Supplementary Material
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Ocean solutions to address climate change and its effects on marine ecosystems

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Introduction to the Supplementary material

- **SM1** describes the 13 measures considered in this study. For each, it provides the heading used in the assessment tables and display items in the main manuscript, and a brief description (with examples).
- **SM2** describes the criteria used for the assessment of the measures. It also provides the methodological background for some criteria being the same in different assessment tables (see SM3).
- **SM3** presents the detailed results and rationale of the assessment scores:
  - Table 1a (Global effects of ocean solutions on key ocean drivers)
  - Table 1b (Local effects of ocean solutions on key ocean drivers)
  - Table 2 (Sensitivity of ecosystems and ecosystem services to key ocean drivers)
  - Table 3 (Contribution of ocean solutions to reduce the impacts of key ocean drivers on ecosystems and ecosystem services).
  - A complementary table provides results on governability (Table 4) which are also reported in Tables 1a and 1b.
- **SM4** provides information on the principal component analysis used to identify clusters of measures.
- **SM5** presents the bibliography used for this SM.

SM1. Glossary of the measures considered in the study

This section describes the 13 measures considered in this study. It provides, in bold, the heading used in the assessment tables and display items in the main manuscript, and a brief description (with examples).

1. Addressing causes: reducing greenhouse gas emissions and increase carbon storage

1.1. Renewable energy

Ocean energy substitution for fossil energy. The focus is on the extraction of physical and potentially chemical energy from or over the marine environment that is relatively rapidly replenished from natural sources, including from offshore wind. Hydrogen generation from seawater (e.g., Davis *et al.*, 2017) or by algae (e.g., Nikolaidis and Poullikkas, 2017) are not covered. Despite recent technical advances, these approaches are still very much at early stages of development.

1.2. Restoration and conservation of vegetation (hereafter "Vegetation")

Restoration and conservation of coastal vegetation to enhance CO_2 uptake and avoid further emissions. ***Vegetation (g)*** refers to the implementation of the solution at the global scale (e.g. restoring all the human-induced degraded salt marshes, mangroves and seagrasses habitats of the planet). ***Vegetation (l)*** refers to the ongoing implementation of the solution at the local scale ($< \sim 100$ km^2).

1.3. Fertilization

Fertilization is the enhancement of ocean productivity by adding nutrients. The focus is on i) the open ocean; ii) primary production by phytoplankton (and hence carbon uptake); iii) the use of iron as the added (micro)nutrient.

1.4. Alkalinization

Alkalinization is the addition of natural or man-made alkalinity, including intentional dissolution of calcium carbonate to enhance CO_2 removal and/or carbon storage.

1.5. Hybrid methods

Hybrids corresponds to measures involving both land and ocean components. These methods include: i) Marine-fueled bioenergy with carbon capture and storage (BECCS); ii) Marine- or land-fueled biomass energy + accelerated weathering of limestone; iii) Marine or land renewable energy based negative emissions electricity/H_2 with ocean alkalinity production; iv) Soil or ocean storage marine organic carbon and biochar; v) Burial of land crop waste in ocean sediment; and vi) Subsurface ocean or under sea floor storage of land-based direct air capture (DAC) or CO_2 generated by BECCS. Other methods initially considered but not included in this analysis are: i) Abiotic seawater extraction and use/storage of CO_2 (Eisaman *et al.*, 2012; Willauer *et al.*, 2014; Koweek *et al.*, 2016); and ii) Increasing marine consumption of and/or reducing marine emissions of other GHGs such as CH_4, N_2O, etc. (e.g. Poffenbarger *et al.*, 2011; Stolaroff *et al.*, 2012).

2. Solar radiation management

Solar radiation management (SRM) is also known as sunlight reflection management.

2.1. Cloud brightening

Marine cloud brightening (***cloud***) is about spraying seawater into the lower atmosphere to enhance the production, longevity and brightness of stratocumulus clouds. This approach is also called marine sky brightening because sea spray climate engineering is sometimes as efficient in clear-sky conditions as in cloudy-sky conditions (Ahlm *et al.*, 2017).

2.2. Albedo enhancement

Increase surface ocean ***albedo*** by producing long-lived ocean foam.

3. Protection of biota and ecosystems

3.1. Pollution reduction

Pollution reduction corresponds to the reduction marine and land-based pollution, including non-CO_2 drivers of ocean acidification (e.g. nitrogen, phosphorus and organic carbon from agricultural, industrial, urban and domestic sources causing eutrophication).

3.2. Restoring hydrology

Hydrology is about the maintenance and restoration of hydrological regime and delivery of water and sediment from watersheds to the coastal marine environment.

3.3. Eliminating overexploitation

Eliminating overexploitation of living resources (including vegetation and fish stocks) and over-extraction of non-living resources (e.g., sand, minerals) through management measures.

3.4. Protection

Protection of marine habitats and ecosystems through spatial measures including marine protected areas and no-take reserves.

4. Manipulation to enhance biological and ecological adaptation

4.1. Assisted evolution

Assisted evolution is the human intervention to accelerate the rate of naturally occurring evolutionary processes. The purpose of *assisted evolution* is to change certain characteristics of an organism, for example corals and bivalves resistance to stress such as elevated temperature and lower pH. Synthetic biology, which involves genome editing using natural of synthetic genes, is not considered because, to our knowledge, its feasibility has not been evaluated on marine species.

4.2. Relocation and reef restoration

Relocation refers to introduction of species, ecosystems and habitats where they were not historically present, but current and future climatic conditions will allow them to exist. ***Restoration*** refers to the enhancement of degraded habitats and ecosystems, and the creation of new habitats. Only coral and oyster reefs are considered here, as vegetated ecosystems (mangroves, salt marshes and seagrass habitats) are already considered in the "vegetation" measure above.

SM2. Glossary of the criteria used for the assessment

This expert assessment is based a an extensive survey of the literature which assembled 862 publications, 160 of which are cited in the paper and 455 in the present supplementary information. The scores and confidence levels of were discussed, assigned, and approved by the authors (except Jean-Olivier Irisson who became involved later) during three workshops in November 2016, Avril 2017, and May 2018.

This section describes the criteria used for the assessment of the solutions. It also provides the methodological background for some criteria being the same in different assessment tables (see SM3), i.e. technological readiness, lead time until full effectiveness, co-benefits, importance of disbenefits, cost effectiveness and governability from an international perspective. The methodological background for the "Effectiveness" criterion is developed in section SM3 as it is table-specific. The description of criteria mostly builds on Williamson and Bodle (Williamson and Bodle, 2016).

Confidence levels are assigned, wherever possible, to the scores. Confidence levels reflect the available peer-reviewed literature and are ranked according to IPCC guidelines (Mastrandrea and Mach, 2011), going from 1* to 5* as shown Table SM2.1.

Table SM2.1. *Confidence levels used in this study.*

Limited evidence High agreement **3***	Medium evidence High agreement **4***	Robust evidence High agreement **5***
Limited evidence Medium agreement **2***	Medium evidence Medium agreement **3***	Robust evidence Medium agreement **4***
Limited evidence Low agreement **1***	Medium evidence Low agreement **2***	Robust evidence Low agreement **3***

2. Sensitivity

Sensitivity refers to the degree to which an ecosystem or ecosystem service is affected, either adversely or beneficially, by changes in the three climate-related drivers that are considered in this study (i.e. ocean warming, ocean acidification and sea level rise). This definition is consistent with the one used in the IPCC (Agard et al. 2014), i.e. "the degree to which a system or species is affected, either adversely or beneficially, by climate variability or change." The effect may be direct (e.g., a change in the composition of biological communities in response to a change in the mean, range, or variability of temperature) or indirect (e.g., reduction of fishery yield caused by alteration of fish community structure due to ocean warming). Sensitivity is evaluated at levels of climate drivers that are consistent with the RCP8.5 scenario in 2100 (Table 2).

Scoring scale: 0 to 5

0: not sensitive (i.e. no matter how big the driver is, no effect or negative effect)
1: very low sensitivity
2: low sensitivity
3: moderate sensitivity
4: high sensitivity
5: very high sensitivity (changes in the 3 drivers under the RCP8.5 scenario cause massive species mortality and regression of an ecosystem and loss of ecosystem services).

Confidence levels: 1* to 5*

2. Potential maximum effectiveness

It is the magnitude of the solution's intrinsic or theoretical potential for both moderating the main climatic drivers of ocean changes (warming, acidification, sea level rise – see SM3.1 for the global scale, and SM3.2 for the local scale) and reducing the impacts of these changes to critical ecosystems and ecosystem services (SM3.4). The timeframe for evaluating this theoretical effectiveness is by 2100. The effectiveness is assessed against the solution's ability to bridge the gap between two contrasted Representative Concentration Pathways (RCP8.5 and

RCP2.6), assuming the full implementation of the solution in the coming decades. It is therefore a maximum potential effectiveness. This assessment of effectiveness does not consider impacts that are not directly generated by the drivers considered (e.g., the economic, societal, and non climate-related environmental impacts). The methodological background is different for global and local mesures and is developed in SM3.

Scoring scale: 0 to 5
0: no or negative effect
1: very low effect
2: low effect
3: moderate effect
4: high effect
5: very high effect
Confidence levels: 1* to 5*

3. Technological readiness

This criterion describes the actual stage of technological development for each of the assessed measures, thus distinguishing for instance measures only discussed theoretically and for which there is no deployment, from those that are already partly deployed.

Scoring scale: 1 to 5
1: concept stage
2: only laboratory experiments
3: first real-world experiments
4: significant deployment already, with needs for improvements
5: fully ready
Confidence levels: 1* to 5*

4. Duration of the effects

This criterion describes the duration of the effects once the measure is implemented, thus referring to the level of sustained commitment the solution requires to continue to produce benefits over time. A measure with permanent effect would continue to produce benefits permanently once implemented.

Scoring scale: 1 to 5
1: days to months
2: years
3: decades/centuries
4: centuries
5: permanent
Confidence levels: not assessed

5. Lead time until full potential effectiveness

This criterion indicates the time needed to achieve the full potential effectiveness of each measure to reduce drivers, either globally or locally, and related local impacts.

