

Blue carbon as a natural climate solution

Macreadie, Peter I.; Costa, Micheli D.P.; Atwood, Trisha T.; Friess, Daniel A.; Kelleway, Jeffrey J.; Kennedy, Hilary; Lovelock, Catherine E.; Serrano, Oscar; Duarte, C.M.

Nature Reviews Earth and Environment

DOI:
[10.1038/s43017-021-00224-1](https://doi.org/10.1038/s43017-021-00224-1)

Published: 01/12/2021

Peer reviewed version

[Cyswllt i'r cyhoeddiad / Link to publication](#)

Dyfyniad o'r fersiwn a gyhoeddwyd / Citation for published version (APA):
Macreadie, P. I., Costa, M. D. P., Atwood, T. T., Friess, D. A., Kelleway, J. J., Kennedy, H., Lovelock, C. E., Serrano, O., & Duarte, C. M. (2021). Blue carbon as a natural climate solution. *Nature Reviews Earth and Environment*, 2, 826-839. <https://doi.org/10.1038/s43017-021-00224-1>

Hawliau Cyffredinol / General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal ?

Take down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Potential of blue carbon as a natural climate solution

Peter I. Macreadie^{1*}, Micheli D. P. Costa^{1,2}, Trisha B. Atwood³, Daniel A. Friess^{4,5}, Jeffrey J. Kelleway⁶, Hilary Kennedy⁷, Catherine E. Lovelock², Oscar Serrano^{8,9} & Carlos M. Duarte¹⁰

¹ Centre for Integrative Ecology, School of Life and Environmental Sciences, Deakin University, Burwood Campus, Burwood, VIC 3125, Australia

² School of Biological Sciences, The University of Queensland, St. Lucia, QLD 4072, Australia

³ Department of Watershed Sciences and Ecology Center, Utah State University, Logan, UT 84322-5210, USA

⁴ Department of Geography, National University of Singapore, 1 Arts Link, Singapore 117570, Singapore

⁵ Centre for Nature-based Climate Solutions, National University of Singapore, 16 Science Drive 4, Singapore 117558, Singapore

⁶ School of Earth, Atmospheric and Life Sciences and GeoQuEST Research Centre, University of Wollongong, Wollongong, NSW 2522, Australia

⁷ School of Ocean Sciences, Bangor University, Menai bridge, Bangor LL59 5AB, UK

⁸ School of Science, Centre for Marine Ecosystems Research, Edith Cowan University, 270 Joondalup Drive, Joondalup, WA 6027, Australia

⁹ Centro de Estudios Avanzados de Blanes, Consejo Superior de Investigaciones Científicas, Blanes, Spain

¹⁰ King Abdullah University of Science and Technology, Red Sea Research Center and Computational Bioscience Research Center, Thuwal, Saudi Arabia

- 26 * Corresponding author:
27 Peter I. Macreadie
28 p.macreadie@deakin.edu.au

29 **Key Points**

- 30 ● Blue carbon ecosystems ('BCE' - mangrove forests, tidal marshes, seagrass meadows)
31 are gaining international recognition as a natural climate solution (NCS) to help meet
32 climate change mitigation and adaptation targets.
- 33 ● BCE potentially have a ~36-185 million hectares global distribution (~the size of
34 Mexico) and store 33 billion tonnes of carbon, while providing important adaptation
35 co-benefits (such as coastal protection, fisheries/biodiversity enhancement).
- 36 ● Protecting existing BCE could avoid emissions of 304 (141-466) Tg CO_{2e} pa and
37 large-scale restoration could remove an extra 841 (621-1,064) Tg CO_{2e} pa by 2030,
38 which is equivalent to ~3% of annual global greenhouse gas emissions.
- 39 ● The potential contribution that blue carbon can make to nature-based solutions in the
40 future will depend on societal actions. Restoring BCE at scale should be a key focus
41 of the UN Decade of Ecosystem Restoration (2021-2030), with opportunities for
42 developing robust information on the scope of small-scale restoration projects at the
43 global or country scale.
- 44 ● Emerging blue carbon markets should aim at incorporating the value of co-benefits
45 into financial frameworks (including via impact investment, blended finance) to assist
46 with the investments required for restoration and conservation.

47

48 **Abstract**

49 Nature climate solutions (NCS) recognise the importance of conservation and restoration of
50 ecosystems for climate change mitigation and adaptation. A global focus on blue carbon
51 ecosystems ('BCE' - including mangrove forests, seagrass meadows, and tidal marshes) as
52 NCS arises because of their capacity for rapid carbon sequestration, long-term storage,
53 avoiding emissions of disturbed ecosystems, and valuable adaptation co-benefits, such as
54 coastal protection, and fisheries enhancement. BCE are calculated to store >30,000 Tg C
55 globally across approximately 185 M ha, with conservation of BCE potentially avoiding
56 emissions of 304 (141-466) Tg CO₂e pa, while large-scale restoration could drawdown an
57 extra 841 (621-1,064) Tg CO₂e pa - collectively amounting to ~3% of global emissions. Most
58 opportunities relate to mangroves, while opportunities from NCS approaches based on tidal
59 marsh and seagrass require better understanding of their global distribution, losses and
60 recovery. It is unlikely that destruction of BCE will come to a full stop, or that all destroyed
61 BCE can be restored; however, innovative engineering solutions and strategic planning for
62 coastal protection from sea level rise with green infrastructure offer opportunities to create or
63 restore BCE. Investments required to fully restore BCE can exceed returns from carbon
64 market financing, but gaps could be met by monetizing and financing for co-benefits,
65 particularly coastal protection. We conclude that BCE are a cost-effective and scalable option
66 for climate change mitigation and adaptation while enhancing human wellbeing.

67

68 **Keywords:** blue carbon, NDCs, climate change, restoration, ecosystem service, wetland,
69 mangrove, seagrass, tidal marsh, protection

70

71

72 **Introduction**

73 Climate change mitigation is a grand societal challenge focused on achieving the goals of the
74 Paris Agreement to limit the global average temperature to below 2°C, preferable to 1.5°C,
75 above pre-industrial levels (Article 2, Paris Agreement, 2015). To achieve this target,
76 signatory countries must develop a national climate plan, also called ‘Nationally Determined
77 Contributions’, aiming for long-term climate change mitigation and adaptation . These
78 actions include efforts to reduce emissions as well as efforts to remove excess greenhouse
79 gasses (GHGs) from the atmosphere. In this context, nature climate solutions (NCS ^{1,2}) have
80 emerged as a preferred option to achieve both these goals. NCS, including carbon
81 sequestration through ecosystem management and reforestation, have the potential to be more
82 cost-effective and scalable than technological options ^{3,4}, such as direct air capture, geological
83 sequestration and biochar production. Many of these technological options have yet to be
84 deployed at large scale, and face significant economic, social and environmental barriers ⁵.

85 NCS were originally based overwhelmingly on terrestrial ecosystems (referred to as
86 ‘Green Carbon’), with coastal and ocean-based opportunities being largely ignored ⁶.
87 However, over the past decade research has shown the globally relevant role of coastal
88 vegetated ecosystems in carbon drawdown, broadly referred to as ‘Blue Carbon’ (to denote a
89 link to coastal ecosystems) (Figure 1). Blue carbon ecosystems (‘BCE’) refers to coastal
90 habitats (particularly seagrass meadows, mangrove forests, tidal marshes, and potentially
91 seaweed beds) that contribute significantly to carbon drawdown due to their intense
92 greenhouse gas removal, their long-term permanence of carbon removed and the large carbon
93 stocks accumulated, which support large potential emissions when disturbed ⁷ (Figure 1).
94 Blue carbon strategies propose the conservation and restoration of these ecosystems as a
95 strategy to mitigate and adapt to climate change ⁸.

96 BCE are widespread, highly productive habitats that rank among the most valuable
97 ecosystems on Earth. They support diverse marine and coastal communities across multiple
98 trophic levels by providing key functions such as food and habitat provision while supporting
99 human wellbeing, including artisanal fisheries, nutrient cycling and coastal protection against
100 erosion and sea level rise, which influence the livelihoods of millions⁹⁻¹¹. BCE occupy
101 approximately 0.5% of the sea floor, but contribute > 50% of global carbon burial in the
102 oceans¹²⁻¹⁴. Their area stretches as a thin ribbon along the world's shorelines, from the upper
103 intertidal zone down to about 50 m depth, depending on underwater light penetration. The
104 high carbon sequestration rates of BCE derive from three main reasons; their ability to
105 produce, capture and preserve carbon. They are highly productive ecosystems that produce
106 large amounts of carbon ('autochthonous carbon'), and their position at the land-sea interface
107 and high trapping capacity allows them to accrete sediment and accumulate carbon produced
108 by other ecosystems ('allochthonous carbon')⁸. They have the ability to accumulate and
109 preserve this carbon in forms that resist microbial attack, which is due to a variety of reasons,
110 but mainly their water-logged, anaerobic conditions that limit decomposition¹⁵. Although
111 BCE are exposed to natural disturbances such as cyclones and flooding, the general absence
112 of fires in BCE provides more confidence on the permanence of carbon stores over
113 climatically-relevant centennial to millennial timescales compared to terrestrial habitats^{8,16}.
114 Unfortunately, about 50% of BCE global extent has been lost across the globe⁸, leading to
115 emissions of greenhouse gases from the carbon stores they supported¹⁷. Hence, halting the
116 loss of BCE, and reversing losses through restoration will help avoid emissions from
117 disturbed BCE and will restore their carbon sequestration role⁶.

118 There is ample scope for both conservation and restoration of BCE, as only about
119 1.5% of the global extent of BCE are included in marine protected areas¹⁸. Restoration of
120 BCE at the scale required to recover much of the lost habitat area is potentially feasible for

121 mangroves and tidal marshes, but challenging for seagrass meadows ¹⁹, with a 10-fold growth
122 in the number of documented restoration projects of BCE since the turn of the century ²⁰. The
123 restoration of about 1,487 km² of mangroves in the Mekong Delta destroyed by the US Air
124 Force during the Vietnam war ²¹ remains one of the largest ecosystem restoration projects
125 ever undertaken ²⁰. The planted forest in Can Gio Mangrove Forestry Park, has accumulated
126 152 Tg of CO₂e, greater than the total C emissions of Vietnam for the year 2013 (130 Tg
127 CO₂e) across the 447 km² of mangroves restored at this site, suggesting the total Mekong
128 mangrove restoration area to have removed an equivalent to about three-times Vietnam's
129 2013 greenhouse gas emissions ²²..

130 An important aspect of NCS that differs from other, more technological climate
131 change mitigation solutions is that in addition to sequestering carbon they also generate a
132 range of other ecosystem services that contribute to local human wellbeing (Figure 2). These
133 ecosystem services include nutrient removal ²³, fisheries enhancement ²⁴ and coastal
134 protection ²⁵ (Figure 2). For example, the establishment of mangrove protected areas has been
135 associated with long-term gains in fisheries production ²⁶. Knowledge of ecosystem services,
136 such as evidence of protection from the 2004 Indian Ocean Tsunami ²⁷, has driven massive
137 mangrove planting programs in South and Southeast Asia. Mangroves are also increasingly
138 valued for their contribution to protecting communities from the impacts of tropical storms
139 and cyclones ^{28,29}. The full suite of functions and services that BCE provide alongside carbon
140 sequestration increases the adaptive capacity for communities to cope with natural hazards
141 and climate change, while helping achieve multiple UN Sustainable Development Goals. As
142 such, the conservation and restoration of BCE can be considered a win-win solution that
143 contributes to both climate change mitigation and adaptation, while enhancing coastal
144 livelihoods ³⁰, thereby being highly valued by coastal communities ³¹.

