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The potential for ocean-based climate action: negative emissions technologies and beyond

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2 ABSTRACT

3 The effectiveness, feasibility, duration of effects, co-benefits, disbenefits, cost effectiveness
4 and governability of four ocean-based negative emissions technologies (NETs) are assessed
5 in comparison to eight other ocean-based measures. Their role in revising UNFCCC Parties'
6 future Nationally Determined Contributions is discussed in the broad context of ocean-based
7 actions for both mitigation and ecological adaptation. All measures are clustered in three policy-
8 relevant categories (Decisive, Low Regret, Concept Stage). None of the ocean-based NETs
9 assessed are identified as Decisive at this stage. One is Low Regret (*Restoring and increasing*
10 *coastal vegetation*), and three are at Concept Stage, one with low to moderate potential
11 disbenefits (*Marine bioenergy with carbon capture and storage*) and two with potentially high
12 disbenefits (*Enhancing open-ocean productivity* and *Enhancing weathering and alkalization*).
13 Ocean-based NETs are uncertain but potentially highly effective. They have high priority for
14 research and development.

15 **Keywords:** ocean-based solutions, blue carbon, bioenergy with carbon capture and storage, ocean fertilization, ocean alkalization,
16 climate action

1 INTRODUCTION

17 Implementing the Paris Agreement is a formidable challenge. In pathways limiting global warming to 1.5°C
18 with no or limited overshoot as well as in pathways with a higher overshoot, CO₂ emissions are reduced to
19 net zero globally around 2050 (IPCC, 2018). This would require far-reaching and unprecedented transitions
20 in all sectors, and also large-scale use of negative emissions technologies (NETs), that is removal of

21 greenhouse gases from the atmosphere by deliberate human activities. Yet the trade-offs for food production
22 and nature conservation limit carbon dioxide removal by most land-based approaches (Boysen et al., 2017).

23 In that context, it is timely to assess the opportunities offered by the ocean to reduce the causes and
24 also the consequences of climate change, globally and locally. Recent papers and reports have reviewed
25 several potential measures (Gattuso et al., 2018; Because the Ocean, 2019; National Academies of Sciences
26 Engineering and Medicine, 2018; GESAMP, 2019; Hoegh-Guldberg et al., 2019). Countries have so far
27 only made limited use of ocean-related measures for tackling climate change and its impacts through their
28 Nationally Determined Contributions (NDC) under the Paris Agreement (Gallo et al., 2017). Among the
29 161 initial NDCs submitted in 2014-2015, 70 mentioned marine issues, most frequently as components of
30 adaptation action or in regard to climate impacts. Just over a third (59) also included ocean-related mitigation
31 measures. The only ocean-based negative emission approach specifically mentioned is the conservation
32 and restoration of coastal blue carbon ecosystems (i.e. mangroves, saltmarshes and seagrasses). The 5-year
33 revisions of NDCs that need to be made before the re-scheduled COP26 in 2021 (26th Conference of the
34 Parties of the United Nations Framework Convention on Climate Change, UNFCCC), offer an opportunity
35 to adopt more ocean-inclusive mitigation and adaptation strategies.

36 Here we assess four ocean-based NETs involving carbon dioxide removal (*Marine bioenergy with carbon*
37 *capture and storage*, *Restoring and increasing coastal vegetation*, *Enhancing open-ocean productivity*,
38 *Enhancing weathering and alkalization*) and put them in the broader context of ocean-based measures to
39 support climate policies, especially greenhouse gas mitigation and ecological adaptation. These carbon
40 dioxide removal pathways are the most documented in the literature. Other pathways are not evaluated here
41 and it is likely that new methods or hybrids between the methods presented here will emerge. Building
42 on recently published material Gattuso et al. (2018), this Policy Brief brings two innovations. It assesses
43 marine-biomass-fueled bioenergy with carbon capture and storage (*Marine BECCS*) and goes a step further
44 by grouping these NETs and a wide range of other options into policy clusters with the aim of guiding
45 decisions on priority areas of action.