Scoring scale: 1 to 5

- This attribute was first scored as follows:
  1: decades
  2: years to decades
  3: years
  4: months to decades
  5: months to years
  6: months
  7: days to months
- For plotting and statistical analysis, it has then been rescaled on a 1 to 5 scale:
  1: decades
  1.7: years to decades
  2.3: years
  3: months to decades
  3.7: months to years
  4.3: months
  5: days to months

Confidence levels: not assessed

6. Co-benefits

This criterion is dealt with in Table 3 (SM3.4) as the contribution of ocean solutions to minimize the impacts of key ocean drivers on ecosystems and ecosystem services. It describes the additional benefits from the solutions that are not related to those from the direct reduction of climate drivers or their impacts. In this study, co-benefits include the improvement of the status of the ecosystems and/or the generation of ecosystem services while it does not consider the magnitude of benefits that human may obtain from such services. The narrower scope of the definition of co-benefit is because of the high uncertainty of the assessment of benefits to people that often depends on different socio-economic scenarios (which we are not considering in this study). For example, increased fish biomass production could be considered a co-benefit while the increased economic benefits from fishing are not. Co-benefit is qualitatively addressed notably in the Supplementary Information of Table 3 (“Caveats and limits” for ecosystems and ecosystem services, see SM4).

Scoring scale: 1 to 5
1: very low level of co-benefits
2: low level of co-benefits
3: moderate level of co-benefits
4: high level of co-benefits
5: very high level of co-benefits

Confidence levels: 1* to 5*

7. Disbenefits

This criterion is shown in Table 3 on the contribution of ocean solutions to minimize the impacts of key ocean drivers on ecosystems and ecosystem services. It is an antonym of co-benefit which describes adverse consequences or negative impacts of the solution on ecosystems and their services. For consistency with the other criteria, disbenefits are scored in such a way that higher scores are more desirable than lower ones.

Similar to co-benefits, the assessment of disbenefits does not consider the collateral negative effects on social systems *per se* (e.g. inequity in accessing economic activities or food resources) because such negative effects would depend on different socio-economic scenarios. Key assumptions in assessing disbenefits are qualitatively addressed in the Supplementary Information of Table 3 (“Caveats and limits” for ecosystems and ecosystem services, see SM4.4).

Scoring scale: 1 to 5, with a reverse scale compared to the other criteria. i.e.:
1: very high level of disbenefits
2: high level of disbenefits
3: moderate level of disbenefits
4: low level of disbenefits
5: very low level of disbenefits
Confidence levels: 1* to 5*

8. Cost effectiveness

This criterion describes the cost effectiveness each ocean measure according to today’s values. It is expressed in US\$/t CO_2 for global solutions (SM3.1, Table 1a) and in US\$/ha of surface area of implementation for local solutions (SM3.2, Table 1b). The differences in spatial scales of Tables 1a (global) and 1b (local) led to the use of different metrics for assessing solutions’ cost effectiveness but the method of assessment was the same for both scales. Each measure was given a score dependent on its cost effectiveness with a range from (1) for very low cost effectiveness to (5) for very high cost effectiveness. This score was associated with a level of confidence (1* to 5*) considering both the amount of available references and the level of the agreement among them. All measures received a low to very low level of confidence (2* for Alkalinisation at the global scale, and 1* for all the others), basically due to (i) the lack of cost data throughout the literature, (ii) the fact that some of the methods are in their infancy, and (iii) the likelihood for cost data to change, often downwards, while more testing and deployment is undertaken.

8.1. Global measures

The cost effectiveness of global measures was derived and scored as follows:

- Costs provided in the literature were converted to US\$/t CO_2;
- For each measure, the range of cost expressed in US\$/ t CO_2 was derived, either by citing the range provided from the literature, or by aggregating several ranges provided in different (sometimes the same) references. Therefore, we ended up with a range for each measure;

- The ranges were averaged;
- The averages were converted into scores from 1 to 5 using the scale shown below.

Scoring scale: 1 to 5
1: very low cost effectiveness (>160 US$/t CO_2)
2: low cost effectiveness (110 - 160 US$/t CO_2)
3: moderate cost effectiveness (60 - 110 US$/t CO_2)
4: high cost effectiveness (10 - 60 US$/t CO_2)
5: very high cost effectiveness (<10 US$/t CO_2)
Confidence levels: 1* to 5*

8.2. Local measures

The cost effectiveness of local measures was derived and scored as follows:

- Costs provided in the literature were converted to US$/ha of surface of implementation;
- For each measure, the range of cost expressed in US$/ha of surface area of implementation was derived, either by citing the range provided by the literature, or by aggregating several ranges provided in different (sometimes the same) references. Therefore, we ended up with a range for each measure;
- The ranges were averaged;
- These averages were converted into scores from 1 to 5 using a scale as shown below.

Scoring scale: 1 to 5
1: very low cost effectiveness (>400 US$/ha)
2: low cost effectiveness (300 - 400 US$/ha)
3: moderate cost effectiveness (200 - 300 US$/ha)
4: high cost effectiveness (100 - 200 US$/ha)
5: very high cost effectiveness (<100 US$/ha)
Confidence levels: 1* to 5*

9. Global governability

This criterion describes the potential for being governed at a global scale, that is, the capability of the global community of nation states and international no-state actors to mitigate conflicts and realize mutual gains in face of ocean-based solutions for climate change. We focus on supranational aspects of governability because the climate problem is a global problem, which requires cooperation and coordination between sovereign nation states and international non-state actors. The unique and defining feature of such governance above the level of nation states is the lack of a sovereign global entity that could regulate, monitor and enforce the implementation of solutions, which makes global governance specifically challenging (Kaul *et al*., 1999; Barrett, 2005; Walker *et al*., 2009). This is not to say that solving climate change problem does not include sub-national governance challenges. Addressing these would, however, require detailed analysis of sub-national actors, their interdependencies and diverse institutional arrangements for each country considered, which is beyond the scope of a single, global scale-focused paper. Hence, sub-national actors, national laws, rules and other governance arrangements are not considered here.

Scoring scale: 1 to 5 The scoring is described in SM3.6.
Confidence levels: not assessed

SM3. Assessment tables

SM3 provides the general methodological background of each table's scoring process, the final results of the assessment (that are made available through links to associated sheets), as well as the justification of the scores.

1. Global effects of ocean solutions on key ocean drivers (Table 1a)

1.1. Rationale and methodological background

We focus here only on ocean-based solutions that have been proposed to mitigate or counteract climate change at the global scale; ocean-based solutions implemented at the local scale are presented in SM3.2 (Table 1b). The solutions discussed here belong to the "Addressing causes" and "Solar radiation management" groups presented in SM1, i.e.: marine *Renewable energy*, *Vegetation*, *Fertilization*, *Alkalinization*, *Hybrid methods*, *Cloud brightening* and *Albedo enhancement*.

The effectiveness of a solution to mitigate any of the key drivers is based on its potential to bridge the gap between our baseline scenario (Representative Concentration Pathway 8.5, RCP8.5) and our target scenario (RCP2.6) over the 21st century. The difference between RCP8.5 and RCP2.6 are estimated at 1,400 PgC in terms of cumulative carbon emissions over 2012-2100 (see Table SPM.3 in IPCC, 2013) and/or at +2.7°C in terms of additional surface air warming at the end of the 21st century (see Table SPM.2 in IPCC, 2013).

For Carbon Dioxide Removal (CDR) approaches, the effectiveness to increase ocean carbon uptake by 2100 is scored 0 to 5 according to the following scale:

- 0: no carbon removing potential or negative effect on ocean carbon uptake
- 1: carbon removing potential of 0 to 250 PgC
- 2: carbon removing potential of 250 to 500 PgC
- 3: carbon removing potential of 500 to 750 PgC
- 4: carbon removing potential of 750 to 1000 PgC
- 5: carbon removing potential above 1,000 PgC

Most scores here rely on the use of Table 6.15 of Ciais *et al*. (Ciais *et al*., 2013).

Similarly, for Solar Radiation Management (SRM) approaches, the effectiveness to cool global climate is scored 0 to 5, according to the decrease in global-mean surface air temperature at the end of the 21st century:

- 0: no cooling potential
- 1: cooling potential of 0 to 0.5°C
- 2: cooling potential of 0.5 to 1°C
- 3: cooling potential of 1 to 1.5°C
- 4: cooling potential of 1.5 to 2°C
- 5: cooling potential of more than 2°C

We then derived the effectiveness to mitigate global ocean warming, global sea level-rise and global ocean acidification for each of the methods from the scores above. Unless specific to the method itself (see Supplementary information in SM4.1), the score for mitigating ocean surface warming equates that of increasing carbon uptake / cooling air surface temperatures. The score for mitigating global sea-level rise is the same as that of global ocean warming to which 1 is subtracted because of the inherent inertia of the sea-level rise response. Finally, the score for mitigating global ocean acidification depends on specificities of each of the method to reflect, for instance, large contrasts between CDR and SRM methods (see SM4.1).

For each solution, we also assessed the technological readiness (SM2.3); duration of the effect (SM2.4); lead time until effective (SM2.5); cost effectiveness (SM2.8; unit abatement cost of the solution measured in US$/t CO2eq); and governability (SM2.9). For score ranges, see the respective SMs.

1.2. Results

Table 1a (Assessment of the effects of globally implemented ocean-based solutions on key ocean drivers) is accessible here: http://www.obs-vlfr.fr/~gattuso/files/supplementary_tables.xlsx.

1.3 Justification of the scores of Table 1a

1.3.1. Renewable energy

– **Effectiveness to increase net carbon uptake -**In addition to off-shore winds, renewable energy in the ocean can come from several distinct sources of energy, i.e. waves, tides, ocean currents, ocean thermal energy conversion(OTEC) and salinity gradients. The theoretical potential for marine renewable energy has been estimated at up to 7400 EJ/yr (Rogner *et al*., 2000; Moomaw *et al*., 2011), without including off-shore winds. Its technical potential is estimated at more than 300 EJ/yr in 2050 (Krewitt *et al*., 2009). We have converted the theoretical potential in avoided carbon emissions, using a coefficient factor of 0.75 kgCO_2/kWh. The avoided emissions would amount to several hundreds of Pg C per year if the full theoretical potential was achieved.