145 In this review, we discuss the global potential of blue carbon contribution to NCS to
146 climate change mitigation and adaptation, focusing on the opportunities of large-scale
147 restoration. We begin by exploring the global estimates of blue carbon stocks and outlining
148 the potential of large-scale restoration of these ecosystems, and discuss the main constraints
149 and feasibility. We subsequently describe the role of BCE on climate change mitigation and
150 adaptation and their co-benefits, and how this information could guide future efforts for
151 restoration strategies and plans for climate change mitigation and adaptation. Finally, we
152 review the role of BCE in helping countries achieve their international emission reduction
153 targets and identify future steps to improve blue carbon estimates on distribution extent,
154 stocks, sequestration, and mitigation potential.

155

156 **Global blue carbon stocks**

157 Robust information on geographical extent and estimates of carbon storage are key to
158 including BCE in national and global climate mitigation accounting. Current efforts to map
159 BCE show that they encompass ~36 - 185 million hectares (due to large uncertainties in the
160 distribution of seagrass meadows^{32,33} and tidal marshes³⁴) within the world's coastal zone
161^{32,34,35}. One major caveat associated with the global estimates provided by our study is that all
162 data supporting this review have been extracted from existing literature, which in most cases
163 did not provide error propagation or uncertainty estimates. To overcome this, we estimated
164 upper and lower interval bounds based on available information (i.e., spatial data or country-
165 level estimates; further details are described in the SI) for soil and biomass carbon stocks
166 (Table S1). Based on available information, BCE could potentially hold ~8,970 – 32, 650 Tg
167 C in their soils and biomass. A full description of existing datasets and those used in this
168 review is available on the Supplementary Material.

169 Mangrove forests occur across ~13.7 million hectares within tropical, subtropical and
170 warm temperate coastal zones³⁵ (Figure 3) and are the best studied (in terms of publication
171 number) and mapped BCE. Mangrove forests have been the focus of global and regional
172 studies that helped scientists to better understand the ecology, distribution, co-benefits and
173 climate change impacts in the ecosystem³⁵⁻⁴⁶. Mangrove forests potentially hold ~70% of
174 their carbon in the soil³⁷, with global estimates ranging from 1,900 Tg C⁴² to 8,400 Tg C⁴¹
175 for the top meter of soil based on previous studies (Table S1). Considering that mangrove
176 forests also store carbon within their living biomass, carbon stocks in this pool could vary
177 from 1,230 Tg C³⁷ to 3,900 Tg C⁴⁷. However, it is important to highlight that different
178 carbon pools have different turnover times with fresh plant litter rapidly decomposing over
179 years, stabilized soil organic matter persisting for thousands of years to centuries, and poorly
180 defined intermediate carbon pools with turnover times of years to centuries^{13,48}. Here, we
181 used the data available on Hutchison et al.⁴⁴ and Simard et al.⁴⁷ for biomass stocks, and
182 Atwood et al.⁴⁵ and Sanderman et al.³⁸ for soil stocks, as our lower and upper bound
183 estimates, respectively (Supplementary Material Methods, Tables S1-S3). In this case,
184 Indonesia (soil ranging from ~830-1,780 Tg C; biomass ranging from ~570-1040 Tg C),
185 Brazil (soil ranging from ~235-514 Tg C; biomass ranging from ~98-313 Tg C), Australia
186 (soil ranging from ~83-464 Tg C; biomass ranging from ~113-115 Tg C) and Malaysia
187 (ranging from ~200-365 Tg C; biomass ranging from ~95-255 Tg C) accounted for ~40-50%
188 of global soil and biomass carbon stocks within mangrove forests, regardless of the dataset
189 used to estimate carbon stocks (Tables S2-S3), with Indonesia alone holding more than 20%
190 of this total (Figure 4, Tables S2-S3). It is estimated that mangrove soils alone have lost 30.4
191 – 122 Tg C due to land-use changes that occurred between 2000 and 2015, with Indonesia,
192 Malaysia and Myanmar contributing to over 75% of these losses³⁸.

193 Recent efforts have focussed on understanding the distribution of blue carbon stocks
194 in mangrove forests, but seagrass meadows and tidal marshes still lack robust and spatial-
195 explicit estimates of soil carbon within their geographical extents. However, it is important to
196 highlight recent efforts to map the habitat extent and soil carbon at local and regional scales
197 for seagrass⁴⁹⁻⁵¹ and tidal marshes^{34,42}. In addition, the Coastal Carbon Research Network,
198 which has been created by the Smithsonian Environmental Research Centre in 2018, is
199 developing publicly available interactive maps of existing soil core data⁵².

200 Considering their mapped^{33,53} and potential³² distribution, seagrass meadows would
201 potentially cover 16 - 165 million ha globally, with these estimates derived from aggregating
202 mapped seagrass areas and modelling the ocean area suitable to support seagrass growth,
203 respectively, resulting in an estimated soil carbon stock varying from ~1,732 - 21,000 Tg C
204 (Supplementary Material). Such order-of-magnitude range is associated with the large
205 uncertainties in seagrass mapping, the difference in methods used in each study and the
206 variability between individual seagrass beds. For example, McKenzie et al.³³ and UNEP-
207 WCMC-Short⁵³ have compiled existing datasets of mapped seagrass meadows globally to
208 estimate and map seagrass extent, respectively, with McKenzie et al.³³ estimating with low
209 confidence that seagrass meadows could occupy 27 million ha³³. On the other hand,
210 Jayathilake & Costello³² used global occurrence records of seagrass and environmental
211 variables to model the potential distribution of seagrass meadows globally at 165 million ha.
212 Despite high variation on numbers, Australia, Indonesia and the United States of America are
213 within the countries with the largest distribution of seagrass meadows, regardless of the
214 dataset used in this review (Table S4).

215 Currently, we still face a great uncertainty on seagrass mapping, with Jayathilake &
216 Costello³² and Howard et al.⁵⁴ highlighting the lack of data on the eastern and western coast
217 of South America, Africa, Indian Ocean and Indo-Pacific region, and we are only beginning

218 to discover vast meadows of deep-water seagrasses (depths > 50 m)⁵⁵⁻⁵⁸. If considering the
219 upper and lower bounds for seagrass distribution extent (Tables S1 and S4)^{32,53} and the
220 global estimates of sediment carbon stocks available in Atwood et al.⁵¹, we estimate that
221 carbon stocks could vary from ~3,760 Tg C to 21,000 Tg C with Australia (~37-2,320 Tg C),
222 United States of America (~6-1,700 Tg C) and Indonesia (~41-1,320 Tg C) accounting for
223 ~2-25% of the total carbon stocks within seagrass meadows (Figure 4, Supplementary
224 Material). Australia is one of the few countries in the world that has a full inventory of carbon
225 stocks within BCE, including seagrass meadows, which shows that this ecosystem would
226 hold ~762-1051 Tg C⁵⁹. Using Australia as an example, we can see that using Jayathilake &
227 Costello³² and UNEP-WCMC-Short⁵³ seagrass extent layers have some limitations that
228 could potentially underestimate and/or overestimate carbon inventories. This highlights that
229 global maps and estimates are a first step towards estimating blue carbon stocks, however,
230 countries that invest on BCE mapping and carbon sampling will have a better evaluation of
231 its carbon storage capacity, required to support policy actions.

232 In contrast to mangrove forests, global distribution maps of tidal marshes remain
233 incomplete. Previous studies suggested that the global area of tidal marshes was in the range
234 of 2.2-40 million ha^{12,60}. The most recent and comprehensive study to date, estimates ~5.5
235 million ha across forty-three countries, however, this estimate is likely conservative and
236 incomplete³⁴. For example, there are known areas of tidal marshes in Canada, Russia, South
237 America and Africa that are not reflected on current maps, so are not included in the global
238 area estimate. In addition, despite their importance, we are still lacking a global and spatially
239 explicit map of soil carbon for tidal marshes. Based on the global tidal marsh distribution
240 mapped by Mcowen et al.³⁴, the global soil map⁶¹ and mean carbon stocks (Tables S1 and
241 S5), we estimated that potential blue carbon stocks in tidal marsh soil could vary from ~862-
242 1,350 Tg C (Table S1 and S5) with United States of America (354-640 Tg C), Australia (112-

243 223 Tg C) and Russia (180-277 Tg C), holding approximately 77-86% of the global soil tidal
244 marsh carbon stocks (Figure 4, Table S5).

245 To better understand the contribution of BCE to the global carbon cycle, improved
246 global scale mapping of BCE, particularly seagrasses and tidal marshes, is required.
247 Furthermore, it is important to highlight that the range of carbon stock estimates for each
248 ecosystem and carbon pool (biomass and soil) provided in this Review reflect the large
249 uncertainties associated with global blue carbon estimates (for example, linked to poorly
250 constrained total seagrass and tidal marsh habitat extent and the large variability in carbon
251 storage among blue carbon habitats across and within countries). Although large uncertainties
252 remain (such as propagation and uncertainty estimates for each country and global values),
253 the ranges provided in our Review encompass the known variability in blue carbon
254 ecosystem extent and stocks across countries (Table S1). Other significant research gaps
255 include understanding the spatial variability - and drivers of such variability - for key carbon
256 parameters. For example, while there have been improvements in understanding how and
257 why soil carbon stocks vary globally in tidal marshes⁶² and mangroves^{63,64}, global drivers of
258 seagrass carbon stock remain largely unexplored. Less still is known about patterns and
259 drivers of carbon fluxes (carbon burial rates, atmospheric and/or lateral greenhouse gas
260 fluxes) beyond particular sites or regional studies^{65,66}. Better understanding of these factors
261 will improve attempts to estimate and model BCE contributions to global carbon cycling, and
262 enhance our capacity to predict the greenhouse gas benefits of restoration activities at
263 national scales⁶⁷.

264

265 **The scope for large scale restoration**

266 Delivering the full restoration potential requires returning these ecosystems to their historical
267 extent, which in many cases remains unknown, but can be derived from consulting historical

268 sources, including paintings ²⁰. In some cases, urbanization has modified or reclaimed
269 mangrove forests or tidal marshes to an extent that restoration is not possible because it is
270 either economically, legally or logistically unfeasible. However, wetland conversion to urban
271 area represents a relatively minor component of the area lost (for example, accounting for just
272 3% of mangrove loss globally between 2000 and 2016 ⁶⁸) although might have been much
273 greater during urban growth in the 19th and 20th centuries. In many regions, blue carbon
274 habitats have largely been claimed for rice paddies (in Asia), aquaculture ponds (Asia and
275 Central America), and pasture lands (temperate tidal marshes) ^{69,70}, a conversion that was
276 initiated centuries ago With appropriate engineering and consideration of land tenure issues,
277 such lands are more feasible for restoration once they fall out of production, although
278 successful tidal marsh and mangrove restoration also depends on sediment supply in
279 minerogenic systems, as well as current and future soil elevation. Mapping converted areas
280 that can be returned to the original habitat has shown that there is the potential for > 800,000
281 ha globally to be biophysically suitable for restoration back to mangrove forests ⁷¹, if land
282 tenure and other socioeconomic issues can be resolved. Likewise, restoring tidal flows can
283 lead to rapid tidal marsh restoration, with tidal marsh restoration successfully expanding tidal
284 marshes even in some of the most densely urbanized cities in the world, such as New York
285 City, USA ²⁰, although restoration failures have also occurred, providing opportunities to
286 learn ^{20,72-74}.

287 However, the scope for global-scale coastal wetland restoration is constrained by
288 multiple socio-economic constraints, especially in countries where a large proportion of the
289 restorable habitat is on small agricultural land holdings where restoration efforts could
290 conflict with the livelihoods and food security of local communities ^{75,76}. Restoration efforts
291 in Southeast Asia highlight the impact of socio-economic constraints on wetland restoration;
292 of the total area that is biophysically suitable for mangrove restoration in Southeast Asia,

293 only 5.5-34.2% is ultimately restorable after various socio-economic (such as livelihoods,
294 food security, and land rights) and operational constraints (including deforestation risk, site
295 accessibility, proximity to seed sources) are considered ⁷⁷.