2 OCEAN NEGATIVE EMISSIONS TECHNOLOGIES

46 Gattuso et al. (2018) published a comprehensive expert assessment of ocean-based measures to reduce
47 climate change and its impacts based on a review of 862 publications and expert judgment. Here we focus
48 on NETs and consider eight criteria: (1) effectiveness to increase net carbon uptake, (2) effectiveness to
49 reduce ocean warming, ocean acidification, and sea level rise; (3) feasibility, covering both technological
50 readiness and lead time until full potential effectiveness; (4) duration of effects; (5) cost effectiveness; (6)
51 co-benefits; (7) disbenefits and (8) governability from an international perspective. Full information is
52 available in the supplementary material of Gattuso et al. (2018) and in Supplementary Material SM3.

53

54 2.1 Marine bioenergy with carbon capture and storage

55 Considering the area, water and nutrient requirements leads to the tentative conclusion that macroalgae
56 (seaweed) based BECCS could be a better long-term option than woody biomass energy crops, because
57 achievable productivity is higher, freshwater demands are eliminated, and nutrient demands may be lower if
58 efficient recycling systems can be developed (Lenton, 2014). Here we do not consider hybrid bioenergy with
59 carbon capture and storage approaches to focus on marine-biomass-fueled BECCS. The latter is expected
60 to involve three overarching steps: increasing carbon uptake by macroalgal aquaculture; converting the

61 biomass to biofuel; and deploying carbon capture (at power stations) and long-term geological storage.
62 Capron et al. (2020) review recent progress by US researchers in using macroalgae for biofuel.

63 The effectiveness of *Marine BECCS* to increase carbon uptake is scored high. Its effectiveness to moderate
64 ocean climate drivers is also scored high given the close relationship between CO₂ and ocean warming,
65 acidification and sea level rise.

66 However, feasibility is considered low because components of this approach have not all been
67 demonstrated at scale and may require a decade or more of research and development to prove capacity,
68 cost effectiveness and safety. Cost effectiveness (based on a single estimate) is high, at 26 US\$ per t CO₂
69 removed for marine biomass fueled BECCS.

70 Climate-relevant alternatives to using macroalgae for BECCS would be to develop methods for deep water
71 disposal of the additional biomass generated through macroalgal aquaculture (Williamson et al., 2021) and
72 the manufacturing of long-lived products, such as plastic, such as the manufacturing of long-lived products,
73 such as plastic, that displace products generating emissions, thereby avoiding emissions, or enhancing soil
74 fertility while contributing to carbon sequestration through use as biochar.

75 2.2 Restoring and increasing coastal vegetation

76 *Restoring and increasing coastal vegetation* (“blue carbon” ecosystems) aims at enhancing CO₂ uptake
77 and avoiding further emissions. Here we look at the implementation of this measure at the global scale,
78 by restoring a high proportion of the human-induced degraded salt marshes, mangroves and seagrasses
79 habitats of the planet.

80 Conservation and restoration of blue carbon ecosystems support and enhance CO₂ sequestration, whilst
81 also reducing emissions associated with habitat degradation and loss (Mcleod et al., 2011; Pendleton
82 et al., 2012; Duarte et al., 2013; Marbà et al., 2015; Howard et al., 2017; Hamilton and Friess, 2018). The
83 theoretical effectiveness of such measures at the global scale is limited by the maximum area that can
84 be occupied by these habitats, with their maximum global carbon burial estimated to be 234 Tg C per
85 year for salt marshes, mangroves and seagrasses combined (Mcleod et al., 2011). Assuming that historic
86 losses of blue carbon ecosystems (50% for mangroves since the 1940s, 29% for seagrass since 1879, 25%
87 for salt marshes since the 1800s; Mcleod et al., 2011; Waycott et al., 2009) are rapidly reversed through
88 restoration, the maximum cumulative carbon burial would be 26 Pg C until 2100, equivalent to about 2.5
89 years of current anthropogenic emissions. This is a theoretical upper estimate because of likely constraints
90 on implementation. The effectiveness to increase carbon uptake is therefore scored very low, noting also
91 that increased methane (CH₄) emissions may fully or partly negate the climatic benefits of CO₂ removal
92 (Al-Haj and Fulweiler, 2020; Rosentreter and Williamson, 2020). Carbonate formation or dissolution in
93 blue carbon habitats will also affect the capacity of these habitats to remove atmospheric carbon; although
94 dissolution may dominate, thereby increasing removal (Saderne et al., 2019), these processes have not yet
95 been explored sufficiently to provide global estimates.