- **Effectiveness to moderate warming** - No direct effect on warming, but the effectiveness to moderate warming was derived from the effectiveness to avoid carbon emissions through the subsequent effect on atmospheric CO_2 and global warming.
- **Effectiveness to moderate acidification** (upper ocean/global) - No direct effect on ocean acidification, but the effectiveness to moderate acidification was derived from the effectiveness to avoid carbon emissions through the subsequent effect on atmospheric CO_2.
- **Effectiveness to moderate global mean sea level rise** - No direct effect on sea level rise. Effects would happen through avoided carbon emissions and reduced warming
- **Technological readiness** - The development status for marine renewable energy technologies ranges from conceptual and pure research and development stages to prototype stages. Only tidal range and off-shore winds can be considered mature technologies (Moomaw *et al*., 2011).
- **Duration of the effect** - Once installed or deployed, the duration of the effect can be considered as permanent, as avoided emissions are sustained.
- **Lead time until full potential effectiveness** - decades. Despite high theoretical and technical potentials, the deployment of marine renewable energy in integrated scenarios to 2050 is seen as very limited, with a contribution of less than 0.1 EJ/yr (Scenario Database, Krey *et al*., 2014).
- **Cost effectiveness** - See SM2.8.
- **Global governability** - See SM2.9.

1.3.2. Fertilization

- **Effectiveness to increase net carbon uptake -** There is limited scope for enhanced ocean productivity and increased carbon uptake due to biological and physical-chemical constraints (Williamson and Bodle, 2016). For iron addition, modelling studies show a maximum effect on atmospheric CO_2 of 15 to 33 ppmv in 2100 for an idealized continuous global iron fertilization (Zeebe and Archer, 2005; Aumont and Bopp, 2006). More recent studies give similar numbers (complete elimination of iron limitation in the Southern Ocean shows a max effect of 45 ppmv on atmospheric CO_2 (in 2100 for RCP8.5; Keller *et al*., 2014, #76640). Ocean fertilization with macro-nutrients (N, P) is usually thought to be much less effective than adding Fe. A recent modelling study, however, shows a max effect of 1.5 PgC/yr (Harrison, 2017), which is about 50% higher than the maximum simulated effects of Southern Ocean iron fertilization of less than 1 Pg C/yr (Oschlies *et al*., 2010). Increasing carbon uptake is difficult and the proposed scaling of this technique seems unrealistic (Williamson and Bodle, 2016). For artificial upwelling, the intended carbon removal by increased productivity (Lovelock and Rapley, 2007) may be matched by the undesirable release of CO_2 from the deeper water (Shepherd *et al*., 2007; Dutreuil *et al*., 2009; Yool *et al*., 2009). The potential impact of artificial upwellings on N_2-fixation, and hence on carbon sequestration is controversial (Fennel, 2008; Karl and Letelier, 2008). Some modelling studies indicate that net $_{CO2}$ drawdown is theoretically possible if upwelling rates are increased in appropriate locations in 2100 for RCP8.5. This justifies a score of 1.
- **Effectiveness to moderate warming -** No direct effect on warming for all nutrient addition. Effects would happen through increased carbon uptake (see example in Keller *et al*., 2014), but may be quite effective at the local scale.
- **Effectiveness to moderate acidification** (upper ocean/global) - No direct effect on ocean acidification, but methods based on *fertilization* may lead to greater deep ocean acidification (Cao and Caldeira, 2010; Keller *et al*., 2014).
- **Effectiveness to moderate global mean sea level rise** - No direct effect on sea level rise for all nutrient addition. Effects would happen through increased carbon uptake and reduced warming. Artificial upwellings may locally even increase sea-level through increased uptake of anthropogenic heat.
- **Technological readiness** - Such methods may appear technologically feasible, as it has been shown for iron / macronutrient addition, as well as for artificial upwellings (Pan *et al*., 2016). Developments at larger scale may however be problematic (see Zeebe and Archer, 2005).
- **Duration of the effect** - decades to centuries. Several modelling studies have shown that when started, nutrient addition should be done continuously. Indeed, when stopped, a large part of the sequestered carbon may be reexposed to the atmosphere in decades to centuries (e.g. Aumont and Bopp, 2006).
- **Lead time until full potential effectiveness** - decades.
- **Cost effectiveness** - See SM2.8.
- **Global governability** - See SM2.9.

1.3.3. Alkalinization (global)

- **Effectiveness to increase net carbon uptake -** According to Ilyina et al. (Ilyina *et al.*, 2013) and Keller (Keller *et al.*, 2014), adding huge amounts of alkalinity globally could substantially mitigate atmospheric CO_2 and ocean acidification without environmental stress generated by elevating biogeochemical properties significantly beyond naturally occurring levels. According to Ciais et al. (Ciais *et al.*, 2013), this approach has no determined limit.
- **Effectiveness to moderate warming -** Addition of huge amounts of alkalinity globally could substantially reduce CO_2 induced global warming (Keller *et al.*, 2014).
- **Effectiveness to moderate acidification** (upper ocean/global) - Adding huge amounts of alkalinity globally could substantially mitigate atmospheric CO_2 and ocean acidification without environmental stress generated by elevating biogeochemical properties significantly beyond naturally occurring levels (Ilyina *et al.*, 2013; Keller *et al.*, 2014). Regional ocean alkalinization could be effective in protecting coral reefs against acidification (but not warming) (Feng *et al.*, 2016).
- **Effectiveness to moderate global mean sea level rise** - No direct effects on sea level. Impacts on sea level will work via surface air temperatures (González and Ilyina, 2016).
- **Technological readiness** - We are technically ready to add alkalinity to the ocean, at least at small scales. What is needed is research and testing to acquire adequate knowledge about the environmental co-benefits and disbenefits of doing so. Readiness is also impeded by lack of infrastructure to mine/produce and distribute alkalinity at large scales.
- **Duration of the effect** - A unit of alkalinity added would sequester CO_2 essentially permanently. See, for example, Keller (Keller *et al.*, 2014) for a model study with termination of alkalinity addition. If the alkalinity initially added to seawater is in the form of calcium carbonate (to consume CO2, forming dissolved calcium bicarbonate alkalinity, e.g. Harvey, 2008), the eventual precipitation of $CaCO_3$ from such alkalinity negates the carbon storage and alkalinity co-benefits afforded by the calcium bicarbonate. Yet the mean residence time of calcium in seawater is about 1 Myrs, implying a similar ocean residence time for carbon stored and alkalinity produced via calcium bicarbonate formation. Because of the huge amount of mass to be moved (and because of finite dissolution kinetics and possibly adverse local effects on ocean chemistry upon too fast addition of too much alkalinity), addition of alkalinity would probably have to be continued for decades to centuries (or longer) to have a substantial impact on atmospheric CO_2, etc.
- **Lead time until full potential effectiveness** – Decades.
- **Cost effectiveness** - See SM2.8.
- **Global governability** - See SM2.9.

1.3.4. Vegetation (global)

- **Effectiveness to increase net carbon uptake -** Conservation and restoration of blue carbon habitats support and enhance CO_2 sequestration and avoid emissions globally by conserving carbon stocks (Mcleod *et al.*, 2011; Pendleton *et al.*, 2012; Duarte *et al.*, 2013a; Marbà *et al.*, 2015; Howard *et al.*, 2017; Hamilton and Friess, 2018). The theoretical effectiveness of such measures to play a significant role at the global scale is limited by the maximum area possibly occupied by these habitats. The maximum global carbon burial of salt marshes, mangroves and seagrasses is 233.6 Tg C per year (Mcleod *et al.*, 2011) or a cumulative burial of 19 Pg C until 2100. Assuming that the upper estimates of historic losses of blue carbon ecosystems (50% for mangroves since the 1940s, 29% for seagrass since 1879, 25% for salt marshes since the 1800s; \Mcleod et al., 2011, #70450; Waycott et al., 2009, #41801} are compensated through restoration and using the burial rates of Mcleod (Mcleod *et al.*, 2011), the maximum, cumulative global carbon burial would be 26 Pg C, hence a score of 1.
- **Effectiveness to moderate warming -** Loss of coastal vegetation, including seagrass meadows, salt-marshes and mangrove forests, has led to loss of their intense carbon sink capacity along with carbon emissions from the large carbon stocks these habitats hold on their sediments (Nellemann *et al.*, 2009; Mcleod *et al.*, 2011; Pendleton *et al.*, 2012; Duarte *et al.*, 2013b), as well as loss of contributions of the export material from these habitats, as well as macroalgal stands, to carbon sequestration in oceanic reservoirs (Krause-Jensen and Duarte, 2016; Duarte and Krause-Jensen, 2017). Protection and restoration of blue carbon habitats avoids CO_2 emissions and loss of carbon sinks, thereby contributing to moderate warming. However, the capacity of this solution to moderate warming is limited by the maximum area possibly occupied by these habitats along the land-ocean interface.
- **Effectiveness to moderate acidification** (upper ocean/global) - The avoidance of CO_2 emissions and loss of carbon sinks derived from the restoration and conservation of blue carbon habitats helps slow down the accumulation of atmospheric CO_2 (Nellemann *et al.*, 2009; Mcleod *et al.*, 2011; Pendleton *et al.*, 2012; Duarte *et al.*, 2013b).
- **Effectiveness to moderate global mean sea level rise** - The avoidance of CO_2 emissions and loss of carbon sinks derived from the restoration and conservation of blue carbon habitats helps slow down the accumulation of