296 Seagrass restoration, however, is comparatively costly and has a lower success rate
297 compared to other marine ecosystems (such as mangrove forests, tidal marshes, coral reefs,
298 oyster reefs) ^{19,78}. Furthermore, it is important to consider that usually carbon stocks in
299 seagrass biomass and marsh grass leaves are not included in carbon inventories since its
300 residence time varies from only a few months to a few decades, and is therefore, irrelevant to
301 climate change mitigation. Around 29% of the known seagrass global extent has disappeared
302 since the 1940s at a mean rate of 1.5% per year, with large scale losses reported in USA,
303 Australia, New Zealand and Europe ⁷⁹. Yet, there is potential to restore areas formerly
304 occupied by seagrass if the pressures that led to the loss, dominated by deteriorated water
305 quality with eutrophication ⁸⁰, are removed ⁸¹. Natural recolonization is, however, a very slow
306 process. For example, more than 70 million seeds of eelgrass (*Zostera marina*) have been
307 distributed in the western Atlantic coastal lagoons since 1999 that resulted in the recovery of
308 3,600 ha ^{82,83}. However, improved seagrass restoration practices are required to enhance the
309 success of previous restoration efforts, which have been largely unsuccessful to date ⁸⁴.

310 Seagrass restoration can benefit from a variety of tools and methods (for example,
311 buoy-deployed seeding, dispenser injection seeding, artificial in-water structures and
312 community involvement) that enhance the cost effectiveness, efficiency and scalability of
313 restoration activities ⁸¹. The restoration of seagrass meadows can catalyse natural recovery
314 processes ^{23,78,85}, along with the recovery of the associated ecosystem services including
315 carbon sequestration, which can otherwise be too slow if left to natural recovery, as
316 demonstrated for seagrass meadows in Virginia, USA coastal waters ²³. Restoration of
317 seagrass meadows is complex but possible, and future efforts should combine actions to

318 improve the suitability of the habitat to allow for natural recovery processes in seagrasses, in
319 addition to state-of-the-art methods that enhance the success of active restoration programs ⁸³.

320

321 *Blue carbon losses from human activities*

322 Quantifying the extent of BCE losses has been hampered by a lack of understanding
323 of their historical and current spatial extent, in particular for seagrasses and tidal marshes.

324 The lack of global time-series for tidal marsh area, comparable to those existing for
325 mangroves ^{35,43,70}, during the satellite record is surprising as they can also be detected using
326 remote sensing tools. However, tidal marsh mapping can be challenging due to their spatial,
327 temporal, and spectral complexity, particularly when bordering other grassland and wetland
328 types ^{86,87}, requiring high spatial resolution of the satellite products, which has only recently
329 been achieved. Uncertainties on past and present seagrass area and distribution are, however,
330 difficult to resolve, as detecting seagrass meadows underwater in satellite images, and
331 separating them from other communities, such as macroalgae, remains challenging ⁸⁸.
332 Furthermore, the lack of remote sensing data before the 1970s precludes a robust assessment
333 of global BCE extent prior to the worldwide establishment of coastal settlements.

334 Despite these difficulties, global losses of tidal marshes have been estimated at ~1-2%
335 per year ⁸⁹, and seagrass loss rates since the 1940s have been estimated at 1.5% per year ⁷⁹,
336 but more recently, conservation actions have resulted in the deceleration and reversal of
337 declining trends in seagrasses in some regions ⁹⁰. Remote sensing methods for terrestrial
338 forests have been adapted for mangroves, allowing for a country-by-country estimate of
339 ecosystem change from 2000 to 2016 ⁶⁸. Globally, annual loss rates of mangroves have
340 decreased sixfold from 0.99% in the 1980s to an average of 0.16% per year between 2000
341 and 2012 ³⁶. Although mangrove loss has slowed considerably, loss rates are still substantial
342 in places like Southeast Asia, which contains ~50% of global mangrove forest area. Some

343 Southeast Asian countries such as Myanmar experienced loss rates as high as 0.5% yr⁻¹
344 between 2000 and 2016 (with 44,485 ha deforested between 2000 and 2016)⁶⁸.

345 The major drivers of BCE loss vary by ecosystem and region, but generally include
346 physical modification (including ecosystem change, drainage), pollution, non-native species,
347 and climate change⁹¹. In most cases, the primary drivers of BCE loss are indirectly driven by
348 socioeconomic factors that centre around coastal development, energy, food,
349 recreation/tourism, and infrastructure expansion. For example, mangrove forests continue to
350 be converted to expand aquaculture and agriculture (such as rice and oil palm), often to meet
351 national food and economic security targets. Commodity production accounted for 47% of
352 global mangrove loss in the early 21st century, with 92% of commodity production occurring
353 in Southeast Asia alone^{68,69}. Similarly, extensive use of fertilizers on agricultural fields and
354 the subsequent eutrophication of coastal ecosystems has been identified as a significant driver
355 of large-scale seagrass and tidal marsh loss^{79,80,92}.

356 The effects of climate change (including increased temperatures, sea-level rise,
357 increased frequency and severity of storms and heatwaves) on BCE loss has been increasing
358 over time^{68,93,94}. For example, increases in the occurrence and extent of marine heatwaves
359 have led to recent and extensive losses (36-80% loss in seagrass cover) in temperate and
360 subtropical seagrasses in the Chesapeake Bay (USA), the western Mediterranean, and
361 Western Australia's Shark Bay⁹⁵⁻⁹⁸. Some mangrove forests, such as those in the Gulf of
362 Carpentaria, Australia⁹⁹, have experienced dieback from factors associated with extreme El
363 Niño events (for example, elevated temperatures, reduced inundation, and drought).
364 Furthermore, recent cyclones have also led to widespread damage and losses in mangrove
365 forests^{16,100,101}.

366 While the complexity of mangrove dynamics at their poleward limit may make it
367 difficult to show causality¹⁰², increasing air temperature has been related to the poleward

368 range extension of mangroves in many instances ¹⁰³⁻¹⁰⁷. For example, in Western Port,
369 Australia, mangrove encroachment was related to increasing annual maximum temperature,
370 at sites with lower elevations and closer to known mangrove-tidal marsh boundaries ¹⁰⁴.
371 Unfortunately, this expansion has generally come at the expense of tidal marshes as they
372 become displaced by mangroves. Such replacement is associated with increases in blue
373 carbon as a carbon-poor herbaceous ecosystem is replaced by a woody ecosystem ^{108,109}.

374 Sea-level rise combined with coastal squeeze (i.e., habitat loss in the intertidal area
375 due to anthropogenic structures or actions, which prevent the landward migration of coastal
376 habitats that would otherwise occur in response to sea level rise) and reduced sediment loads
377 to coastal systems from the damming of rivers threatens the future persistence of many
378 mangrove and tidal marsh ecosystems ^{39,110-112}. Although the effects of sea-level rise on BCE
379 loss might not begin to truly manifest for several decades, it is predicted that 5-30% of
380 coastal wetlands can be submerged by 2080 if upslope migration pathways, through lateral
381 accommodation space, are precluded ^{104,113,114}. Conversely, moderate rates of sea-level rise
382 can be beneficial to the burial of BCE soil carbon, in particular geomorphic settings, or
383 locations - such as much of the southern hemisphere - which have experienced stable relative
384 sea level over recent millennia ⁶², constraining the soil space available to accumulate
385 sediments by BCE.

386

387 *Restoration of blue carbon ecosystems*

388 The protection and restoration of BCE has the potential to add substantially to climate
389 mitigation efforts and Nationally Determined Contributions (NDCs). Under business as usual
390 operations, it is expected that blue carbon ecosystems (BCE) will continue to decline due to
391 ongoing global losses, but if protection is prioritised, then blue carbon trajectories should
392 stabilise ¹¹⁵ and even reverse to lead to recovery ²⁰. Rehabilitation and restoration of BCE will

393 increase the contribution of blue carbon to NCS, as will planning for sea level rise to
394 maximise accommodation space for BCEs under sea level rise.

395 Despite difficulties in measuring the extent of ecosystem loss in BCE, Griscom et al.
396 ¹¹⁶ estimated the potential for avoided emissions at 304 (141-466) Tg CO₂e yr⁻¹ through the
397 protection of these systems, while large-scale restoration could drawdown an extra 841 (621-
398 1,064) Tg CO₂e yr⁻¹ by 2030 through further avoided emissions and additional carbon
399 sequestration from growth (mangroves only) and soil carbon sequestration (Figure 5). For
400 example, the maximum mitigation potential from avoided coastal impacts has been estimated
401 for mangrove forests ¹¹⁶, showed that countries in Southeast Asia would have the highest
402 mitigation potential at up to 65 Tg CO₂e yr⁻¹ (Figure 5). Considering the estimated global
403 annual emissions from fossil fuels for 2019 and 2020 ¹¹⁷ (36,400 and 34,100 Tg CO₂e,
404 respectively), this equates to potential abatement of ~3% of global emissions (0.5-0.8% from
405 protection, and 2.3-2.5% from restoration, further details on this estimate are available in the
406 Supplementary Material). Although mangroves and seagrasses contribute equally to avoided
407 emissions potential through the protection of existing habitat (Figure 5), mangroves
408 contribute the largest proportion to mitigation potential from the restoration of disturbed or
409 lost habitats ¹¹⁶ (Figure 5). The substantial contribution of mangroves to mitigation potential
410 through restoration compared to seagrasses and tidal marshes, in part likely reflects our
411 broader understanding of ecosystem loss, and thus the opportunities for restoration in
412 mangroves compared to the other systems. Since we do not understand the full extent of
413 habitat loss for seagrasses and tidal marshes, the potential for seagrass and tidal marsh
414 restoration to contribute to climate mitigation efforts estimated by Griscom et al. ¹¹⁶ are more
415 uncertain. Estimated maximum extent of available habitat for restoration in Griscom et al.'s
416 ¹¹⁶ analysis ranged from 0.2 to 3.2 million hectares for tidal marshes, and 0.8 to 25.4 million
417 hectares for seagrasses. In contrast, restorable habitat for mangroves is much more resolved

418 with estimates between 9 and 13 million hectares ⁷¹. Such large differences in the estimated
419 restorable habitat for tidal marshes and seagrasses cause potential avoidable GHG fluxes and
420 additional carbon sequestration to vary by orders of magnitude.

421 An important area for future research is therefore to better estimate where future
422 opportunities exist for BCE restoration. Griscom et al. ¹¹⁶ estimated the restoration potential
423 to climate mitigation based on the estimated total extent of ecosystem loss; however, it is not
424 realistic to assume that all BCE that have been lost can be restored. In cases such as the
425 conversion of mangroves to a port or the conversion of tidal marsh to urban development, it
426 is improbable that these lands can be converted to their natural state. For example, it has been
427 estimated that of the 973,640 ha of mangroves lost between 1996-2016, 17% is not restorable
428 due to urbanization and erosion ⁷¹, and possible due to restoration costs. On the other hand,
429 the creation and expansion of new BCE through engineering solutions (including
430 modification of hydrodynamics to restore historical tidal exchange) and plantings (such as
431 mangrove plantations) that allow BCE to grow where historically they were absent, has the
432 potential to add to NDC (assuming plantations do not occur on or convert other BCE), while
433 deriving additional benefits like coastal defence against sea level rise ¹¹⁸. Thus, future studies
434 should aim to estimate and map the available BCE area that can be restored to its natural state
435 as well as identify potential new areas for the expansion of BCE and the associated carbon
436 fluxes linked to blue carbon projects. Furthermore, the time taken for restored ecosystems to
437 achieve carbon stocks that are equivalent to natural ecosystems, and data on the trajectory of
438 carbon accumulation with time since restoration is limited, with an opportunity for future
439 studies to answer this fundamental question in blue carbon question ¹¹⁹. Whether restoration
440 and conservation measures are effective for long-term survival depends on a number of
441 contributing factors. To ensure success, restoration policies should be based on globally
442 accepted best practice, with particular attention to site suitability, while taking into account

443 local conditions and the management policies that are relevant to the local community ^{73,120-}
444 ¹²⁴.