96 Like carbon uptake, the effectiveness to moderate warming, acidification and sea level rise is limited
97 by the maximum area possibly occupied by these habitats, hence it is scored very low. Feasibility is high
98 as blue carbon approaches are well tested and deployed around the world (Howard et al., 2014) but the
99 full delivery of the benefits at their maximum global capacity will require years to decades to be achieved.
100 Protection of blue carbon habitats must be multi-decadal in order to be effective, and successful restoration
101 also requires a long term commitment (e.g., Duarte et al., 2013; Marbà et al., 2015; Reynolds et al., 2016)
102 — with the assumption that future temperature increases can be kept below 2°C (under higher warming, blue

103 carbon ecosystems are at risk, and their stored carbon is likely to be lost; Bindoff et al., 2019). The duration
104 of the effect is scored permanent, with those provisos. At median costs of 240, 30,000 and 7800 US\$ per
105 t CO₂, respectively for mangroves, saltmarshes and seagrass habitats, the cost effectiveness (for climate
106 mitigation) is collectively scored very low (Siikamaki et al., 2012; Bayraktarov et al., 2016; Narayan et al.,
107 2016), recognising that there are large differences in restoration costs between the three ecosystems (and at
108 the local level), and that the cost effectiveness of restoration for the delivery of other ecosystem services
109 could nevertheless be very high.

110 2.3 Enhancing open-ocean productivity

111 *Enhancing open-ocean productivity* (hereafter *Fertilization*) is based on nutrients addition directly or
112 indirectly to increase CO₂ drawdown by phytoplankton. Such methods may appear technologically feasible,
113 as it has been shown for iron/macronutrient addition, as well as for artificial upwellings (Pan et al., 2016).

114 For iron addition, modelling studies show a maximum effect on atmospheric CO₂ of 15 to 45 ppmv in
115 2100 (Zeebe and Archer, 2005; Aumont and Bopp, 2006; Keller et al., 2014). Ocean fertilization with
116 macro-nutrients (N, P) has a higher theoretical potential of 1.5 PgC yr⁻¹ (Harrison, 2017), about 50 times
117 more than the maximum simulated effects of Southern Ocean iron fertilization (Oschlies et al., 2010);
118 however, very large quantities of macronutrients are needed and the proposed scaling of this technique
119 seems unrealistic (Williamson and Bodle, 2016). For artificial upwelling (upward pumping of nutrient-rich
120 deep waters), the intended carbon removal by increased productivity (Lovelock and Rapley, 2007) may
121 be matched by the undesirable release of CO₂ from the deeper water (Shepherd et al., 2007; Dutreuil
122 et al., 2009; Yool et al., 2009). The potential impact of artificial upwellings on nitrogen fixation, and
123 hence on natural carbon sequestration is controversial (Fennel, 2008; Karl and Letelier, 2008). Some
124 modelling studies indicate that net CO₂ drawdown is theoretically possible if upwelling rates are increased
125 in appropriate locations in 2100 for RCP8.5. Because of the many associated uncertainties, the overall
126 effectiveness of *Fertilization* to increase carbon uptake is scored low.