atmospheric CO_2 (Nellemann *et al*., 2009; Mcleod *et al*., 2011; Pendleton *et al*., 2012; Duarte *et al*., 2013b) and, therefore, indirectly moderate sea-level rise
– **Technological readiness** - Blue carbon approaches are well tested and deployed around the world, including IPCC-approved emission factors for mangroves and salt-marshes (Howard *et al*., 2014). Guidelines to ensure the success of seagrass restoration have been recently formulated, based on an analysis of all available experiences (van Katwijk *et al*., 2016). The recovery of carbon sink capacity and protection of stocks following conservation and restoration are also well supported by evidence including seagrass ecosystems (Duarte *et al*., 2013a; Greiner *et al*., 2013; Sutton-Grier *et al*., 2014; Marbà *et al*., 2015; Reynolds *et al*., 2016; Wylie *et al*., 2016; Wylie *et al*., 2016) and mangrove ecosystems, as demonstrated by the successful complete restoration of the Mekong Delta mangrove forest - the largest-scale ecosystem restoration ever attempted by humans (Nam *et al*., 2016) - after its complete destruction during the USA-Vietnam war.
– **Duration of the effect** - Permanent. Restoration and conservation of blue carbon habitats would have a permanent effect in terms of avoided carbon emissions / increased carbon uptake. But protection of blue carbon habitats must be permanent in order to be effective, whereas restoration approaches require limited time commitment, but are most successful when followed over time (e.g., Duarte *et al*., 2013a; Marbà *et al*., 2015; Reynolds *et al*., 2016).
– **Lead time until full potential effectiveness** - Whereas conservation and restoration of blue carbon habitats can be deployed within annual time scales, the full delivery of the benefits at their maximum global capacity will require years to decades to be achieved.
– **Cost effectiveness** - See SM2.8.
– **Global governability** - See SM2.9.

1.3.5. Hybrid methods

– **Effectiveness to increase net carbon uptake** - Collectively these methods are very effective in increasing CO2 uptake and storage from point and non-point sources, potentially at global scales, e.g., marine-biomass-fueled bioenergy and carbon capture and storage (Hughes *et al*., 2012; Lenton, 2014); bioenergy and accelerated weathering of limestone (Rau, 2011; Taylor *et al*., 2016); marine-renewable-energy-based negative emissions electricity/H_2 (House *et al*., 2007; Rau, 2008; Rau *et al*., 2013; Lu *et al*., 2015); marine biochar (Roberts *et al*., 2015); crops (Strand and Benford, 2009); direct air capture or bioenergy and CO_2 injection into or under the ocean (Caldeira *et al*., 2005; Schrag, 2009; Reith *et al*., 2016). Net effectiveness of the preceding also depends on security of sequestration, the sea-to-air CO_2 rebound effects (Cao and Caldeira, 2010; Vichi *et al*., 2013), and degree of emissions reduction by other methods. The confidence level of scores for this category represents an approximate estimated average among the preceding approaches.
– **Effectiveness to moderate warming -** Given close relationship between CO_2 and warming, effectiveness here is closely correlated with effectiveness to increase carbon/GHG uptake (above), though with increased uncertainty. See the scoring methodology in SM3.1.
– **Effectiveness to moderate acidification** (upper ocean/global) - Effectiveness here somewhat lower than effectiveness to increase C uptake with equivalent uncertainty (above). See the scoring methodology in SM3.1. Exceptions: i) Storage of captured CO_2 in the water column increases ocean acidity; and ii) Conversion of CO_2 to alkalinity, and subsequent storage in the water column moderates ocean acidity and counters acidification effects (i.e., increases carbonate saturation state). Mathesius et al. (Mathesius *et al*., 2016) point out that global, post-emissions CO_2 removal cannot quickly restore ocean pH in the subsurface ocean.
– **Effectiveness to moderate global mean sea level rise** - Diminished effectiveness with greater uncertainty relative to effectiveness to moderate warming. See the scoring methodology in SM3.1.
– **Technological readiness** - Many of the methods have not been demonstrated at scale and may require a decade or more of research and development to prove capacity, cost effectiveness and safety.
– **Duration of the effect** - Long term effect of CO_2 removed from the ocean/atmosphere system, however, will be diminished via sea-to-air re-equilibration (Cao and Caldeira, 2010).
– **Lead time until full potential effectiveness** - A decade or more.
– **Cost effectiveness** - See SM2.8.
– **Global governability** - Would probably require new governing, accounting, monitoring, and verification entities. See SM2.9.

1.3.6. Cloud brightening

– **Effectiveness to increase net carbon uptake -** Limited information is available. Model simulations indicate slight decrease in global ocean net primary production and ocean carbon uptake when using Marine Cloud Brightening (MCB)-based SRM in RCP4.5 scenario (Partanen *et al*., 2016)). Strong regionality of ocean effects likely, depending on MCB deployment locations. Also regionality of effects on terrestrial productivity, mostly via precipitation changes; both negative and positive effects seem possible (Muri *et al.*, 2015).

- **Effectiveness to moderate warming -** High theoretical effectiveness of MCB at global scale in many, but not all, model simulations, counteracting mean radiative forcing of up to 5 Wm^{-2} (~600 ppm CO_2) (Alterskjær *et al.*, 2012; Partanen *et al.*, 2012). Cooling effectiveness depends on achieving large increases in cloud droplet number concentration, and hence cloud albedo, for >50% of Earth's surface. There are many technical uncertainties relating to attainability at that scale (Latham *et al.*, 2012; Stuart *et al.*, 2013; Connolly *et al.*, 2014). Spatial heterogeneity of effects is likely, linked to sea-spray injection techniques and locations (Kravitz *et al.*, 2013; Partanen *et al.*, 2016), resulting in global mean radiative forcing potential of only about 1 W m^{-2} (Partanen *et al.*, 2016). For example, Pacific-only MCB deployment could achieve mean global cooling yet still with Arctic warming and with major changes in weather patterns elsewhere (Baughman et al. 2012). Arctic-only MCB may be able to achieve Arctic cooling (Kravitz *et al.*, 2014; Latham *et al.*, 2014). There however still many uncertainties.
- **Effectiveness to moderate acidification** (upper ocean/global) - No direct effects on ocean acidification. Potential for modest indirect benefits (as for other SRM techniques) if MCB is effective in limiting warming and terrestrial biospheric CO_2 release. Magnitude of ocean acidification amelioration depends on RCP comparison made (Matthews *et al.*, 2009; Keller *et al.*, 2014). Acidification might become slightly more severe because of higher solubility at lower temperatures (Keller *et al.*, 2014).
- **Effectiveness to moderate global mean sea level rise** - No direct effects on sea level rise. Potential for indirect benefits (as for other SRM techniques) if MCB is effective in limiting warming, particularly at high latitudes.
- **Technological readiness** - Requirement for robust, at-sea spraying system capable of producing particles of required physical properties. Designs exist (Salter *et al.*, 2008) and engineering issues relating to spray formation have been considered (Latham *et al.*, 2012). Cloud full deployment requires ~1500 spray vessels: these might be wind-powered (Flettner rotors) and unmanned.
- **Duration of the effect** - Duration is given by the lifetime of clouds, i.e. days to a week.
- **Lead time until full potential effectiveness** - Probably several decades. Extensive field trials (with ships and aircraft) will initially be required to investigate feasibility and effectiveness (Latham *et al.*, 2012). Regulatory issues will not be straightforward; they have not been given attention to date.
- **Cost effectiveness** - See SM2.8.
- **Global governability** - See SM2.9.

1.3.7. Albedo enhancement

- **Effectiveness to increase net carbon uptake -** Not specifically investigated. Whilst surface downward shortwave (light) flux would be reduced, this did not significantly reduce ocean primary production in model simulations (Hardman-Mountford *et al.*, 2013; Crook *et al.*, 2016). A likely side effect of surfactants added to stabilize foam as well as the addition of material at the sea surface could be the reduction of air-sea gas exchange.
- **Effectiveness to moderate warming -** Effectiveness depends on particular method and spatial area (Seitz, 2011). Based on existing shipping, a global forcing of ~1 Wm^{-2} has been simulated with microbubbles (with surfactants to prolong bubble-life) that increase ship-wake albedo by 0.2 and wake-lifetime by ~1500 (Crook *et al.*, 2016). Modelling of Arctic-only ocean albedo change, with generic albedo-change method, had a much smaller global effect, but large regional effects of more than 5 W/m2 over the Arctic Ocean (Cvijanovic *et al.*, 2015; Mengis *et al.*, 2016), similar to model results for the subtropical gyres of the southern hemisphere (Gabriel *et al.*, 2017). Extrapolating these regional effects to global albedo enhancement, we arrive at a very high score for the potential moderation of warming. From theoretical calculations, Seitz (2011) inferred that for small enough bubbles (micrometer range) a fraction of air in water in the range of 1 to 10 ppmv could have a cooling potential of several tens of Wm^{-2}.
- **Effectiveness to moderate acidification** (upper ocean/global) - Not investigated, but may be regionally significant. Bubbles could enhance gas exchange, whilst surfactants (or floating reflectants) could inhibit it (Crook *et al.*, 2016).
- **Effectiveness to moderate global mean sea level rise** - Only indirect effect, via cooling. If existing shipping is used, main cooling effect would be northern hemisphere.
- **Technological readiness** - Some ongoing work in developing long-lived foams and reflectants (Aziz *et al.*, 2014; Rowland *et al.*, 2015). Production of microbubbles by ships may increase fuel efficiency by 5-10% (by reducing drag; Kumagai *et al.*, 2015, #81942).
- **Duration of the effect** - Not much information available. Foams unclear. Lifetime of bubble wakes has been estimated as a few weeks (Crook *et al.*, 2016).
- **Lead time until full potential effectiveness** - Likely to be decades for full implementation; could be started sooner at much smaller scale, to assess impacts.

- **Cost effectiveness** - We have to take into account the additional energy of a ship, while performing an itinerary, which is needed in order to create the turbulence and the corresponding foam, and also the cost of the chemicals which are going to be delivered → No data provided-no score.
- **Global governability** - See SM2.9.