445

446 **Practical aspects of restoration**

447 While conservation of remaining BCE is a highly cost effective way of reducing GHG
448 emissions, restoration requires significant investments and is, therefore, less cost effective ¹¹⁶.
449 However, both conservation and restoration contribute to adaptation to climate change, and
450 therefore restoration activities can offer opportunities to develop market-based mechanisms
451 that take advantage of existing frameworks for carbon offsets ¹²⁵. For example, the
452 application of Verified Carbon Standard (VCS) Methodology for Tidal Wetland and Seagrass
453 Restoration (VM0033) has opened up the opportunity for projects to gain financial help
454 through carbon offsets. Projects can be developed in partnership with those wanting to
455 purchase offsets, whether in the public or private sector, with the opportunity to make
456 additional contributions from other financial streams ³⁰. In Cispatá Bay, Colombia, 11,000
457 hectares of mangrove forest are being protected and restored, which will reduce potential
458 emissions by 17,000 metric tons CO₂ within two years ¹²⁶. Conservation International, along
459 with Colombia community partners, intend to use the carbon value generated through the
460 project to contribute to a long-term sustainable financing strategy for the region, and Apple©
461 is investing into the project as part of their emissions reduction strategy ¹²⁶. Alongside the
462 growing experience of restoration has come the refinement of the VCS methodology, so that
463 projects that follow these procedures should be successful as experience grows. In many
464 cases, restoration can be effective using simple methods such as natural or purposeful re-
465 seeding or replanting that can be very cost-effective.

466 Restoration of BCE provide other ecosystem service benefits (besides carbon
467 drawdown) that support coastal communities and their economies ^{9,127} and many open up

468 opportunities for developing payment for ecosystem service (PES) schemes that are
469 complementary to carbon management. PES can provide flexibility in financing and a
470 broader outlook on ecosystem service provision. Moreover, ecosystem service co-benefits
471 from BCE restoration are supported by a wide range of policy goals, for example contributing
472 to multiple of the Sustainable Development Goals, Convention on Biodiversity Aichi targets,
473 Ramsar Convention, UNESCO (Biosphere reserves, Natural World Heritage sites) and
474 others, marine protected areas (MPAs), as well as community goals for development ^{128,129}.
475 Achieving the restoration scale required to deliver maximum climate change mitigation
476 benefits from BCE (Figure 5), needs strong governance, and support from governments,
477 beneficiary industries, corporations and communities, all committed with a global effort
478 propelled by the UN Decade of Ecosystem Restoration ¹³⁰.

479 MPAs and other listed sites can be used to help achieve the Aichi and Durban targets,
480 as well as Sustainable Development Goals (SDG). The Aichi Target 11 was intended to
481 protect 10% of marine areas within national jurisdictions by 2020 and this target has been
482 further embedded under Target 14.1 of the United Nations SDG, while the Durban Action
483 Plan called for an expansion to 30% of global marine protected area ^{131,132}. A common feature
484 of MPA establishment is to protect and conserve biodiversity, rather than carbon, meaning
485 that some proposed locations for new MPAs might not be able to serve both goals. An
486 economic analysis of the development of MPAs to reach their future targeted expansions
487 concluded that although benefits exceed costs, regardless of the degree of human impact in an
488 area, expansion into more biodiverse low-usage areas would be the most cost effective ¹³³. In
489 terms of climate change mitigation, use of the same criteria to locate MPA's expansion might
490 not yield the same benefit as projects can only claim carbon credits if they can verify that the
491 carbon stored there would be at risk ¹³⁴. In this context, established MPAs might not meet
492 requirements of 'additionality' criteria of existing blue carbon methodologies ¹³⁵ - that is,

493 projects are generally unable to claim credits for carbon abatement achieved through
494 conservation or restoration actions that are not already prescribed by existing legislation or
495 management requirements. This is an area of current policy debate and development, with
496 approaches for dealing with additionality likely to vary among jurisdictions and accounting
497 mechanisms ¹³⁶.

498

499 *Relevance to Nationally-Determined Contributions (NDCs)*

500 Nationally Determined Contributions (NDC) to the Paris Agreement (2016)
501 encourage nations to decide what activities they will undertake to lower their GHG
502 emissions. Currently, blue carbon commitments within NDCs are limited. Recently it has
503 been estimated that 64 countries have included a reference to coastal and marine ecosystems
504 in terms of climate adaptation and mitigation in their NDCs. The majority of these countries
505 list NDC commitments related to mangroves (45), with fewer (10) for seagrass ¹²⁵. Tidal
506 marshes are not specifically mentioned, although many countries NDC refer generally to
507 wetlands or commits to using the IPCC Wetland Supplement ¹³⁷, which provides guidance for
508 estimating GHG emissions and removals for some activities associated with mangroves,
509 seagrass and tidal marshes ¹²⁵. A few countries such as the Bahamas and Belize have
510 ambitious, quantified targets for BCE in their NDCs, but many countries still lack any
511 measurable targets ¹³⁸.

512 The IPCC Wetland Supplement ¹³⁷ provides methodologies and default emission
513 factors such that nations can include 1) emissions from a limited range of management
514 activities for conservation and 2) removals through restoration activities. To date, only three
515 countries have reported GHG emissions and removals associated with land-use change of
516 coastal wetlands (Australia, United Arab Emirates and USA). Market-based methodologies
517 are linked to the underlying IPCC guidance, and focus on generating carbon credits for

518 conservation and restoration of coastal wetlands ^{67,120,135} However, their use is still limited
519 with few pilot projects, mostly within mangroves ¹²⁰. The Livelihoods Carbon Funds are
520 partnering with communities in India (The Sundarbans Mangrove Restoration Project),
521 Indonesia (Yagasu) and Senegal (with Senegalese NGO Océanium) to restore and protect
522 mangrove forests. In the Sundarbans 16 million trees, in Indonesia 18 million trees, and in
523 Senegal 8,000 hectares have been planted, with the carbon credits generated being used to
524 help repay the project's costs ⁷⁵. Together, these initiatives are predicted to sequester 2.7
525 million tons of CO₂ over 20 years. On a smaller scale, Tahiry Honko (Madagascar) and
526 Mikoko Pamoja (Kenya) have been among the first projects where Plan Vivo has certified
527 blue carbon credits ¹²⁰. In Tahiry Honko the conservation and restoration of over 1200 ha of
528 mangrove forest generates over 1300 carbon credits per year, where half of the funds
529 generated goes to help support the local communities. The Mikoko Pamoja project helps
530 conserve 117 ha and has established 10 ha of mangrove forest ¹²⁰. In 2019, the project sold
531 1912 credits with 65% of the revenue going to support community development projects.

532 A number of countries can benefit from the inclusion of their coastal ecosystems in
533 NDCs. In terms of adoption, this might include small island states with low emissions and
534 small land area relative to the length of coastlines and/or shallow shelf, which could support
535 extensive blue carbon habitats (for example, in Madagascar and Solomon Islands), as well as
536 countries (such as USA and Canada) where there are large opportunities for restoration or
537 habitat creation (including landward retreat with sea level rise). In terms of climate change
538 mitigation, the main beneficiaries would be those countries with extensive, carbon-rich, BCE
539 that have experienced high rates of loss ³⁷. For example, in Indonesia, conversion of
540 mangroves to shrimp ponds accounts for up to 20% of GHG emissions associated with land-
541 cover change ¹³⁹. However, many nations do not have the necessary data to assess either the

542 extent of BCE or carbon stocks, which is particularly the case for tidal marsh and seagrass
543 ecosystems.

544 Increasing the inclusion of blue carbon within NDCs can be supported in numerous
545 ways (Figure 6). First, the use of existing ^{67,134} or new frameworks can aid in the
546 identification of blue carbon restoration opportunities at national or subnational scales. In
547 Australia, for example, this process allowed prioritisation of leading opportunities which are
548 now being included within the domestic carbon accounting framework ⁶⁷. Resourcing of field
549 data collection and the development of new tools, including spatial data products (such as
550 Jones et al. ¹⁴⁰ and Holmquist et al. ¹⁴¹), is integral to understanding the scope and scale of
551 such opportunities at the national scale. Second, the improvement of standardised protocols
552 for the accounting of GHG benefits ¹³⁵, and accessibility to low-cost data collection
553 approaches such as remote sensing and affordable field sensors (such as Maher et al. ¹⁴²) will
554 enhance feasibility and uptake of carbon crediting projects. Finally, further demonstration
555 projects are needed (but see Wylie et al. ¹²⁰), to showcase successes and failures across a
556 broader range of geographic settings, land use and ecosystem types, to build datasets, insights
557 and awareness for future restoration projects ¹¹⁹.

558

559 *Other considerations*

560 There have been unsuccessful or poorly planned attempts at long-term restoration,
561 which have utilised, non-native or inappropriate species, monoculture without consideration
562 of plant traits and functional diversity and/or unsuitable sites for planting, including planting
563 over other BCE ^{73,123,143}. The capacity of many BCE plant species to recolonise via vegetative
564 growth and/or transportation of propagules and seeds on the tide, means that passive
565 revegetation techniques (such as improvements in tidal connectivity and water quality, and/or
566 alterations to hydrodynamic energy) can be preferred in many circumstances ⁶⁷.

567 Positive steps can be taken to mitigate sea level rise through restoration projects that
568 include a mix of species and at increased densities and scale, while taking into account local
569 hydrology, the potential for landward expansion of mangroves and tidal marshes and
570 relevance to the socio-economic factors affecting the local communities^{39,114,144,145}. Global
571 warming can also have an impact; for example, increasing temperatures can result in
572 changing gas fluxes in BCE that lead to enhanced emissions^{97,121,146}. The effect of
573 temperature increase on greenhouse gas emissions in seagrass meadows has indicated the
574 potential negative effects of climate change. In 2010/2011 an unprecedented heatwave led to
575 a 22% loss of seagrass cover in Shark Bay (Australia), resulting in an estimated increase in
576 national CO₂ emissions from land use change by 4-21% per annum⁹⁷. Also, using an
577 experimental approach, it has been shown for the first time that increasing temperature up to
578 37 °C led to a four-fold increase in methane fluxes if compared to the community held at 25
579 °C from Red Sea seagrass sediments¹⁴⁶. Increase in temperature is likely to lead to a range of
580 different responses in BCE including an increase or decrease in primary productivity, faster
581 decomposition of organic matter and changes in BCE spatial distribution, but there are still
582 many uncertainties regarding the nature and extent of these changes and how they might
583 differ with latitude and environmental setting^{112,121}. Conversely, enhanced removals can
584 occur when mangroves expand into tidal marsh or invasive species colonise tidal marsh and
585 seagrass meadows^{147,148,147,148}. Biological invasions of this type will require their own type of
586 management actions based on site-specific conservation strategies^{104,149}.