127 *Fertilization* has no direct effect on sea level rise nor on ocean warming hence its effectiveness to
128 reduce those drivers is low. Acidification could be ameliorated in the short term in the upper ocean
129 (by CO₂ removal), but enhanced in the long term in the ocean interior (by CO₂ release); the overall
130 effectiveness is considered to be low. Effects would happen through increased carbon uptake but there is
131 limited scope for enhanced ocean productivity and increased carbon uptake due to biological and physical-
132 chemical constraints (Williamson and Bodle, 2016). Mesoscale variability in the strength of different
133 processes responsible for long-term carbon removal (Boyd and Vivian, 2019) make carbon accounting
134 highly uncertain. Furthermore, once *Fertilization* is started, it would need to be done continuously; if
135 not, a large part of the sequestered carbon will be returned to the atmosphere on decadal timescales
136 (e.g., Aumont and Bopp, 2006). Ocean *Fertilization* is considered to have negative consequences for 8
137 Sustainable Development Goals (SDGs), and a combination of both positive and negative consequences
138 for 7 SDGs (Honegger et al., in press). The cost of iron fertilization has been estimated at 22-119 and
139 457 US\$ per t CO₂ sequestered (Harrison, 2013). There are lower cost estimates for *Fertilization* using
140 macronutrients, at around US\$ 20 per t CO₂ (Jones, 2014), but scalability is questionable and monitoring
141 costs are excluded. The median of all estimates is 230 US\$ per t CO₂, indicating very low cost effectiveness.
142

143 2.4 Enhancing weathering and alkalization

144 Enhancing weathering and alkalization (hereafter *Alkalinization*) is the addition of natural or man-
145 made alkalinity (ground carbonate or silicate rocks, such as olivine or basalt), to enhance CO₂ removal
146 and/or carbon storage. Adding huge amounts of alkalinity globally could, in theory, substantially mitigate
147 atmospheric CO₂ without elevating biogeochemical properties significantly beyond naturally occurring
148 levels (Ilyina et al., 2013; Keller et al., 2014).

149 Since the carbon uptake capacity of this approach is very high, without a determined limit (Ciais et al.,
150 2013), its effectiveness to reduce ocean warming and acidification is also very high, with impacts on sea
151 level via surface air temperature (González and Ilyina, 2016). Regional *Alkalinization* could be effective in
152 protecting coral reefs against acidification (but not warming; Feng et al., 2016). There is technological
153 readiness to add alkalinity to the ocean, at least at small scales. What is needed is research and testing
154 to acquire adequate knowledge about the environmental co-benefits and disbenefits. Feasibility is also
155 impeded by lack of infrastructure to mine or produce, process and distribute alkalinity at large scales.
156 Feasibility is therefore scored very low.

157 A unit of alkalinity added would sequester CO₂ essentially permanently, hence the duration of the effect
158 is scored very high. Some of the inorganic carbon could precipitate as CaCO₃, releasing CO₂ and reducing
159 the carbon storage and alkalinity co-benefits afforded. The addition of alkalinity would probably have to be
160 continued for decades to centuries (or longer) to have a substantial impact on atmospheric CO₂ (Keller
161 et al., 2014).

162 The cost of various ocean alkalinity carbon storage technologies is largely speculative at this stage.
163 Renforth et al. (2013) indicated a range of 72-159 US\$ per t CO₂ taken up. This range reflects the extraction,
164 calcination, hydration, and surface ocean dispersion costs at a global scale (including transportation). In
165 the case of direct addition of alkaline minerals to the ocean (i.e., without calcination), the cost is 20-50
166 US\$ per t CO₂ (Harvey, 2008; Köhler et al., 2013; Renforth and Henderson, 2017). Overall, at 10-190 US\$
167 per t CO₂, the cost effectiveness is moderate.
168

3 POLICY-RELEVANCE OF NEGATIVE EMISSION TECHNOLOGIES

169 Understanding the policy relevance of NETs requires putting them into a broader context of global and/or
170 local climate action. Here we consider 12 ocean-related measures to enhance both global mitigation and
171 local coastal ecological adaptation¹ (Fig. 2). These options can be clustered into three overarching policy-
172 relevant clusters (Decisive, Low Regret, Concept Stage) that are defined in Panel A of Fig. 2 according to
173 their state of implementation, effectiveness to reduce climate-related ocean drivers globally, effectiveness
174 to reduce impacts/risks locally, and potential co-benefits and disbenefits (i.e. associated adverse impacts
175 and other undesirable consequences, including opportunity costs).