2. Local effects of ocean solutions on key ocean drivers (Table 1b)

2.1. Rationale and methodological background

We assessed the potential effectiveness of locally implemented ocean-based solutions to reduce, at the local scale, the key ocean drivers (warming, acidification, and sea-level rise, and also net carbon uptake) and their impacts to coastal and marine ecosystems (Kappel, 2005; Lawler *et al*., 2006; Billé *et al*., 2013; Gattuso *et al*., 2015). We considered measures under the "Protection of biota and ecosystems" and "Manipulation to enhance biological and ecological adaptation" areas of action (SM1). The four approaches considered under "Protection of biota and ecosystems" (Pollution reduction, Restoring hydrology, Eliminating overexploitation, Protection), while not exhaustive, represent the major approaches designed to protect biodiversity, ecosystem function, and services. We did not include management actions to reduce disease because, while it may have significant impacts to specific ecosystems in some areas (e.g., coral reefs in the Caribbean), disease is not considered a globally significant threat (Lawler *et al*., 2006) to all ecosystems, species, and services included in this analysis, i.e. seagrass, coral reefs, mangroves and salt marshes, polar biota, finfish and bivalves fisheries, aquaculture, and coastal protection.

The effectiveness was scored according to the literature and expert consensus. As for the global measures above (section 1), the effectiveness describes the solution's potential to bridge the gap between our baseline scenario (RCP8.5) and our target scenario (RCP2.6) over the 21st century. Scores were thus assigned according to the solution's potential to bring changes in key ocean drivers from their level according to the RCP8.5-related 2100 to their level expected according to RCP2.6 (i.e., reducing local relative sea-level rise by the global mean difference between RCP8.5 and RCP2.6 gets a score of 5; reducing local temperature by the global mean difference between RCP8.5 and RCP2.6 gets a score of 5).

For each solution, we also assessed the technological readiness (SM2.3), duration of the effect (SM2.4), lead time until effective (SM2.5), cost effectiveness (SM2.8); and governability (SM2.9).

2.2. Results

Table 1b (Assessment of additional effects of locally implemented ocean-based solutions on key ocean drivers) is accessible here: http://www.obs-vlfr.fr/~gattuso/files/supplementary_tables.xlsx.

2.3 Justification of the scores of Table 1b

2.3.1. Vegetation (local)

- **Effectiveness to increase net carbon uptake -** Conservation and restoration of blue carbon habitats support and enhance CO_2 sequestration and avoid emissions globally (cf. Table 1a) by conserving carbon stocks but they do not increase carbon uptake locally. Indirect effects as protection of healthy blue carbon ecosystems as they support carbon sequestration (see effectiveness to increase carbon uptake above); when degraded they can release emissions.
- **Effectiveness to moderate local warming -** The effectiveness of restoring and conserving vegetation to moderate warming will be felt globally, not at local levels (cf. Table 1a).
- **Effectiveness to moderate local acidification -** The protection and restoration of coastal and marine habitats can help to reduce ocean acidification at local scales. Mangroves and seagrasses have been found to reduce OA locally (e.g., Mcleod *et al*., 2013; Unsworth *et al*., 2012; Manzello *et al*., 2012; Garrard *et al*., 2014; Sippo *et al*., 2016). Seagrass habitats have been documented in the Caribbean (Manzello *et al*., 2012) and the Mediterranean (Hendriks *et al*., 2014) to elevate local mean pH.
- **Effectiveness to moderate relative sea level rise -** Protection and restoration of mangroves, salt marshes and seagrasses can reduce sea level rise locally as these habitats reduce wave height and energy. Salt marshes play an important role in wave attenuation and shoreline stabilization (Shepard *et al*., 2011) and can reduce the height of damaging waves in storm surge conditions by close to 20% (Möller *et al*., 2014). Mangroves can reduce the height of wind and swell waves (Bao, 2011)and tsunami impacts (Alongi, 2015); wave height can be reduced by between 13-66% over 100 m of mangroves (McIvor *et al*., 2012). Seagrasses also can attenuate the wave height and wave energy with a percentage of wave reduction by as much as 50% using artificial seagrass (John *et al*., 2015), and 40% with natural seagrass (Fonseca and Cahalan, 1992).

- **Technological readiness -** High as no new technology is needed and examples of best practices implementing conservation and restoration exist (e.g., Erwin, 2009; Roman and Burdick, 2012; UNEP and CIFOR, 2014; van Katwijk *et al*., 2016).
- **Duration of the effect -** Depends on existing political will, local support for management, and capacity constraints to implementation (technical and financial). If the conservation and/or restoration measures are maintained over time, then the duration of the effect is assumed to be permanent as long as climate conditions support healthy vegetated ecosystems.
- **Lead time until full local potential effectiveness -** Could be implemented immediately if protection is the goal, for restoration, could begin immediately but drivers of degradation should be addressed before restoration is implemented.
- **Cost effectiveness** - See SM2.8.
- **Global governability -** Guidance for effective carbon governance in vegetated systems has been established (Lederer, 2011; Herr *et al*., 2012). Key challenges for mangrove governance (as most are located in developing countries on communally or state-owned lands) include integration of national and local governance to ensure equitable benefit sharing within local communities (Locatelli *et al*., 2014). A key issue in addressing leakage is improving the governance and local ownership of a project; particularly for mangroves which are often collectively owned and managed (Locatelli *et al*., 2014). In most countries where mangroves grow, governance at national and local levels may be weak, unstable and prone to inequitable resource sharing (Locatelli *et al*., 2014) highlighting the need for community engagement in planning and management to ensure benefits are shared equitably. See SM2.9 for more details.

2.3.2. Alkalinization (local)

- **Effectiveness to increase net carbon uptake -** Local air-sea CO_2 fluxes per area are large, but because of the small area, absolute carbon fluxes are very mall compared to the atmospheric carbon load between RCP8.5 minus RCP2.6.
- **Effectiveness to moderate local warming -** Local (and global) cooling by local alkalinity enhancement is related to atmospheric CO_2 drawdown and thus very small, i.e. a small fraction of the global mean sea surface temperature difference between RCP8.5 and 2.6 (Feng *et al*., 2016).
- **Effectiveness to moderate local acidification** - Local changes in pH can be very large and fully compensate the differences between RCP8.5 and 2.6 (Feng *et al*., 2016).
- **Effectiveness to moderate relative sea level rise** - Little direct effect on regional relative sea level by changes in ocean chemistry. Indirect effects via improved health of coral reefs and possibly other parts of the ecosystem.
- **Technological readiness** - Only one very small-scale field experiment until now (Albright *et al*., 2016), would take years to decades to deploy as a continuously operating system.
- **Duration of the effect** - Short (days to months), because the benefits of added alkalinity only exist as long as the alkaline substances remain in the system. Flushing by waters from outside of the region of deployment will reduce the duration of effect. Global benefits remain permanently, but are very small.
- **Lead time until full local potential effectiveness** - To achieve full and lasting potential, a lot of mass has to be moved, requiring substantial infrastructure. Building up this infrastructure will take decades.
- **Cost effectiveness** - See SM2.8.
- **Global governability** - See SM2.9.

2.3.3. Pollution reduction

- **Effectiveness to increase net carbon uptake -** Controlling pollutants into coastal ecosystems helps to increase carbon uptake, particularly by maintaining healthy blue carbon ecosystems. When healthy, blue carbon systems can sequester significant amounts of CO_2. Researchers estimate carbon storage in the top meter of soil to be approximately 280 Mg C ha^{-1} for mangroves, 250 Mg C ha^{-1} for tidal marshes, and 140 Mg C ha^{-1} for seagrass meadows, equivalent to 1,030 megagrams of carbon dioxide equivalent per hectare (Mg CO_2eq ha^{-1}) for estuarine mangroves, 920 Mg CO_2eq ha^{-1} for tidal marshes, and 520 Mg CO_2eq ha^{-1} for seagrass meadows. Adding the carbon in the plants, the mean carbon storage is 1,494, 951 and 607 Mg CO_2eq ha^{-1} for mangroves, tidal marshes and seagrass meadows, respectively (Pendleton *et al*., 2012). When degraded, they can become significant sources of CO_2 emissions. For example, their annual loss accounts for up to 19% of carbon emissions from tropical deforestation globally resulting in economic costs of USD$6–42 billion annually (Pendleton *et al*., 2012).
- **Effectiveness to moderate local warming -** Indirect effects as pollutants damage coastal systems which can sequesters and store carbon (see carbon uptake below); when degraded they can release emissions. This is likely to have a minimal effect on reducing warming.

