total top 20</td>
<td>46 618</td>
<td>11.4 [8.6; 13.5]</td>
<td>125.7</td>
<td>6.58</td>
<td>4.79 [2.00; 6.96]</td>
<td>761.7</td>
<td>0.62 [0.26; 0.91]</td>
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<tr>
<td>global</td>
<td>81 484</td>
<td>13.3 [10.0; 15.8]</td>
<td>140.4</td>
<td>7.22</td>
<td>6.71 [3.45; 9.23]</td>
<td>9264</td>
<td>0.07 [0.03; 0.10]</td>
</tr>
</tbody>
</table>

Data from [7].

Data from [8].

Data from [9].
importance of being conservative when estimating carbon sequestration. At the plot scale, it is challenging to provide a representative average carbon sequestration rate as we and other studies [3,6] have done. High variability exists within each ecosystem as vegetation type or density, geomorphology, hydrology and climate all influence primary productivity and carbon sequestration. Similarly, sediment carbon burial studies are often based on site-specific assessments, which may not be fully representative of the studied ecosystem. Still, all terrestrial and coastal ecosystems will have these issues. Thus, large-scale studies can still show relative differences in carbon sequestration between ecosystems.

Estimates of national and global carbon sequestration are hindered by poor estimates of ecosystem extent. Determining ecosystem extent remains a challenge because of technological constraints and boundaries ambiguity [19], particularly for saltmarshes and seagrasses [25]. Such knowledge gaps have implications for estimates of ecosystem service provision and change, as seen in mangroves [26]. We considered this issue by using conservative values in conjunction with a sensitivity analysis for our global estimates. Despite these limitations, national and global scale studies help identify research gaps and policy recommendations. Consistent protocols on carbon dynamics should be developed and applied within and between ecosystems, while surface cover must be better constrained, especially for seagrasses and saltmarshes.

4. Conclusion

Blue carbon has received international attention for its potential role in mitigating CO₂ emissions. Our assessment suggests that blue carbon sequestration is of limited importance globally, but can play a role in countries with extensive coastlines if coupled with complementary mitigation schemes and reductions in deforestation. Conserving blue carbon ecosystems will maintain carbon sequestration into the future and prevent emissions from land-use change. However, severe data limitations need to be addressed if we are to robustly demonstrate the role of blue carbon in meeting the targets of the Paris Agreement.

Data accessibility. Additional data and detailed methods are available as the electronic supplementary material.

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