176 **Cluster 1** – The only ocean-based Decisive measure that we have identified addresses the causes of
177 climate change: *Marine renewable energy*. It includes energy from offshore winds, tides, waves, ocean
178 currents as well as thermal gradients. This action has the theoretical potential to meet all global electricity
179 requirements, although requiring massive infrastructure development. Whilst some local adverse impacts
180 are inevitable, these can be minimised.

¹ Societal adaptation measures such as infrastructure-based or community-based adaptation, risk reduction policies improvement, and the relocation of people, assets and economic activities are not included.

181 **Cluster 2** – Low Regret measures provide both climatic and non-climatic benefits, with few disbenefits.
182 For example, *Conservation* measures can protect carbon-rich coastal ecosystems from direct human
183 disturbance and loss, and play an important role in limiting local climate impacts. Similarly, *Restoring and*
184 *enhancing coastal vegetation* supports ecological adaptation whilst providing storm protection, contributing
185 to food security, and enhancing biodiversity. It can also increase carbon uptake (i.e. addressing the causes
186 of climate change), at levels that may be locally and/or nationally significant. Nevertheless, because of the
187 limited total area for restoring such blue carbon ecosystems and also associated methane emissions, this
188 action can only make a very small contribution to climate mitigation at the global scale (IPCC, 2019; Al-Haj
189 and Fulweiler, 2020). *Pollution reduction* in coastal waters removes contaminants and excess nutrients
190 that impair ecosystem function, thereby supporting ecosystem-based adaptation. Reducing atmospheric
191 pollution from shipping can also, to a limited degree, address the causes of climate change. However, Low
192 Regret measures are not cost-free, requiring well-informed planning and effective coordination over a wide
193 range of spatial and temporal scales.

194 **Cluster 3** – Concept Stage measures are illustrated by the NET *Marine BECCS*, and some forms of
195 *Assisted evolution* (alterations to species and genetics). The former would use cultivated macroalgae (or
196 possibly microalgae) as the biomass source for bioenergy. Such measures have potential but their feasibility
197 and cost-effectiveness for climatic benefits have yet to be demonstrated. Several measures have potentially
198 high disbenefits, as identified for *Fertilization*, *Alkalinization* and the sunlight reflection techniques of
199 marine *Cloud brightening* and *Surface albedo enhancement* (e.g. covering the ocean surface with reflective
200 foam). Whilst all these approaches have a very large theoretical potential to address climate change globally,
201 only *Fertilization* has been investigated through field experiments (although not carried out for climate
202 mitigation purposes), with limited success. Much more attention needs to be given to their governance and
203 public acceptability before they can be considered for implementation as climate policy responses. This
204 agrees with and extends the conclusion of Boyd and Vivian (2019) for marine geoengineering.

205 The effectiveness of measures such as *Assisted evolution* to support ecological adaptation critically
206 depends on the environmental and societal contexts of their implementation. For example, while some
207 *Assisted evolution* tools could have local benefits, others such as the spread of genetically alien populations
208 have serious risks.