- **Effectiveness to moderate local acidification** - Anthropogenic inputs exacerbate the effects of ocean acidification at local scales (Feely *et al*., 2010; Cai *et al*., 2011). Cai *et al*. (Cai *et al*., 2011) found that eutrophication in the northern Gulf of Mexico and the East China Sea. is associated with the development of hypoxia and the acidification of subsurface waters. Borges and Gypens (Borges and Gypens, 2010) highlight the significant effects that nutrient inputs can have on coastal ocean chemistry. They show that changing phosphate loads from terrestrial sources could shift coastal surface waters from net heterotrophy to net autotrophy, with an overall effect greater than that of anthropogenic CO_2 (Billé *et al*., 2013). Feely *et al*. (Feely *et al*., 2010) measure a related effect in Puget Sound, Washington, USA, showing that respiration—in part stimulated by anthropogenic nutrient input—in the surface and bottom waters had a greater acidifying effect than uptake of anthropogenic CO_2. Similarly, Kelly *et al*. (Kelly *et al*., 2011) found that freshwater inputs and pollutants can acidify coastal waters at higher rates than CO_2 alone (e.g., Kennebec River plume in the Gulf of Maine, Chesapeake Bay, Manning River estuary in New South Wales, Australia). These inputs can have significant impacts when they coincide with upwelling events that bring low-pH water to nearshore areas. Further, sulfur dioxide precipitation, hypoxia, eutrophication, and emissions and runoff from acidic fertilizers can exacerbate the impacts of ocean acidification. Industrial production, transport, and environmental release of organic chemicals and trace metals (e.g., mercury, lead) also affect seawater chemistry (Doney, 2010). Therefore, controlling coastal pollutants such as nitrogen and sulfur oxides can reduce ocean acidification at local scales (Mcleod *et al*., 2013). Further, mangroves and seagrasses have been found to reduce ocean acidification locally (e.g., Mcleod *et al*., 2013; Unsworth *et al*., 2012; Manzello *et al*., 2012; Garrard *et al*., 2014; Sippo *et al*., 2016)Unsworth. Seagrass habitats have been documented in the Caribbean (Manzello *et al*., 2012), Mediterranean (Hendriks *et al*., 2014), and Indo-Pacific (Anthony *et al*., 2013) to elevate local mean pH, and can potentially buffer coral populations by off-setting future decreases in seawater pH and a recent analysis supports this role (Camp *et al*., 2016).
- **Effectiveness to moderate relative sea level rise** - Adverse impacts of pollution on coastal and marine ecosystems are well documented (Ellison and Farnsworth, 1996; Hughes *et al*., 2003; Islam and Tanaka, 2004; Fabricius, 2005; Waycott *et al*., 2009; Duke, 2016). Indirect effects possible as pollutants damage coastal systems which can sequesters and store carbon (see carbon uptake below); when degraded they can release emissions. This is likely to have a minor effect on reducing sea-level rise. Mangroves, coral reefs, and seagrasses can reduce sea-level rise locally by reducing wave height and energy. Coral reefs reduce wave energy by an average of 97% (Ferrario *et al*., 2014). Salt marshes also play an important role in wave attenuation and shoreline stabilization (Shepard *et al*., 2011) and can reduce the height of damaging waves in storm surge conditions by close to 20% (Möller *et al*., 2014). Mangroves can reduce the height of wind and swell waves (Bao, 2011) and tsunami impacts (Alongi, 2015); wave height can be reduced by between 13-66% over 100 m of mangroves (McIvor *et al*., 2012). Seagrasses also can attenuate the wave height and wave energy with a percentage of wave reduction by as much as 50% using artificial seagrass (John *et al*., 2015), and 40% with natural seagrass (Fonseca and Cahalan, 1992).
- **Technological readiness** - Most nations have regulations and management options to control coastal pollution and run-off (e.g., Clean Water Act; stormwater surge prevention; coastal and riparian buffer; intact wetlands, and water treatment facilities). In many cases, federal funding is available to support local governments to implement such activities in partnership with local groups. While local efforts (e.g., increasing vegetation cover) may be effective at small scales, coordination across state or regional governments is needed to control pollution at scale which adds a layer of regulatory complexity (Kelly *et al*., 2011). Other strategies include managing land-use changes through local and regional planning, zoning and permitting policies. Enforcing existing federal emissions limits for pollutants such as nitrogen oxide and sulfur oxide (e.g., to reduce local drivers of ocean acidication), and reductions could have immediate local effects, because these pollutants have short atmospheric residence times (Kelly *et al*., 2011).
- **Duration of the effect** - The duration of effect is maintained as long as the source of pollutants are controlled.
- **Lead time until full local potential effectiveness** - Available now - no new technology needed.
- **Cost effectiveness** - See SM2.8.
- **Global governability -** Degradation of coastal and marine ecosystems due to the effects of terrestrially derived pollution is a universal issue and the subject of intense management activity (Doney, 2010). National action plans to control pollution have been developed (e.g., Great Barrier Reef Water Quality Action Plan 2001; Great Barrier Reef Protection Amendment Act 2009). However, such plans often focus on diffuse pollution, and assume point source pollution (e.g., sewage) are well managed which may not be the case (Brodie *et al*., 2012).The importance of institutional arrangements that allow the numerous stakeholder groups to contribute and commit to successful implementation of strategies for water quality improvement has been recognised through a range of research efforts (Brodie *et al*., 2012). See SM2.9 for more details.

2.3.4. Restoring hydrology

- **Effectiveness to increase net carbon uptake -** The role of MPAs in protecting sequestered carbon and prevention of reduce emissions has been recently acknowledged (Miteva *et al*., 2015; Simard *et al*., 2016). Protecting blue carbon habitats helps to both increase carbon uptake and reduce emissions released when they are degraded and destroyed. When healthy, blue carbon systems can sequester significant amounts of CO_2. Researchers estimate carbon storage in the top meter to be approximately 280 Mg C ha^{-1} for mangroves, 250 Mg C ha^{-1} for tidal marshes, and 140 Mg C ha^{-1} for seagrass meadows, equivalent to 1,030 Mg of carbon dioxide equivalent per hectare (Mg CO_2eq ha^{-1}) for estuarine mangroves, 920 Mg CO_2eq ha^{-1} for tidal marshes, and 520 Mg CO_2eq ha^{-1} for seagrass meadows. Adding the carbon in the plants, the mean carbon storage is 1, 494, 951 and 607 Mg CO_2eq ha^{-1} for mangroves, tidal marshes and seagrass meadows, respectively (Pendleton *et al*., 2012). A more recent global review found that estimates of carbon stocks in these systems range from 10.4–25.1 Pg of carbon and wetland loss is estimated to be between 0.7–3% per year (depending on vegetation type and location), resulting in 0.23–2.25 Pg of CO_2 released (Howard *et al*., 2017). When degraded, these systems can become significant sources of CO_2 emissions (e.g., Hamilton and Friess, 2018). For example, their annual loss accounts for up to 19% of carbon emissions from tropical deforestation globally resulting in economic costs of USD$ 6-42 billion annually (Pendleton *et al*., 2012). The establishment of MPAs in Indonesia has been shown to avoid emissions through mangrove protection and avoided release of approximately 13Mt CO_2 into the atmosphere (Miteva *et al*., 2015).
- **Effectiveness to moderate local warming -** Maintaining and restoring hydrology can maintain healthy coastal systems which can sequester and store carbon (see carbon uptake below); when degraded they can release CO_2. Impaired hydrological regimes can lead to flooding of coastal habitats resulting in release of stored carbon. However, the impact on local warming is very low.
- **Effectiveness to moderate local acidification -** Maintaining the hydrological regimes in coastal habitats can help to reduce ocean acidification at local scales based on supporting healthy coastal habitats. Mangroves and seagrasses have been found to reduce ocean acidification locally (e.g., Mcleod *et al*., 2013; Unsworth *et al*., 2012; Manzello *et al*., 2012; Garrard *et al*., 2014; Sippo *et al*., 2016). Seagrass habitats have been documented in the Caribbean (Manzello *et al*., 2012), Mediterranean (Hendriks *et al*., 2014), and Indo-Pacific (Anthony *et al*., 2013) to elevate local mean pH, and can potentially buffer coral populations by off-setting future decreases in seawater pH and a recent analysis supports this role (Camp *et al*., 2016). However, a recent review suggests that the most effective seaweed farm can only delay the impacts of global ocean acidification at the reef scale by 7–21 years, depending on future global carbon emissions (Mongin *et al*., 2016). Mongin et al. (Mongin *et al*., 2016) suggest that only a kilometer-scale farm can partially mitigate global ocean acidification for a particular reef.
- **Effectiveness to moderate relative sea level rise** - Maintaining and restoring hydrological regimes in mangroves, coral reefs, and seagrasses can reduce sea-level rise locally because they can reduce wave height and energy. Coral reefs reduce wave energy by an average of 97% (Ferrario *et al*., 2014). Salt marshes also play an important role in wave attenuation and shoreline stabilization (Shepard *et al*., 2011) and can reduce the height of damaging waves in storm surge conditions by close to 20% (Möller *et al*., 2014). Mangroves can reduce the height of wind and swell waves (Bao, 2011) and tsunami impacts (Alongi, 2008); wave height can be reduced by between 13-66% over 100 m of mangroves (McIvor *et al*., 2012). Seagrasses also can attenuate the wave height and wave energy with a percentage of wave reduction by as much as 50% using artificial seagrass (John *et al*., 2015) and 40% with natural seagrass (Fonseca and Cahalan, 1992).
- **Technological readiness** - Extensive guidance existing on maintaining and restoring hydrological regimes and has been implemented extensively to support healthy coastal ecosystems (Weinstein *et al*., 2001; Lewis, 2005; Erwin, 2009; NOAA Restoration Center and NOAA Coastal Services, 2010; Roman and Burdick, 2012; UNEP and CIFOR, 2014).
- **Duration of the effect** - The duration of effect is permanent as long as the natural hydrological regime is maintained.
- **Lead time until full local potential effectiveness** - Can be implemented immediately.
- **Cost effectiveness** - See SM2.8.
- **Global governability** - Engagement with local stakeholders at the outset including all stages of planning and implementation, helps to ensure that their needs are incorporated into the project design (Wylie *et al*., 2016). As with other conservation approaches, political will is a key determinant of project success. Maintaining/restoring hydrological regimes may be implemented through an MPA or other coastal management policies. Challenges may occur when catchments transcend political boundaries, increasing the number of institutions and legislative instruments water-management interests, including competing water-resource development and conservation objectives which are seldom resolved (Kingsford, 2011). Integration of different governance, legislative and regulatory frameworks is essential for effective conservation (Kingsford, 2011). See SM2.9 for more details.