587

588 **Future pathways**

589 Restoring and managing BCE for climate change mitigation and adaptation is exciting and
590 feasible²⁸ - with capacity to drawdown an extra 841 Tg CO₂e pa - but it is complex, as it
591 must take into account a range of issues including social factors, existing policy, variation in

592 geomorphological settings and human impacts, and the impacts of climate change. For
593 example, monitoring and management of restored areas is needed to ensure their permanence,
594 but many projects do not take into consideration sea level rise and/or socio-economic or other
595 human-related impacts in their initial planning ^{120,121,123}. These complexities are not
596 insurmountable, but they do require further research and planning, including reconsideration
597 of how international policies can better reward long-term carbon drawdown through BCE (as
598 opposed to rewarding cheaper, shorter-term abatement). As we progress toward bringing
599 losses of BCE to a halt, by removing the pressures that led to their losses (for example, $\frac{1}{3}$ of
600 seagrass loss in Europe was due to disease, poor water quality and coastal development, de
601 los Santos et al. ⁹⁰) and protecting BCE, the goal should shift to one of deploying a sustained
602 effort to restore BCE back to their historical extent ²⁰.

603 The development and uptake of blue carbon financing mechanisms have been
604 supported in recent years through national and international initiatives, comprising
605 government and non-government groups ^{125,149}. The incorporation of blue carbon within
606 NDCs in the IPCC Paris Agreement has seen a number of countries explore domestic
607 mechanisms to promote blue carbon projects and include emissions abatement in their
608 national accounts ^{67,128}. Within the voluntary market, projects have utilised existing forestry-
609 based mechanisms (such as Gold Standard and Plan Vivo) to quantify carbon credits in
610 mangroves ¹⁵⁰, while new mechanisms, such as the VCS methodology VM0033 described
611 above, have also been developed specifically for seagrass and tidal wetlands including tidal
612 marshes and mangroves ^{135,151}. Although such voluntary market projects have commenced in
613 a number of countries, only a very small number have been verified to date ^{150,152}. Novel
614 approaches such as blended financing (whereby a commercial project provides societal
615 benefits plus financial returns to investors), and/or pairing with co-benefits such as reduction
616 of insurance premiums related to coastal protection ^{153,154}, can help to enhance uptake and

617 progression to verification in coming years. Importantly, there remain divergent views on the
618 application of market-based approaches to quantifying ecosystem service provision to finance
619 environmental protection and restoration, including for coastal wetlands ^{155,156}.

620 Scientific research has multiple roles in facilitating the development of blue carbon
621 accounting frameworks (Figure 6). Ongoing, original research of carbon cycling in the
622 coastal zone underpins our capacity to quantify and account for emissions abatement
623 achieved at local through to national scales ^{59,157}. However, further research is required to fill
624 substantial gaps in scientific understanding ¹¹². These include the need to address geographic
625 biases in the coverage of blue carbon data (including imbalances between the developed -
626 developing nations divide); develop robust information on the scope of small-scale
627 restoration projects at the global or country scale, improved estimates of the influence of
628 disturbances and interventions on greenhouse gas fluxes ¹¹⁹; and the impacts of climate
629 change and sea-level rise on BCE and the permanence of carbon sequestration ³⁹.

630 Furthermore, future studies should focus on developing new spatial products with similar
631 resolutions, particularly for seagrasses and tidal marshes, and also assess propagation and
632 uncertainty estimates in global blue carbon estimates to constrain the large variability in the
633 estimates provided in our Review. Therefore, providing more meaningful information for
634 policy and other initiatives aiming to implement blue carbon into climate change mitigation
635 strategies. At the project scale, demonstration is required to generate knowledge and data
636 specific to natural, degraded, restored and created wetlands. Demonstration projects will also
637 help to identify and ameliorate policy and governance roadblocks. These might include issues
638 of land tenure, project boundaries and rights to carbon ¹⁵⁸, economic barriers to uptake (such
639 as, high transaction costs), demonstrating additionality, and issues with double-counting of
640 carbon gains ⁶⁷. The carbon export and storage beyond the boundaries of BCE, including
641 macroalgae, has been raised as an important but unquantified carbon sink ¹⁴. However, future

642 research needs to overcome scientific and policy barriers that currently preclude the inclusion
643 of carbon export and sequestration beyond BCE extent in blue carbon accounting and
644 abatement associated with management activities.

645 The success of the blue carbon strategy over the decade since it was first put forward
646 in 2009 ⁶ reflected in its growing uptake within NDCs and has led to an effort to ascertain
647 additional pathways for climate change mitigation through ocean-based NCS ¹⁵⁹). A growing
648 slate of options is arising, including carbon sequestration from alkalinity release with
649 carbonate dissolution, organic carbon preservation in anoxic conditions within BCE ^{66,119,160},
650 management of seaweed farms ^{161,162} and conservation of natural kelp forests ¹⁴ for carbon
651 sequestration ^{161,162}, management of sediments beyond BCE to avoid emissions, and
652 rebuilding populations of large marine animals ¹¹⁹. The success of these emerging blue
653 carbon options requires robust scientific evidence along with accountability of their
654 contribution to greenhouse gas mitigation, including meeting the requirements of
655 additionality and permanence of this benefit. A research road map to increase the scientific
656 evidence supporting blue carbon options was recently put forward ¹¹⁹. There is an opportunity
657 to further catalyse these actions through synergies between the concurrent UN Decades for
658 Ocean Science (2021-2030) and Ecosystem Restoration (2021-2030) ¹³⁰, as both robust
659 scientific knowledge and more cost-effective technologies to further restoration efforts are
660 needed. The potential for BCE to offset global emissions (~3% pa, or approximately the
661 combined global emissions from landfill and wastewater sectors ¹⁶³), while also providing
662 numerous additional ecosystem services for coastal adaptation and local livelihoods, along
663 with the novel BCE components arising, justifies the attention blue carbon is currently
664 receiving as a nature-based solution to climate change mitigation and adaptation.

665

666 **Acknowledgements**

667 We are thankful for the funding provided by Deakin University (to PIM and MDPC), Qantas
668 (to PIM and MDPC), HSBC (to PIM and MDPC), Australian Research Council Discovery
669 Grants (to PIM and CMD; DP200100575), King Abdullah University of Science and
670 Technology (to CMD) under KAUST's Circular Carbon Economy Initiative, and Early
671 Career Research Fellowship from the Gulf Research Program of the National Academies of
672 Sciences, Engineering, and Medicine (to TBA; the content is solely the responsibility of the
673 authors and does not necessarily represent the official views of the Gulf Research Program of
674 the National Academies of Sciences, Engineering, and Medicine). We are also thankful to
675 NY who helped with the creation of the figures.

676 **Competing interests**

677 The authors declare no competing interests.

678

679 **References**

- 680 1. Nesshöver, C. *et al.* The science, policy and practice of nature-based solutions: An
681 interdisciplinary perspective. *Sci. Total Environ.* **579**, 1215–1227 (2017).
- 682 2. Chausson, A. *et al.* Mapping the effectiveness of nature-based solutions for climate
683 change adaptation. *Glob. Chang. Biol.* **26**, 6134–6155 (2020).
- 684 3. Pires, J. C. M. Negative emissions technologies: A complementary solution for climate
685 change mitigation. *Sci. Total Environ.* **672**, 502–514 (2019).
- 686 4. McLaren, D. A comparative global assessment of potential negative emissions
687 technologies. *Process Saf. Environ. Prot.* **90**, 489–500 (2012).
- 688 5. Anderson, K. & Peters, G. The trouble with negative emissions. *Science (80-.)*. **354**,
689 182 LP – 183 (2016).

- 690 6. Nellemann, C. *et al.* *Blue Carbon - The Role of Healthy Oceans in Binding Carbon*.
691 (UN Environment, 2009).
- 692 7. Lovelock, C. E. & Duarte, C. M. Dimensions of Blue Carbon and emerging
693 perspectives. *Biol. Lett.* **15**, (2019).
- 694 8. Duarte, C. M., Losada, I. J., Hendriks, I. E., Mazarrasa, I. & Marbà, N. The role of
695 coastal plant communities for climate change mitigation and adaptation. *Nat. Clim.*
696 *Chang.* **3**, 961–968 (2013).
- 697 9. Barbier, E. B. *et al.* The value of estuarine and coastal ecosystem services. *Ecol.*
698 *Monogr.* **81**, 169–193 (2011).
- 699 10. Himes-Cornell, A., Grose, S. O. & Pendleton, L. Mangrove Ecosystem Service Values
700 and Methodological Approaches to Valuation: Where Do We Stand? *Front. Mar. Sci.*
701 **5**, (2018).
- 702 11. Friess, D. A. *et al.* Ecosystem Services and Disservices of Mangrove Forests and Salt
703 Marshes. *Oceanogr. Mar. Biol. An Annu. Rev.* (2020).
- 704 12. Duarte, C. M., Middelburg, J. J. & Caraco, N. Major role of marine vegetation on the
705 oceanic carbon cycle. *Biogeosciences* **2**, 1–8 (2005).
- 706 13. Mcleod, E. *et al.* A blueprint for blue carbon: toward an improved understanding of the
707 role of vegetated coastal habitats in sequestering CO₂. *Front. Ecol. Environ.* **9**, 552–
708 560 (2011).
- 709 14. Krause-Jensen, D. & Duarte, C. M. Substantial role of macroalgae in marine carbon
710 sequestration. *Nat. Geosci.* **9**, 737–742 (2016).

- 711 15. Macreadie, P. I. *et al.* Vulnerability of seagrass blue carbon to microbial attack
712 following exposure to warming and oxygen. *Sci. Total Environ.* **686**, 264–275 (2019).
- 713 16. Sippo, J. Z., Lovelock, C. E., Santos, I. R., Sanders, C. J. & Maher, D. T. Mangrove
714 mortality in a changing climate: An overview. *Estuar. Coast. Shelf Sci.* **215**, 241–249
715 (2018).
- 716 17. Lovelock, C. E. *et al.* Assessing the risk of carbon dioxide emissions from blue carbon
717 ecosystems. *Front. Ecol. Environ.* **15**, 257–265 (2017).
- 718 18. Zhao, Q. *et al.* Where Marine Protected Areas would best represent 30% of ocean
719 biodiversity. *Biol. Conserv.* **244**, 108536 (2020).
- 720 19. Bayraktarov, E. *et al.* The cost and feasibility of marine coastal restoration. *Ecol. Appl.*
721 **26**, 1055–1074 (2016).
- 722 20. Duarte, C. M. *et al.* Rebuilding marine life. *Nature* **580**, 39–51 (2020).
- 723 21. Van, T. T. *et al.* Changes in mangrove vegetation area and character in a war and land
724 use change affected region of Vietnam (Mui Ca Mau) over six decades. *Acta Oecol.*
725 **63**, 71–81 (2015).
- 726 22. Nam, V. N., Sasmito, S. D., Murdiyarso, D., Purbopuspito, J. & MacKenzie, R. A.
727 Carbon stocks in artificially and naturally regenerated mangrove ecosystems in the
728 Mekong Delta. *Wetl. Ecol. Manag.* **24**, 231–244 (2016).
- 729 23. Reynolds, L. K., Waycott, M., McGlathery, K. J. & Orth, R. J. Ecosystem services
730 returned through seagrass restoration. *Restor. Ecol.* **24**, 583–588 (2016).
- 731 24. Das, S. Ecological Restoration and Livelihood: Contribution of Planted Mangroves as

- 732 Nursery and Habitat for Artisanal and Commercial Fishery. *World Dev.* **94**, 492–502
733 (2017).
- 734 25. Kiesel, J. *et al.* Effective design of managed realignment schemes can reduce coastal
735 flood risks. *Estuar. Coast. Shelf Sci.* **242**, 106844 (2020).
- 736 26. McNally, C. G., Uchida, E. & Gold, A. J. The effect of a protected area on the
737 tradeoffs between short-run and long-run benefits from mangrove ecosystems. *Proc.*
738 *Natl. Acad. Sci.* **108**, 13945 LP – 13950 (2011).
- 739 27. Danielsen, F. *et al.* The Asian tsunami: a protective role for coastal vegetation. *Science*
740 (80-). **310**, 643 (2005).
- 741 28. Chow, J. Mangrove management for climate change adaptation and sustainable
742 development in coastal zones. *J. Sustain. For.* **37**, 139–156 (2018).
- 743 29. Dasgupta, S., Islam, M. S., Huq, M., Huque Khan, Z. & Hasib, M. R. Quantifying the
744 protective capacity of mangroves from storm surges in coastal Bangladesh. *PLoS One*
745 **14**, e0214079 (2019).
- 746 30. Sutton-Grier, A. E. & Moore, A. Leveraging Carbon Services of Coastal Ecosystems
747 for Habitat Protection and Restoration. *Coast. Manag.* **44**, 259–277 (2016).
- 748 31. Owuor, M. A., Mulwa, R., Otieno, P., Icely, J. & Newton, A. Valuing mangrove
749 biodiversity and ecosystem services: A deliberative choice experiment in Mida Creek,
750 Kenya. *Ecosyst. Serv.* **40**, 101040 (2019).
- 751 32. Jayathilake, D. R. M. & Costello, M. J. A modelled global distribution of the seagrass
752 biome. *Biol. Conserv.* **226**, 120–126 (2018).