209 The global governability of NETs refers in this study to the potential capability of the international
210 community (both nation states and international non-state actors) to implement them, managing associated
211 conflicts and harnessing mutual benefits. It is therefore a key dimension to be considered when discussing
212 the potential role of NETs within a broader range of climate actions. In our assessment, global governability
213 is considered moderate to very high for more than half of the measures considered (Fig. 1), but low to very
214 low for *Fertilization* and *Alkalinisation* as well as for *Assisted evolution* and the two SRM options (*Cloud*
215 *brightening*, *Surface Albedo enhancement*). *Marine BECCS* score is moderate: although this measure could
216 have high co-benefits and could be implemented at modest scale without having to rely on international
217 cooperation, wider scale implementation could raise serious national and international complications,
218 hence potentially requiring new governing arrangements and accounting, monitoring, and verification
219 entities. *Alkalinization* and *Fertilization* score very low, but for different reasons: concerns regarding their
220 potential adverse environmental impacts result in low public acceptability, reflected in political rejection of
221 such methods (and legal constraints) by the London Convention/London Protocol ², the UN Convention
222 on Biological Diversity, and other bodies. These findings align with recent conclusions that “marine

² As regulated by the London Protocol, with an amendment prohibiting such action unless constituting legitimate scientific research authorised under permit. That amendment has not yet legally entered force.

223 geoengineering” challenges the ability of the international law system, as it stands now, to govern the
224 implementation of these ideas (McGee et al., 2018).

4 CONCLUSION AND ACTIONABLE RECOMMENDATIONS

225 Other than by eliminating nearly all anthropogenic greenhouse gas emissions, there is no single measure
226 to dramatically accelerate progress in achieving the net zero target of the Paris Agreement. Nevertheless,
227 opportunities exist for all coastal countries to implement a wide range of ocean-based climate actions,
228 including negative emission approaches. Guidelines and actionable recommendations are required to
229 address the urgency of climate action. Marine geoengineering techniques (e.g., Boyd and Vivian, 2019)
230 and other ocean-based measures need to be assessed and ranked (e.g., Gattuso et al., 2018). Here we build
231 on previous assessments to provide a first attempt to define policy-relevant clusters for climate action, both
232 global mitigation and local ecological adaptation.

233 None of the four ocean-based NETs assessed are Decisive, one is Low Regret (*Restoring and increasing*
234 *coastal vegetation*), and three are at Concept Stage with either low to moderate potential disbenefits (*Marine*
235 *bioenergy with carbon capture and storage*) or with high potential disbenefits (*Enhancing open-ocean*
236 *productivity* and *Enhancing weathering and alkalization*). The next iteration of more ambitious NDCs
237 should scale up ocean-based climate action by prioritising the implementation of Decisive and Low Regret
238 measures, and urgently improving knowledge on Concept Stage measures. Decisive and Low Regret
239 measures are both key priorities for implementation because, on the one hand, the full implementation of
240 Decisive measures will not completely eliminate coastal risks while, on the other hand, the effectiveness
241 and security of Low Regret conservation/nature-based solutions are being put at risk by increasing climate
242 change and rising sea level. Concept Stage measures require further scientific investigations because the
243 full implementation of proven measures runs the risk of falling short of providing enough cost effective
244 NETs capacity.

245 Balancing ocean-based measures also calls for securing robust national-to-local enabling conditions and
246 enhanced international support for climate action. This is important because the majority of ocean-inclusive
247 NDCs are conditional on external financing and support. They were discussed at COP25, referred to
248 the “Blue COP”, and could be, with nature-based solutions, one of the priority concerns for COP26
249 and the subsequent Global Stocktake in 2023. Enhancing the enabling conditions can be achieved by (i)
250 strengthening the formal recognition of the ocean-climate nexus and the ocean as a provider of solutions
251 for climate change, and (ii) facilitating the UNFCCC Party delegations’ understanding of the role of
252 ocean-related measures and how to include them in the next generation of NDCs.

CONFLICT OF INTEREST STATEMENT

253 The authors declare that the research was conducted in the absence of any commercial or financial
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AUTHOR CONTRIBUTIONS

255 All co-authors contributed ideas, JPG wrote the first draft which was then finalized by all co-authors.

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265 No new data was generated in this policy brief.