2.3.5. Eliminating overexploitation

- **Effectiveness to increase net carbon uptake -** The role of MPAs in protecting sequestered carbon and prevention of reduce emissions has been recently acknowledged (Miteva *et al.*, 2015; Simard *et al.*, 2016). Protecting blue carbon habitats helps to both increase carbon uptake and reduce emissions released when they are degraded and destroyed. When healthy, blue carbon systems can sequester significant amounts of CO_2. Researchers estimate carbon storage in the top meter to be approximately 280 Mg C ha^{-1} for mangroves, 250 Mg C ha^{-1} for tidal marshes, and 140 Mg C ha^{-1} for seagrass meadows, equivalent to 1,030 Mg of carbon dioxide equivalent per hectare (Mg CO_2eq ha^{-1}) for estuarine mangroves, 920 Mg CO_2eq ha^{-1} for tidal marshes, and 520 Mg CO_2eq ha^{-1} for seagrass meadows. Adding the carbon in the plants, the mean carbon storage is 1, 494, 951 and 607 Mg CO_2eq ha^{-1} for mangroves, tidal marshes and seagrass meadows, respectively (Pendleton *et al.*, 2012). A more recent global review found that estimates of carbon stocks in these systems range from 10.4–25.1 Pg of carbon and wetland loss is estimated to be between 0.7–3% per year (depending on vegetation type and location), resulting in 0.23–2.25 Pg of CO_2 released (Howard *et al.*, 2017). When degraded, these systems can become significant sources of CO_2 emissions (e.g., Hamilton and Friess, 2018). For example, their annual loss accounts for up to 19% of carbon emissions from tropical deforestation globally resulting in economic costs of USD$ 6-42 billion annually (Pendleton *et al.*, 2012). The establishment of MPAs in Indonesia has been shown to avoid emissions through mangrove protection and avoided release of approximately 13Mt CO_2 into the atmosphere (Miteva *et al.*, 2015).
- **Effectiveness to moderate local warming -** Indirect effects as reducing overexploitation can maintain healthy coastal systems which can sequester and store carbon (see carbon uptake above); when degraded they can release emissions.
- **Effectiveness to moderate local acidification** - Reducing the overexploitation of coastal habitats can help to reduce ocean acidification at local scales. Mangroves and seagrasses have been found to reduce ocean acidification locally (e.g., Mcleod *et al.*, 2013; Unsworth *et al.*, 2012; Manzello *et al.*, 2012; Garrard *et al.*, 2014; Sippo *et al.*, 2016). Seagrass habitats have been documented in the Caribbean (Manzello *et al.*, 2012), Mediterranean (Hendriks *et al.*, 2014), and Indo-Pacific (Anthony *et al.*, 2013) to elevate local mean pH, and can potentially buffer coral populations by off-setting future decreases in seawater pH and a recent analysis supports this role (Camp *et al.*, 2016). However, a recent review suggests that the most effective seaweed farm can only delay the impacts of global ocean acidification at the reef scale by 7–21 years, depending on future global carbon emissions (Mongin *et al.*, 2016). (Mongin *et al.*, 2016) suggest that only a kilometer-scale farm can partially mitigate global ocean acidification for a particular reef.
- **Effectiveness to moderate relative sea level rise** - Reducing the overexploitation of mangroves, coral reefs, and seagrasses can reduce the effects of sea-level rise locally. These habitats reduce wave energy. Coral reefs reduce wave energy by an average of 97% (Ferrario *et al.*, 2014). Salt marshes also play an important role in wave attenuation and shoreline stabilization (Shepard *et al.*, 2011)and can reduce the height of damaging waves in storm surge conditions by close to 20% (Möller *et al.*, 2014). Mangroves can reduce the height of wind and swell waves (Bao, 2011) and tsunami impacts (Alongi, 2015); wave height can be reduced by between 13-66% over 100 m of mangroves (McIvor *et al.*, 2012). Seagrasses also can attenuate the wave height and wave energy with a percentage of wave reduction by as much as 50% using artificial seagrass (John *et al.*, 2015), and 40% with natural seagrass (Fonseca and Cahalan, 1992). Other ecosystems provide coastal protection, including macroalgae, oyster and mussel beds, and also beaches, dunes and barrier islands (stabilized by organisms; Defeo *et al.*, 2009; Spalding *et al.*, 2014, #59996). Therefore, the protection of these habitats helps to ensure that their coastal protection value is secured.
- **Technological readiness** - Management to control overexploitation of coastal habitats does not require technological advancements. It can be built into existing conservation efforts (e.g., MPAs, coastal zone management plans).
- **Duration of the effect** - The duration of the effect is permanent as long as overexploitation is eliminated.
- **Lead time until full local potential effectiveness** - Lead time would involve community/local stakeholder engagement if new regulations were planned but would be dependent on the history of regulation in a place, whether local stakeholders were included in the planning/implementation process.
- **Cost effectiveness** - See SM2.8.
- **Global governability** - Engagement with local stakeholders at the outset including all stages of planning and implementation, helps to ensure that their needs are incorporated into the project design and reduces the chance for leakage (e.g., protecting one mangrove forest which leads to deforestation of another) to occur (Wylie *et al.*, 2016). Such efforts are critical as controlling overexploitation may involve reductions in valuable natural resources for local communities. Governance mechanisms to control overexploitation (e.g., national policies which control the harvest of natural resources) need to be integrated with bottom-up approaches, through integrated

coastal management. Governments, in partnership with international agencies and NGOs, can facilitate coastal resource conservation by providing user communities with the legal framework and capacity for active co-management of these resources through capacity building, awareness raising, improved education on the causes of degradation and possible solutions, along with assistance to develop sustainable alternative livelihoods. This will result in the local declaration, planning, management and enforcement of many more marine managed areas that include significant no-take zones (Wilkinson and Salvat, 2012). See SM2.9 for more details.

2.3.6. Protection

- **Effectiveness to increase net carbon uptake -** The role of MPAs in protecting sequestered carbon and prevention of reduce emissions has been recently acknowledged (Miteva *et al*., 2015; Simard *et al*., 2016). Protecting blue carbon habitats helps to both increase carbon uptake and reduce emissions released when they are degraded and destroyed. When healthy, blue carbon systems can sequester significant amounts of CO_2. Researchers estimate carbon storage in the top meter to be approximately 280 Mg C ha^{-1} for mangroves, 250 Mg C ha^{-1} for tidal marshes, and 140 Mg C ha^{-1} for seagrass meadows, equivalent to 1,030 Mg of carbon dioxide equivalent per hectare (Mg CO_2eq ha^{-1}) for estuarine mangroves, 920 Mg CO_2eq ha^{-1} for tidal marshes, and 520 Mg CO_2eq ha^{-1} for seagrass meadows. Adding the carbon in the plants, the mean carbon storage is 1, 494, 951 and 607 Mg CO_2eq ha^{-1} for mangroves, tidal marshes and seagrass meadows, respectively (Pendleton *et al*., 2012). A more recent global review found that estimates of carbon stocks in these systems range from 10.4–25.1 Pg of carbon and wetland loss is estimated to be between 0.7–3% per year (depending on vegetation type and location), resulting in 0.23–2.25 Pg of CO_2 released (Howard *et al*., 2017). When degraded, these systems can become significant sources of CO_2 emissions (e.g., Hamilton and Friess, 2018). For example, their annual loss accounts for up to 19% of carbon emissions from tropical deforestation globally resulting in economic costs of USD$ 6-42 billion annually (Pendleton *et al*., 2012). The establishment of MPAs in Indonesia has been shown to avoid emissions through mangrove protection and avoided release of approximately 13 Mt CO_2 into the atmosphere (Miteva *et al*., 2015).
- **Effectiveness to moderate local warming -** Indirect effects as protection of healthy coastal systems supports carbon sequestration (see carbon uptake below); when degraded they can release emissions.
- **Effectiveness to moderate local acidification** - Protecting coastal habitats can help to reduce ocean acidification at local scales. Mangroves and seagrasses have been found to reduce ocean acidification locally (e.g., Mcleod *et al*., 2013; Unsworth *et al*., 2012; Manzello *et al*., 2012; Garrard *et al*., 2014; Sippo *et al*., 2016). Seagrass habitats have been documented in the Caribbean (Manzello *et al*., 2012), Mediterranean (Hendriks *et al*., 2014), and Indo-Pacific (Anthony *et al*., 2013) to elevate local mean pH, and can potentially buffer coral populations by off-setting future decreases in seawater pH and a recent analysis supports this role (Camp *et al*., 2016). However, a recent review suggests that the most effective seaweed farm can only delay the impacts of global ocean acidification at the reef scale by 7–21 years, depending on future global carbon emissions (Mongin *et al*., 2016). Mongin *et al*. (Mongin *et al*., 2016) suggest that only a kilometer-scale farm can partially mitigate global ocean acidification for a particular reef.
- **Effectiveness to moderate relative sea level rise** - Protecting mangroves, coral reefs, and seagrasses can reduce the effects of sea-level rise locally as these habitats reduce wave energy. Coral reefs reduce wave energy by an average of 97% (Ferrario *et al*., 2014). Salt marshes also play an important role in wave attenuation and shoreline stabilization (Shepard *et al*., 2011) and can reduce the height of damaging waves in storm surge conditions by close to 20% (Möller *et al*., 2014). Mangroves can reduce the height of wind and swell waves (Bao, 2011) and tsunami impacts (Alongi, 2015); wave height can be reduced by between 13-66% over 100 m of mangroves (McIvor *et al*., 2012). Seagrasses also can attenuate the wave height and wave energy with a percentage of wave reduction by as much as 50% using artificial seagrass (John *et al*., 2015), and 40% with natural seagrass (Fonseca and Cahalan, 1992).
- **Technological readiness** - High as no new technology is needed and examples of best practices implementing locally managed marine areas and Marine protected areas exists.
- **Duration of the effect** - The duration of the effect is permanent as long as effective management is in place to support protection of marine habitats and ecosystems.
- **Lead time until full local potential effectiveness** - Lead time depends on community/local stakeholder engagement if new protected areas are planned and depend on the history of regulation in a place and whether local stakeholders were included in the planning/implementation process.
- **Cost effectiveness** - See SM2.8.
- **Global governability** - See SM2.9.