- 753 33. McKenzie, L. J. *et al.* The global distribution of seagrass meadows. *Environ. Res. Lett.*
754 **15**, 74041 (2020).
- 755 34. Mcowen, C. J. *et al.* A global map of saltmarshes. *Biodivers. Data J.* **5**, e11764 (2018).
- 756 35. Bunting, P. *et al.* The global mangrove watch—a new 2010 global baseline of
757 mangrove extent. *Remote Sens.* **10**, 1669 (2018).
- 758 36. Hamilton, S. E. & Casey, D. Creation of a high spatio-temporal resolution global
759 database of continuous mangrove forest cover for the 21st century (CGMFC-21).
760 *Glob. Ecol. Biogeogr.* **25**, 729–738 (2016).
- 761 37. Hamilton, S. E. & Friess, D. A. Global carbon stocks and potential emissions due to
762 mangrove deforestation from 2000 to 2012. *Nat. Clim. Chang.* **8**, 240–244 (2018).
- 763 38. Sanderman, J. *et al.* A global map of mangrove forest soil carbon at 30 m spatial
764 resolution. *Environ. Res. Lett.* **13**, 55002 (2018).
- 765 39. Saintilan, N. *et al.* Thresholds of mangrove survival under rapid sea level rise. *Science*
766 (80-.). **368**, 1118 LP – 1121 (2020).
- 767 40. Taillardat, P., Friess, D. A. & Lupascu, M. Mangrove blue carbon strategies for
768 climate change mitigation are most effective at the national scale. *Biol. Lett.* **14**,
769 20180251 (2018).
- 770 41. Kauffman, J. B. *et al.* Total ecosystem carbon stocks of mangroves across broad global
771 environmental and physical gradients. *Ecol. Monogr.* **90**, e01405 (2020).
- 772 42. Ouyang, X. & Lee, S. Y. Improved estimates on global carbon stock and carbon pools
773 in tidal wetlands. *Nat. Commun.* **11**, 317 (2020).

- 774 43. Worthington, T. A. *et al.* Harnessing Big Data to Support the Conservation and
775 Rehabilitation of Mangrove Forests Globally. *One Earth* **2**, 429–443 (2020).
- 776 44. Hutchison, J., Manica, A., Swetnam, R., Balmford, A. & Spalding, M. Predicting
777 Global Patterns in Mangrove Forest Biomass. *Conserv. Lett.* **7**, 233–240 (2014).
- 778 45. Atwood, T. B. *et al.* Global patterns in mangrove soil carbon stocks and losses. *Nat.*
779 *Clim. Chang.* **7**, 523–528 (2017).
- 780 46. Van Coppenolle, R., Schwarz, C. & Temmerman, S. Contribution of Mangroves and
781 Salt Marshes to Nature-Based Mitigation of Coastal Flood Risks in Major Deltas of the
782 World. *Estuaries and Coasts* **41**, 1699–1711 (2018).
- 783 47. Simard, M. *et al.* Mangrove canopy height globally related to precipitation,
784 temperature and cyclone frequency. *Nat. Geosci.* **12**, 40–45 (2019).
- 785 48. Trumbore, S. E. Potential responses of soil organic carbon to global
786 environmental change. *Proc. Natl. Acad. Sci.* **94**, 8284 LP – 8291 (1997).
- 787 49. Traganos, D. *et al.* Towards Global-Scale Seagrass Mapping and Monitoring Using
788 Sentinel-2 on Google Earth Engine: The Case Study of the Aegean and Ionian Seas.
789 *Remote Sens.* **10**, 1227 (2018).
- 790 50. Hossain, M. S. & Hashim, M. Potential of Earth Observation (EO) technologies for
791 seagrass ecosystem service assessments. *Int. J. Appl. Earth Obs. Geoinf.* **77**, 15–29
792 (2019).
- 793 51. Atwood, T. B., Witt, A., Mayorga, J., Hammill, E. & Sala, E. Global Patterns in
794 Marine Sediment Carbon Stocks . *Frontiers in Marine Science* vol. 7 165 (2020).

- 795 52. Coastal Carbon Atlas. (2019).
- 796 53. UNEP-WCMC, S. F. T. Global distribution of seagrasses (version 6.0). Sixth update to
797 the data layer used in Green and Short (2003). *Cambridge UN Environ. World*
798 *Conserv. Monit. Cent.* (2018) doi:<http://data.unep-wcmc.org/datasets/7>.
- 799 54. Howard, J., Hoyt, S., Isensee, K., Telszewski, M. & Pidgeon, E. Coastal blue carbon:
800 methods for assessing carbon stocks and emissions factors in mangroves, tidal salt
801 marshes, and seagrasses. (2014)
802 doi:https://www.cifor.org/publications/pdf_files/Books/BMurdiyarso1401.pdf.
- 803 55. Hammerstrom, K. K., Kenworthy, W. J., Fonseca, M. S. & Whitfield, P. E. Seed bank,
804 biomass, and productivity of *Halophila decipiens*, a deep water seagrass on the west
805 Florida continental shelf. *Aquat. Bot.* **84**, 110–120 (2006).
- 806 56. Pergent-Martini, C. *et al.* Descriptors of *Posidonia oceanica* meadows: Use and
807 application. *Ecol. Indic.* **5**, 213–230 (2005).
- 808 57. Esteban, N., Unsworth, R. K. F., Gourlay, J. B. Q. & Hays, G. C. The discovery of
809 deep-water seagrass meadows in a pristine Indian Ocean wilderness revealed by
810 tracking green turtles. *Mar. Pollut. Bull.* **134**, 99–105 (2018).
- 811 58. York, P. H. *et al.* Dynamics of a deep-water seagrass population on the Great Barrier
812 Reef: annual occurrence and response to a major dredging program. *Sci. Rep.* **5**, 13167
813 (2015).
- 814 59. Serrano, O. *et al.* Australian vegetated coastal ecosystems as global hotspots for
815 climate change mitigation. *Nat. Commun.* **10**, 4313 (2019).
- 816 60. Chmura, G. L., Anisfeld, S. C., Cahoon, D. R. & Lynch, J. C. Global carbon

- 817 sequestration in tidal, saline wetland soils. *Global Biogeochem. Cycles* **17**, 1111
818 (2003).
- 819 61. Hengl, T. *et al.* SoilGrids250m: Global gridded soil information based on machine
820 learning. *PLoS One* **12**, e0169748 (2017).
- 821 62. Rogers, K. *et al.* Wetland carbon storage controlled by millennial-scale variation in
822 relative sea-level rise. *Nature* **567**, 91–95 (2019).
- 823 63. Rovai, A. S. *et al.* Global controls on carbon storage in mangrove soils. *Nat. Clim.*
824 *Chang.* **8**, 534–538 (2018).
- 825 64. Worthington, T. A. *et al.* A global biophysical typology of mangroves and its
826 relevance for ecosystem structure and deforestation. *Sci. Rep.* **10**, 14652 (2020).
- 827 65. Maher, D. T., Call, M., Santos, I. R. & Sanders, C. J. Beyond burial: lateral exchange
828 is a significant atmospheric carbon sink in mangrove forests. *Biol. Lett.* **14**, (2018).
- 829 66. Santos, I. R., Maher, D. T., Larkin, R., Webb, J. R. & Sanders, C. J. Carbon outwelling
830 and outgassing vs. burial in an estuarine tidal creek surrounded by mangrove and
831 saltmarsh wetlands. *Limnol. Ocean.* **64**, 996–1013 (2019).
- 832 67. Kelleway, J. J. *et al.* A national approach to greenhouse gas abatement through blue
833 carbon management. *Glob. Environ. Chang.* **63**, 102083 (2020).
- 834 68. Goldberg, L., Lagomasino, D., Thomas, N. & Fatoyinbo, T. Global declines in human-
835 driven mangrove loss. *Glob. Chang. Biol.* **68**, (2020).
- 836 69. Richards, D. R. & Friess, D. A. Rates and drivers of mangrove deforestation in
837 Southeast Asia, 2000–2012. *Proc. Natl. Acad. Sci.* **113**, 344 LP – 349 (2016).

- 838 70. Thomas, N. *et al.* Distribution and drivers of global mangrove forest change, 1996–
839 2010. *PLoS One* **12**, e0179302 (2017).
- 840 71. Worthington, T. & Spalding, M. Mangrove restoration potential: A global map
841 highlighting a critical opportunity. (2018).
- 842 72. Kearney, M. S., Riter, J. C. A. & Turner, R. E. Freshwater river diversions for marsh
843 restoration in Louisiana: Twenty-six years of changing vegetative cover and marsh
844 area. *Geophys. Res. Lett.* **38**, (2011).
- 845 73. Lee, S. Y., Hamilton, S., Barbier, E. B., Primavera, J. & Lewis, R. R. Better restoration
846 policies are needed to conserve mangrove ecosystems. *Nat. Ecol. Evol.* **3**, 870–872
847 (2019).
- 848 74. Lovelock, C. E. & Brown, B. M. Land tenure considerations are key to successful
849 mangrove restoration. *Nat. Ecol. Evol.* **3**, 1135 (2019).
- 850 75. Herr, D., Blum, J., Himes-Cornell, A. & Sutton-Grier, A. An analysis of the potential
851 positive and negative livelihood impacts of coastal carbon offset projects. *J. Environ.*
852 *Manag.* **235**, 463–479 (2019).
- 853 76. Mojica Vélez, J. M., Barrasa García, S. & Espinoza Tenorio, A. Policies in coastal
854 wetlands: Key challenges. *Environ. Sci. Policy* **88**, 72–82 (2018).
- 855 77. Zeng, Y. *et al.* Economic and social constraints on reforestation for climate mitigation
856 in Southeast Asia. *Nat. Clim. Chang.* (2020) doi:10.1038/s41558-020-0856-3.
- 857 78. van Katwijk, M. M. *et al.* Global analysis of seagrass restoration: the importance of
858 large-scale planting. *J. Appl. Ecol.* **53**, 567–578 (2016).