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FIGURE CAPTIONS

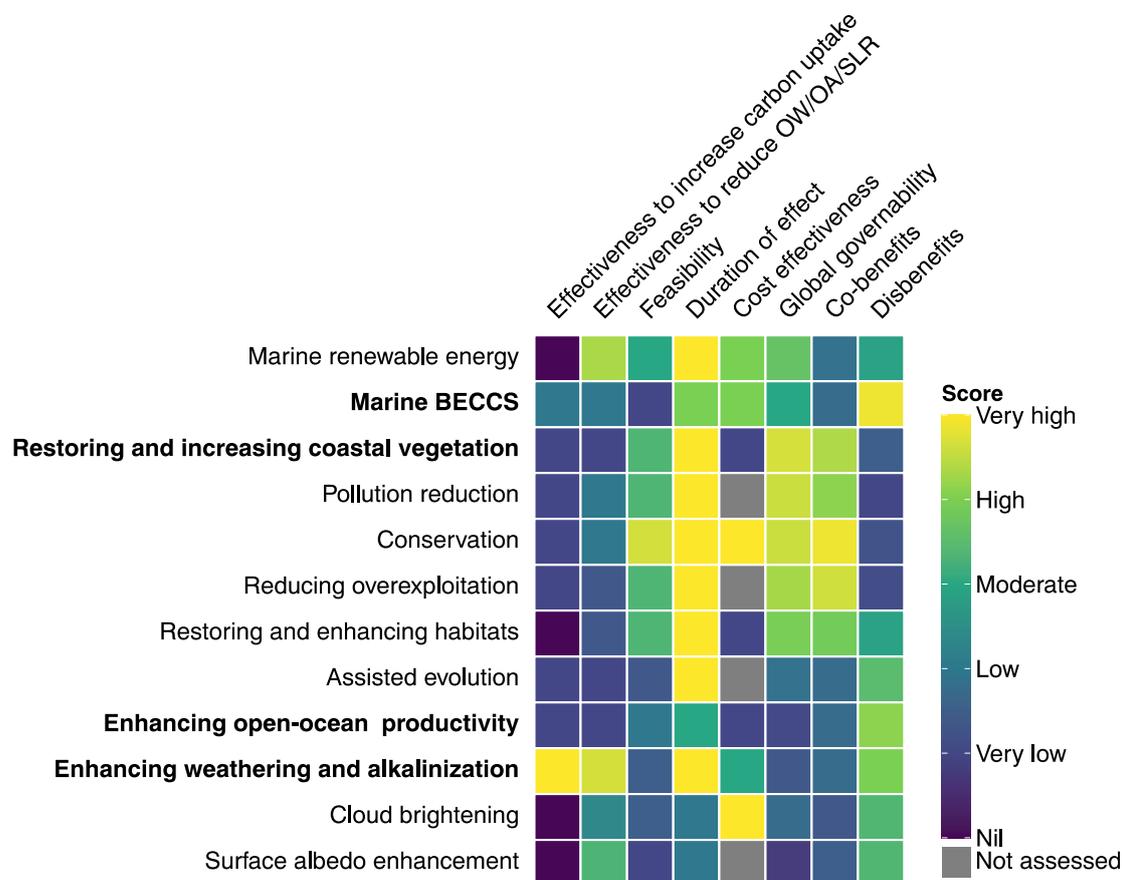


Figure 1. Fig. 1- Assessment of ocean negative emissions approaches (in bold) compared with other ocean-based measures. Based on Gattuso et al. (2018), except for marine BECCS (see SM3), with the following changes: Vegetation and Alkalinization are only considered at global scale except the co-benefits and disbenefits which are considered at local scale. Two criteria are newly defined by combining criteria assessed earlier. Feasibility is the mean of Technological readiness and Lead time until full potential effectiveness. Effectiveness to reduce OW/OA/SLR (ocean warming, ocean acidification and sea level rise) is the mean of the effectiveness to Moderate warming, Moderate acidification and Moderate sea level rise. Grey tiles indicate criteria not assessed for the corresponding measure. Further information on the measures and criteria are available in Supplementary Information SM1 and SM2.