- 859 79. Waycott, M. *et al.* Accelerating loss of seagrasses across the globe threatens coastal
860 ecosystems. *Proc. Natl. Acad. Sci.* **106**, 12377–12381 (2009).
- 861 80. Orth, R. J. *et al.* A Global Crisis for Seagrass Ecosystems. *Bioscience* **56**, 987–996
862 (2006).
- 863 81. Tan, Y. M. *et al.* Seagrass Restoration Is Possible: Insights and Lessons From
864 Australia and New Zealand. *Frontiers in Marine Science* vol. 7 (2020).
- 865 82. Greiner, J. T., McGlathery, K. J., Gunnell, J. & McKee, B. A. Seagrass restoration
866 enhances ‘blue carbon’ sequestration in coastal waters. *PLoS One* **8**, e72469 (2013).
- 867 83. Orth, R. J. *et al.* Restoration of seagrass habitat leads to rapid recovery of coastal
868 ecosystem services. *Sci Adv* **6**, (2020).
- 869 84. Cunha, A. H. *et al.* Changing Paradigms in Seagrass Restoration. *Restor. Ecol.* **20**,
870 427–430 (2012).
- 871 85. Rezek, R. J., Furman, B. T., Jung, R. P., Hall, M. O. & Bell, S. S. Long-term
872 performance of seagrass restoration projects in Florida, USA. *Sci. Rep.* **9**, 15514
873 (2019).
- 874 86. Kandus, P. *et al.* Remote sensing of wetlands in South America: status and challenges.
875 *Int. J. Remote Sens.* **39**, 993–1016 (2018).
- 876 87. Gallant, A. L. The Challenges of Remote Monitoring of Wetlands. *Remote Sens.* **7**,
877 10938–10950 (2015).
- 878 88. Unsworth, R. K. F. *et al.* Sowing the Seeds of Seagrass Recovery Using Hessian Bags.
879 *Frontiers in Ecology and Evolution* vol. 7 311 (2019).

- 880 89. Duarte, C. M., Dennison, W. C., Orth, R. J. W. & Carruthers, T. J. B. The Charisma of
881 Coastal Ecosystems: Addressing the Imbalance. *Estuaries and Coasts* **31**, 233–238
882 (2008).
- 883 90. de los Santos, C. B. *et al.* Recent trend reversal for declining European seagrass
884 meadows. *Nat. Commun.* **10**, 3356 (2019).
- 885 91. Pendleton, L. *et al.* Estimating Global “Blue Carbon” Emissions from Conversion and
886 Degradation of Vegetated Coastal Ecosystems. *PLoS One* **7**, e43542 (2012).
- 887 92. Deegan, L. A. *et al.* Coastal eutrophication as a driver of salt marsh loss. *Nature* **490**,
888 388–392 (2012).
- 889 93. Cardoso, P. G., Raffaelli, D. & Pardal, M. A. The impact of extreme weather events on
890 the seagrass *Zostera noltii* and related *Hydrobia ulvae* population. *Mar. Pollut. Bull.*
891 **56**, 483–492 (2008).
- 892 94. Rogers, K. Accommodation space as a framework for assessing the response of
893 mangroves to relative sea-level rise. *Singap. J. Trop. Geogr.* **42**, 163–183 (2021).
- 894 95. Marbà, N. & Duarte, C. M. Mediterranean warming triggers seagrass (*Posidonia*
895 *oceanica*) shoot mortality. *Glob. Chang. Biol.* **16**, 2366–2375 (2010).
- 896 96. Lefcheck, J. S., Wilcox, D. J., Murphy, R. R., Marion, S. R. & Orth, R. J. Multiple
897 stressors threaten the imperiled coastal foundation species eelgrass (*Zostera marina*) in
898 Chesapeake Bay, USA. *Glob. Chang. Biol.* **23**, 3474–3483 (2017).
- 899 97. Arias-Ortiz, A. *et al.* A marine heatwave drives massive losses from the world’s
900 largest seagrass carbon stocks. *Nat. Clim. Chang.* **8**, 338–344 (2018).

- 901 98. Kendrick, G. A. *et al.* A Systematic Review of How Multiple Stressors From an
902 Extreme Event Drove Ecosystem-Wide Loss of Resilience in an Iconic Seagrass
903 Community . *Frontiers in Marine Science* vol. 6 455 (2019).
- 904 99. Duke, N. C. *et al.* Large-scale dieback of mangroves in Australia’s Gulf of
905 Carpentaria: a severe ecosystem response, coincidental with an unusually extreme
906 weather event. *Mar. Freshw. Res.* **68**, 1816–1829 (2017).
- 907 100. Taillie, P. J. *et al.* Widespread mangrove damage resulting from the 2017 Atlantic
908 mega hurricane season. *Environ. Res. Lett.* **15**, 64010 (2020).
- 909 101. Asbridge, E., Lucas, R., Rogers, K. & Accad, A. The extent of mangrove change and
910 potential for recovery following severe Tropical Cyclone Yasi, Hinchinbrook Island,
911 Queensland, Australia. *Ecol. Evol.* **8**, 10416–10434 (2018).
- 912 102. Hickey, S. M. *et al.* Is climate change shifting the poleward limit of mangroves?
913 *Estuaries Coasts* **40**, 1215–1226 (2017).
- 914 103. Saintilan, N., Wilson, N. C., Rogers, K., Rajkaran, A. & Krauss, K. W. Mangrove
915 expansion and salt marsh decline at mangrove poleward limits. *Glob. Chang. Biol.* **20**,
916 147–157 (2014).
- 917 104. Whitt, A. A. *et al.* March of the mangroves: Drivers of encroachment into southern
918 temperate saltmarsh. *Estuar. Coast. Shelf Sci.* **240**, 106776 (2020).
- 919 105. Cavanaugh, K. C. *et al.* Sensitivity of mangrove range limits to climate variability.
920 *Glob. Ecol. Biogeogr.* **27**, 925–935 (2018).
- 921 106. Cavanaugh, K. C. *et al.* Poleward expansion of mangroves is a threshold response to
922 decreased frequency of extreme cold events. *Proc. Natl. Acad. Sci. U. S. A.* **111**, 723–

- 923 727 (2014).
- 924 107. Coldren, G. A., Langley, J. A., Feller, I. C. & Chapman, S. K. Warming accelerates
925 mangrove expansion and surface elevation gain in a subtropical wetland. *J. Ecol.* **107**,
926 79–90 (2019).
- 927 108. Yando, E. S. *et al.* Salt marsh-mangrove ecotones: using structural gradients to
928 investigate the effects of woody plant encroachment on plant--soil interactions and
929 ecosystem carbon pools. *J. Ecol.* **104**, 1020–1031 (2016).
- 930 109. Doughty, C. L. *et al.* Mangrove Range Expansion Rapidly Increases Coastal Wetland
931 Carbon Storage. *Estuaries and Coasts* **39**, 385–396 (2016).
- 932 110. Lovelock, C. E. *et al.* Sea level and turbidity controls on mangrove soil surface
933 elevation change. *Estuar. Coast. Shelf Sci.* **153**, 1–9 (2015).
- 934 111. Woodroffe, C. D. *et al.* Mangrove Sedimentation and Response to Relative Sea-Level
935 Rise. *Ann. Rev. Mar. Sci.* **8**, 243–266 (2016).
- 936 112. Lovelock, C. E. & Reef, R. Variable Impacts of Climate Change on Blue Carbon. *One*
937 *Earth* **3**, 195–211 (2020).
- 938 113. Nicholls, R. J. Coastal flooding and wetland loss in the 21st century: changes under the
939 SRES climate and socio-economic scenarios. *Glob. Environ. Chang.* **14**, 69–86 (2004).
- 940 114. Schuerch, M. *et al.* Future response of global coastal wetlands to sea-level rise. *Nature*
941 **561**, 231–234 (2018).
- 942 115. Adame, M. F. *et al.* Future carbon emissions from global mangrove forest loss. *Glob.*
943 *Chang. Biol.* **n/a**, (2021).

- 944 116. Griscom, B. W. *et al.* Natural climate solutions. *Proc. Natl. Acad. Sci.* **114**, 11645 LP
945 – 11650 (2017).
- 946 117. Friedlingstein, P. *et al.* Global carbon budget 2020. *Earth Syst. Sci. Data* **12**, 3269–
947 3340 (2020).
- 948 118. Morris, R. L., Boxshall, A. & Swearer, S. E. Climate-resilient coasts require diverse
949 defence solutions. *Nat. Clim. Chang.* **10**, 485–487 (2020).
- 950 119. Macreadie, P. I. *et al.* The future of Blue Carbon science. *Nat. Commun.* **10**, 3998
951 (2019).
- 952 120. Wylie, L., Sutton-Grier, A. E. & Moore, A. Keys to successful blue carbon projects:
953 Lessons learned from global case studies. *Mar. Policy* **65**, 76–84 (2016).
- 954 121. Howard, J. *et al.* Clarifying the role of coastal and marine systems in climate
955 mitigation. *Front. Ecol. Environ.* **15**, 42–50 (2017).
- 956 122. Lenihan, H. S. & Peterson, C. H. How Habitat Degradation Through Fishery
957 Disturbance Enhances Impacts of Hypoxia on Oysters Reefs. *Ecol. Appl.* **8**, 128–140
958 (1998).
- 959 123. Ellison, A. M., Felson, A. J. & Friess, D. A. Mangrove Rehabilitation and Restoration
960 as Experimental Adaptive Management. *Front. Mar. Sci.* **7**, 327 (2020).
- 961 124. Lester, S. E., Dubel, A. K., Hernan, G., McHenry, J. & Rassweiler, A. Spatial Planning
962 Principles for Marine Ecosystem Restoration. *Front. Mar. Sci.* (2020).
- 963 125. Herr, D. & Landis, E. *Coastal blue carbon ecosystems. Opportunities for Nationally*
964 *Determined Contributions.* (IUCN and Washington, DC, USA: TNC, 2016).

- 965 126. Apple. Conserving mangroves, a lifeline for the world. (2019).
- 966 127. Hochard, J. P., Hamilton, S. & Barbier, E. B. Mangroves shelter coastal economic
967 activity from cyclones. *Proc. Natl. Acad. Sci.* **116**, 12232 LP – 12237 (2019).
- 968 128. Herr, D., von Unger, M., Laffoley, D. & McGivern, A. Pathways for implementation
969 of blue carbon initiatives. *Aquat. Conserv. Mar. Freshw. Ecosyst.* **27**, 116–129 (2017).
- 970 129. Friess, D. A. *et al.* SDG 14: Life below Water – Impacts on Mangroves. in *Sustainable*
971 *Development Goals: Their Impacts on Forests and People* (eds. Pierce Colfer, C. J. *et*
972 *al.*) 445–481 (Cambridge University Press, 2019). doi:DOI: undefined.
- 973 130. Waltham, N. J. *et al.* UN Decade on Ecosystem Restoration 2021–2030—What
974 Chance for Success in Restoring Coastal Ecosystems? . *Frontiers in Marine Science*
975 vol. 7 71 (2020).
- 976 131. Convention on Biological Diversity. Conference of the Parties Decision X/2: Strategic
977 plan for biodiversity 2011–2020. www.cbd.int/decision/cop/?id=12268 (2011).
- 978 132. UNGA. Transforming our world: the 2030 Agenda for Sustainable Development. *Div.*
979 *Sustain. Dev. Goals New York, NY, USA* (2015).
- 980 133. Brander, L. M. *et al.* The global costs and benefits of expanding Marine Protected
981 Areas. *Mar. Policy* **116**, 103953 (2020).
- 982 134. Howard, J. *et al.* The potential to integrate blue carbon into MPA design and
983 management. *Aquat. Conserv.* **27**, 100–115 (2017).
- 984 135. Needelman, B. A. *et al.* The Science and Policy of the Verified Carbon Standard
985 Methodology for Tidal Wetland and Seagrass Restoration. *Estuaries and Coasts* **41**,

- 986 2159–2171 (2018).
- 987 136. Michaelowa, A., Hermwille, L., Obergassel, W. & Butzengeiger, S. Additionality
988 revisited: guarding the integrity of market mechanisms under the Paris Agreement.
989 *Clim. Policy* **19**, 1211–1224 (2019).
- 990 137. IPCC. *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas*
991 *Inventories: Wetlands*. (IPCC, 2014).
- 992 138. United Nations Environment Programme. *Out of the Blue: The Value of Seagrasses to*
993 *the Environment and to People*. (UNEP, Nairobi, 2020).
- 994 139. Murdiyarso, D. *et al.* The potential of Indonesian mangrove forests for global climate
995 change mitigation. *Nat. Clim. Chang.* **5**, 1089–1092 (2015).
- 996 140. Jones, T. *et al.* Madagascar’s Mangroves: Quantifying Nation-Wide and Ecosystem
997 Specific Dynamics, and Detailed Contemporary Mapping of Distinct Ecosystems.
998 *Remote Sensing* vol. 8 106 (2016).
- 999 141. Holmquist, J. R. *et al.* Uncertainty in United States coastal wetland greenhouse gas
1000 inventorying. *Environmental Research Letters* vol. 13 115005 (2018).
- 1001 142. Maher, D. T., Drexler, M., Tait, D. R., Johnston, S. G. & Jeffrey, L. C. iAMES: An
1002 inexpensive, Automated Methane Ebullition Sensor. *Environ. Sci. Technol.* **53**, 6420–
1003 6426 (2019).
- 1004 143. Primavera, J. H. & Esteban, J. M. A. A review of mangrove rehabilitation in the
1005 Philippines: successes, failures and future prospects. *Wetl. Ecol. Manag.* **16**, 345–358
1006 (2008).