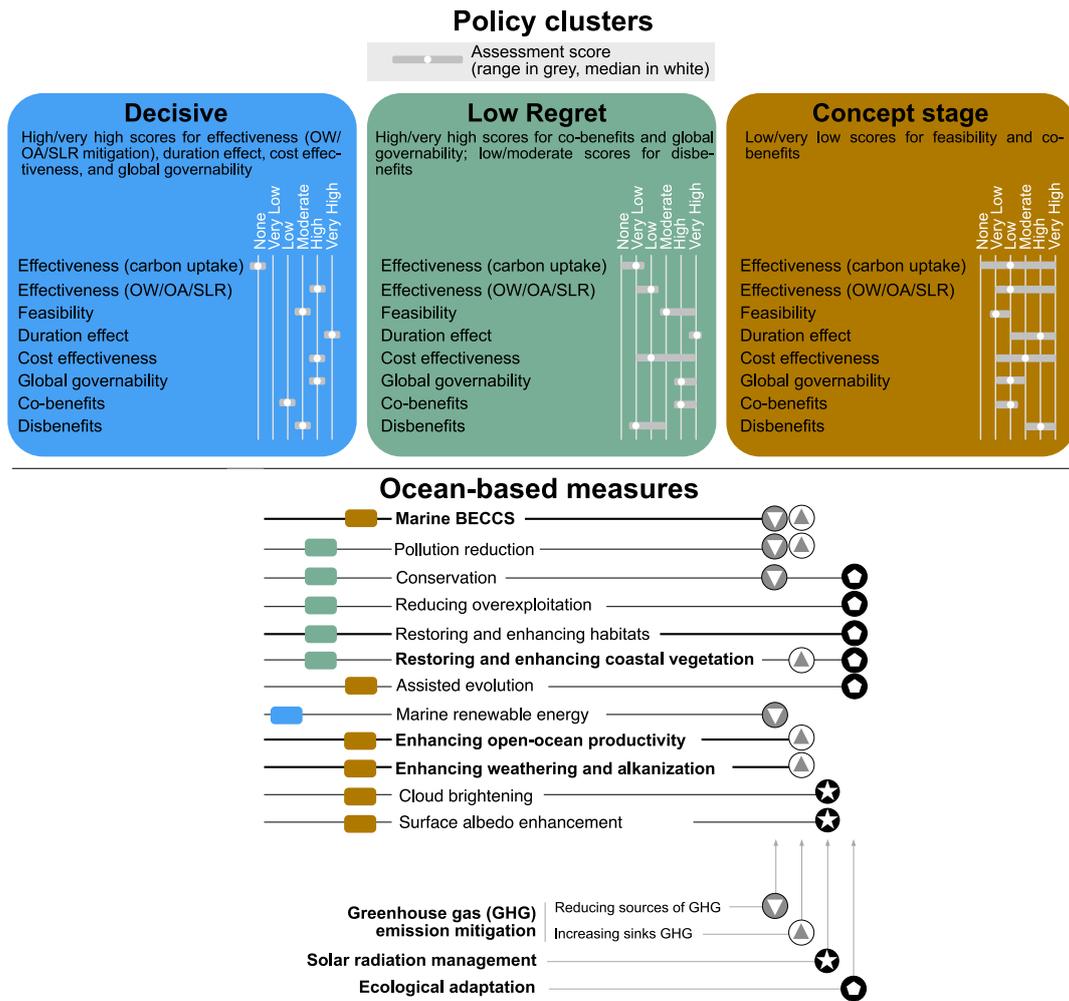


Figure 2. Policy clusters of ocean-based climate action. The measures considered are modified from Gattuso et al. (2018).