- 1007 144. Silliman, B. R. *et al.* Facilitation shifts paradigms and can amplify coastal restoration
1008 efforts. *Proc. Natl. Acad. Sci.* **112**, 14295 LP – 14300 (2015).
- 1009 145. Enwright, N. M., Griffith, K. T. & Osland, M. J. Barriers to and opportunities for
1010 landward migration of coastal wetlands with sea-level rise. *Front. Ecol. Environ.* **14**,
1011 307–316 (2016).
- 1012 146. Burkholz, C., Garcias-Bonet, N. & Duarte, C. M. Warming enhances carbon dioxide
1013 and methane fluxes from Red Sea seagrass (*Halophila stipulacea*) sediments.
1014 *Biogeosciences* **17**, 1717–1730 (2020).
- 1015 147. Bianchi, T. S. *et al.* Historical reconstruction of mangrove expansion in the Gulf of
1016 Mexico: Linking climate change with carbon sequestration in coastal wetlands. *Estuar.*
1017 *Coast. Shelf Sci.* **119**, 7–16 (2013).
- 1018 148. Apostolaki, E. T. *et al.* Exotic *Halophila stipulacea* is an introduced carbon sink for the
1019 Eastern Mediterranean Sea. *Sci. Rep.* **9**, 9643 (2019).
- 1020 149. International Partnership for Blue Carbon. Blue Carbon and the Partnership.
1021 <https://bluecarbonpartnership.org/about/blue-carbon-and-the-partnership> (2017).
- 1022 150. Sapkota, Y. & White, J. R. Carbon offset market methodologies applicable for coastal
1023 wetland restoration and conservation in the United States: A review. *Sci. Total*
1024 *Environ.* **701**, 134497 (2020).
- 1025 151. Restore America’s Estuaries & Silvestrum. *VCS Methodology Methodology for tidal*
1026 *wetland and seagrass restoration*. (Verified Carbon Standard, 2015).
- 1027 152. Deverel, S., Oikawa, P., Dore, S., Mack, S. & Silva, L. *Restoration of California*
1028 *Deltaic and Coastal Wetlands*. (American Carbon Registry, 2017).

- 1029 153. Bell, J. & Lovelock, C. E. Insuring Mangrove Forests for Their Role in Mitigating
1030 Coastal Erosion and Storm -Surge: An Australian Case Study. *Wetlands* **33**, 279–289
1031 (2013).
- 1032 154. Reguero, B. G. *et al.* Financing coastal resilience by combining nature-based risk
1033 reduction with insurance. *Ecol. Econ.* **169**, 106487 (2020).
- 1034 155. Thomas, S. Blue carbon: Knowledge gaps, critical issues, and novel approaches. *Ecol.*
1035 *Econ.* **107**, 22–38 (2014).
- 1036 156. Boon, P. I. & Prahalad, V. Ecologists, economics and politics: problems and
1037 contradictions in applying neoliberal ideology to nature conservation in Australia.
1038 *Pacific Conserv. Biol.* **23**, 115–132 (2017).
- 1039 157. Adame, M. F. *et al.* The undervalued contribution of mangrove protection in Mexico
1040 to carbon emission targets. *Conserv. Lett.* **11**, e12445 (2018).
- 1041 158. Bell-James, J. & Lovelock, C. E. Legal barriers and enablers for reintroducing tides:
1042 An Australian case study in reconverting ponded pasture for climate change
1043 mitigation. *Land use policy* **88**, 104192 (2019).
- 1044 159. Gattuso, J.-P. *et al.* Ocean Solutions to Address Climate Change and Its Effects on
1045 Marine Ecosystems . *Frontiers in Marine Science* vol. 5 337 (2018).
- 1046 160. Saderne, V. *et al.* Role of carbonate burial in Blue Carbon budgets. *Nat. Commun.* **10**,
1047 1106 (2019).
- 1048 161. Duarte, C. M., Wu, J., Xiao, X., Bruhn, A. & Krause-Jensen, D. Can Seaweed Farming
1049 Play a Role in Climate Change Mitigation and Adaptation? *Frontiers in Marine*
1050 *Science* vol. 4 100 (2017).

- 1051 162. Froehlich, H. E., Afflerbach, J. C., Frazier, M. & Halpern, B. S. Blue Growth Potential
1052 to Mitigate Climate Change through Seaweed Offsetting. *Curr. Biol.* **29**, 3087-3093.e3
1053 (2019).
- 1054 163. Ritchie, H. & Roser, M. CO₂ and greenhouse gas emissions. *Our World Data* (2017).
- 1055 164. Smith, S. V. Marine macrophytes as a global carbon sink. *Science* (80-.). **211**, 838–
1056 840 (1981).
- 1057 165. IPCC, I. P. on C. C. Special Report on the Ocean and Cryosphere in a Changing
1058 Climate. (2019).
- 1059 166. Methodology, V. C. S. *VM0007: REDD+ Methodology Framework (REDD+ MF)*.
1060 (2020).
- 1061 167. Carnell, P. E. *et al.* Mapping Ocean Wealth Australia: The value of coastal wetlands to
1062 people and nature. (2019) doi:10.21153/carnell2019mapping.
- 1063 168. Jänes, H. *et al.* Stable isotopes infer the value of Australia’s coastal vegetated
1064 ecosystems from fisheries. *Fish and Fisheries* vol. 21 80–90 (2020).
- 1065 169. Jänes, H. *et al.* Quantifying fisheries enhancement from coastal vegetated ecosystems.
1066 *Ecosyst. Serv.* **43**, 101105 (2020).
- 1067 170. Huang, B. *et al.* Quantifying welfare gains of coastal and estuarine ecosystem
1068 rehabilitation for recreational fisheries. *Sci. Total Environ.* **710**, 134680 (2020).

1069 **Figure Legends**

1070 **Figure 1:** Description of blue carbon cycling and its publication timeline: (a) Key elements
1071 and processes in blue carbon cycling. 1: BCEs drawdown CO₂ from the atmosphere through

1072 photosynthesis, contributing to net accumulation of organic carbon within plant biomass and
1073 sediments – termed ‘autochthonous’ carbon. 2: BCEs can also accumulate organic carbon
1074 from outside sources (such as via terrestrial runoff, plankton), termed ‘allochthonous’ carbon.
1075 Anoxic sediment conditions and the positioning of BCEs in depositional settings (at the
1076 interface between land and sea) make them ideal for carbon accumulation. Net carbon
1077 drawdown represents ‘sequestration’, while the pool of accumulated blue carbon is referred
1078 to as the ‘stock’. 3: Environmental factors such as climate change and coastal development
1079 can diminish stored blue carbon stocks by making them more susceptible to microbial attack.
1080 Microbial respiration converts organic carbon into inorganic carbon, or greenhouse gases
1081 (such as CO₂). This figure was created using symbols from the Integration and Application
1082 Network (ian.umces.edu/media-library). (b) Timeline showing the evolution of blue carbon
1083 notable papers (classified as ‘ISI Highly Cited’ papers with ‘blue carbon’ title as at 3 June
1084 2021, plus one paper from 1981 that first reported the ‘blue carbon’ term), major moments in
1085 international climate change policy and significant events in Blue Carbon policy and
1086 management. (1: Smith ¹⁶⁴, 2: Nellemann et al. ⁶, 3: McLeod et al. ¹³, 4: Pendleton et al. ⁹¹, 5:
1087 Wylie et al. ¹²⁰, 6: IPCC ¹⁶⁵, 7: Macreadie et al. ¹¹⁹, and 8: Verra method for blue carbon ¹⁶⁶).

1088 **Figure 2:** Co-benefits (or ‘ecosystem services’) provided by blue carbon ecosystems that
1089 contribute to the livelihoods and wellbeing of coastal communities. The figure shows an
1090 example from the Mapping Ocean Wealth Australia Program, which has quantified
1091 (Australian dollar - AUD) and mapped the value of Fisheries ^{167–169}, Coastline protection ¹⁶⁷,
1092 and Recreation ^{167,170} provided by BCE.

1093 **Figure 3:** Global distribution of mangrove forests (Bunting et al. ³⁵), tidal marshes (Mcowen
1094 et al. ³⁴) and seagrass meadows (mapped ⁵³ and modelled ³² distributions).

1095 **Figure 4:** Potential distribution of blue carbon soil stocks (Tg C) per country: a) upper bound
1096 and b) lower bound, and blue carbon soil stocks per coastline length (Tg C/km): c) upper

1097 bound and d) lower bound. A full description of the methods and data sources used is
1098 available in the Supplementary Material. Note: blue carbon stocks are along the coastline (not
1099 inland). Colour coding by country is for display purposes only.

1100 **Figure 5:** Maximum mitigation potential at country level for avoided coastal impacts in
1101 mangrove forests ¹¹⁶, estimated annual loss rates (%) for seagrass ⁷⁹, tidal marshes ⁸⁹, and
1102 mangroves ^{36,68,116}, global average soil carbon stocks (for mineral soils) per area (95% CI) ¹³⁷,
1103 avoidable flux for avoided coastal wetland impacts pathway (Mg C ha⁻¹) ¹¹⁶, avoidable flux
1104 and additional sequestration rates (95% CI) for the coastal wetland restoration pathway (Mg
1105 C ha⁻¹ y⁻¹) ¹¹⁶, potential area extent available to restoration (Million ha) ¹¹⁶, maximum
1106 mitigation potential from avoided emissions due to conversion (i.e., mineralization of carbon
1107 stocks in biomass and soils, and loss of carbon sequestration potential; Tg CO₂e y⁻¹) ¹¹⁶ and
1108 maximum mitigation potential from restoration (i.e., mineralization of carbon stocks in
1109 biomass and soils, and recovery of carbon sequestration potential; Tg CO₂e y⁻¹) extracted
1110 from previous studies ¹¹⁶. Maximum mitigation potential for avoided emissions assumes that
1111 100% of the carbon stocks are lost following habitat loss ¹¹⁶ (1 Mg ha = 1,000,000 ha; 1 Tg =
1112 1,000,000 Mg). Uncertainty estimates in grey bars represent 95% confidence intervals Tidal
1113 marshes and seagrass meadows do not have information available on the potential for
1114 avoided emissions per country.

1115 **Figure 6:** Roadmap for incorporating local, national and demonstration project data into
1116 carbon accounting frameworks and conservation strategies. This figure was created using
1117 symbols from the Integration and Application Network (ian.umces.edu/media-library).

1118

1119

1120

1121

1122

1123

1124

1125

1126

1127

1128

1129

1130

1131

1132

1133

1134

1135

1136

1137