2.3.7. Assisted evolution

- **Effectiveness to increase net carbon uptake -** If effective and scaled, coral reef restoration through the use of resistant populations will provide a small contribution to carbon uptake through calcification. Global contribution is not expected to be large because of limited spatial extent of coral reefs globally.
- **Effectiveness to moderate local warming -** These approaches leverage and propagate natural variation in the responses of organisms to stress. The biological materials produced is used in restoration to sustain historical states or assembled in "new" ways to meet desired attributes and maintain the goods and services provided by the historical ecosystem (Jackson and Hobbs, 2009; Hobbs *et al*., 2011; Higgs *et al*., 2014).
- Low and indirect effect. Sustaining and enhancing natural marine ecosystem is in the conceptual stage but genetic direction (climate optimization) of stocks to elevate thermal thresholds has the potential to enhance the survival of communities and perpetuate ecosystem services (Rau *et al*., 2012; van Oppen *et al*., 2015; van Oppen *et al*., 2017). These techniques are new to wild marine systems and have not implemented at scale hence low confidence associated with this assessment.
- **Effectiveness to moderate local acidification** - Very low indirect effect. Genetic direction of communities (assisted stocks coupled with restoration) has potential to sustain healthy coastal ecosystems and perpetuate local moderation of ocean acidification.
- **Effectiveness to moderate relative sea level rise** - Very low indirect effect. Similar to warming – assisted evolution for species that provide coastal protection has the potential to have an indirect beneficial effect scaling with extent and size of intervention.
- **Technological readiness** - For most systems development is in its infancy however, they are technologically feasible (Rau *et al*., 2012; van Oppen *et al*., 2015; van Oppen *et al*., 2017).
  - Increased climate resilience in the Sydney oyster is a by-product of selective breeding for pathogen resistance (Parker *et al*., 2011; Thompson *et al*., 2015). This confirms that selection on components of the minimal cellular stress response may have positive effects on the tolerance to a number of different stressors. Positive trans-generational acclimatization and parental effects have been documented in one species of coral (*Pocillopora damicornis*) following preconditioning of parents to high temperature and pCO_2, but the relative frequency and importance of this trans-generational plasticity are even less well understood (Putnam and Gates, 2015).
  - The development of quantitative traits loci for environmental stress tolerance in corals (Jin *et al*., 2016), and the growing body of knowledge on the interactions between coral host and *Symbiodinium* symbionts (Barott *et al*., 2015; Parkinson *et al*., 2015), the host and symbiont genes regulated in response to stress (Barshis, 2015; Levin *et al*., 2016) or under selection from environmental variables such as temperature (Lundgren *et al*., 2013; Bay and Palumbi, 2014), are important developments.
  - While data are not available for assisted migration in mangroves, research from terrestrial forests suggest that the lack of target migration distances (i.e., distance that populations should be moved to address future climate change and ensure adaptation throughout a tree's lifetime) is a major limitation in making informed decisions about assisted migration, given the uncertainty about which climate to prepare for (Williams and Dumroese, 2013). Further, climate change effects might be so abrupt that assisted migration may not be an option, even within a species' current range (Williams and Dumroese, 2013) Researchers suggest that while sufficient knowledge exists to initiate assisted gene flow for temperate and boreal forests, insufficient evidence exists for tropical forests (Aitken and Bemmels, 2016).
- **Duration of the effect** - In use for farmed oysters and in development for many other organisms. If assisted evolution and assisted migration can be effectively implemented and scaled, effects are expected to last for decades to centuries, particularly when involving long-lived species such as corals, seagrass, and mangroves. However, information available to date on the effectiveness of these solutions is still very limited. For example, research in terrestrial forests suggests that there is a lag in response time to both climate change and assisted migration that will make it especially difficult to determine success, in addition to the fact that the ecological consequences of assisted migration on recipient ecosystems may be delayed and/or difficult to measure (Williams and Dumroese, 2013). Projects will need long-term intervention/monitoring due to uncertainties about the impact of a species assisted migration (Williams and Dumroese, 2013).
- **Lead time until full local potential effectiveness** - Almost all are in proof of concept phase. 5-10 years Advancement of methods for the large-scale rearing and deployment of stocks manipulated for enhanced stress resistance are urgently required. A pressing need also exists to preserve a representative portion of the extant genetic diversity by establishing genomic repositories using cryopreservation (Hagedorn *et al*., 2012), analogous to seed banks established for plants (Westengen *et al*., 2013; Haidet and Olwell, 2015).
- **Cost effectiveness** - See SM2.8.
- **Global governability** - See SM2.9.

2.3.8. Relocation and reef restoration

- **Effectiveness to increase net carbon uptake -** Creation of new blue carbon habitats supports and enhances CO_2 sequestration (Mcleod *et al*., 2011; Pendleton *et al*., 2012; Duarte *et al*., 2013a; Marbà *et al*., 2015; Howard *et al*., 2017).
- **Effectiveness to moderate local warming -** Indirect effect scaling with extent and size of restoration and relocation effort.
- **Effectiveness to moderate local acidification** - Potentially large local effect scaling with extent and size of restoration.
- **Effectiveness to moderate relative sea level rise** -A global analysis found that reefs reduce wave energy by an average of 97% (Ferrario *et al*., 2014). Wetland creation (i.e., converting land from another non-wetland to a wetland where there was previously no wetland in existence) is a key strategy identifies to support carbon sequestration (Crooks *et al*., 2011) and the suite of ecosystem services they provide including coastal protection. Creation of new habitats (mangroves, salt marshes and seagrasses) may reduce sea-level rise locally as these habitats reduce wave height and energy. Salt marshes play an important role in wave attenuation and shoreline stabilization (Shepard *et al*., 2011) and can reduce the height of damaging waves in storm surge conditions by close to 20% (Möller *et al*., 2014). Mangroves can reduce the height of wind and swell waves (Bao, 2011) and tsunami impacts (Alongi, 2008); wave height can be reduced by between 13-66% over 100 m of mangroves (McIvor *et al*., 2012). Seagrasses also can attenuate the wave height and wave energy with a percentage of wave reduction by as much as 50% using artificial seagrass (John *et al*., 2015), and 40% with natural seagrass (Fonseca and Cahalan, 1992).
- **Technological readiness** - See Table 3 in Bayraktarov (Bayraktarov *et al*., 2016) for feasibility and success in five marine ecosystems – coral reefs, mangroves, seagrass, salt marsh and oyster reefs
  - Adaptation strategies that include the restoration or introduction of coral reef ecosystems provide a cost-effective option for addressing the increased risk from flooding and erosion under climate change in vulnerable areas. Moreover, producing vegetated coastal protections, unlike cement-based structures, generates limited CO_2 emissions and in fact removes atmospheric CO_2 (Duarte *et al*., 2013a).
  - Coral reef restoration efforts have mostly been based on the use of asexually produced coral fragments (Young *et al*., 2012). These fragments are generally sourced from healthy coral colonies that are still present either on the disturbed reefs or on less damaged nearby reefs, or represent "corals of opportunity". A two-step protocol in which fragments are first grown in in situ or ex situ nurseries ("gardening"), followed by explanting them onto denuded reefs, has proven far more successful, in particular when floating in situ nurseries are used (Rinkevich, 2014). when an environment is severely altered or expected to change rapidly in the near future (as is the case under climate change scenarios), the original stock may be ill-suited for restoration. As a consequence, use of the original stock will likely result in high levels of mortality and a loss of ecosystem function (van Oppen *et al*., 2015).
  - The results of the workshop revealed that seagrass restoration success in all/most of the European projects presented during the workshop was very low (Cunha *et al*., 2012). Major recommendations for improvements included here.van Katwijk et al. (van Katwijk *et al*., 2016) found that 55% of the seagrass restoration trials worldwide have <1000 shoots or seeds initially planted, which may have contributed to the low overall trial survival from 1786 trials (conservatively estimated to be 37% after median 36 months). They also provide best practices for seagrass restoration success.
- **Duration of the effect** - Permanent. The duration of the effect of relocation and reef restoration are permanent as long as climate conditions support healthy coral reefs and the local stresses leading to reef decline have been eliminated.
- **Lead time until full local potential effectiveness** - Short as guidance is established for coral reef restoration (e.g., Edwards and Gomez, 2007; Johnson *et al*., 2011) and best practices for the restoration/creation of new blue carbon habitats (e.g., Erwin, 2009; Roman and Burdick, 2012; UNEP and CIFOR, 2014; van Katwijk *et al*., 2016).
- **Cost effectiveness** - See SM2.8..
- **Global governability** - See SM2.9.

3. Sensitivity of ecosystems and ecosystem services to key ocean drivers (Table 2)

3.1. Rationale and methodological background

The rationale and methodological background used in this study to characterize the sensitivity of ecosystems (seagrass habitats, coral reefs, mangroves and salt-marshes, Arctic biota) and ecosystem services (finfish fisheries, fish aquaculture, coastal protection by natural ecosystems, bivalves fisheries and aquaculture) to climate-related drivers is partly based on Gattuso et al. (Gattuso *et al*., 2015).

3.2. Results

Table 2 (Ecosystems' and ecosystem services' sensitivity to key ocean drivers, assuming RCP8.5) is accessible here: http://www.obs-vlfr.fr/~gattuso/files/supplementary_tables.xlsx.

3.3 Justification of the scores of Table 2

3.3.1. Seagrass habitats

Seagrasses, important habitats in coastal waters around the world, will be affected by climate change through a number of routes including direct effects of temperature on growth rates (Nejrup and Pedersen, 2008; Höffle *et al.*, 2011), occurrence of disease (Burge *et al.*, 2013), mortality and physiology, changes in light levels arising from sea level changes, changes in exposure to wave action (Short and Neckles, 1999)), sometimes mediated through effects on adjacent ecosystems (Saunders *et al.*, 2014), and also by changes in the frequency and magnitude of extreme weather events. Temperate seagrass meadows have already been negatively impacted by rising sea surface temperatures (Marbà and Duarte, 2010). Models based on observations of natural populations indicate that at temperature increases of 1.5 to 3°C mortality of shoots of seagrasses will be such that populations will be unsustainable and meadows will decline to the point where their ecological functions as a habitat will cease (reduction to 10% of present density of a healthy meadow; Marbà and Duarte, 2010, #16921; Carr *et al.*, 2012; Jordà *et al.*, 2012; York *et al.*, 2013).

Because of their capacity to raise the seafloor, seagrass are unlikely to be affected much from sea level rise, except through indirect effects derived from, for instance, coastal erosion or changes in light levels.

The confidence level is very high under RCP2.6 because of strong agreement in the literature. Confidence declines to high under RCP8.5 due to some uncertainty surrounding regional differences. For example, it has been suggested that the balance of effects on seagrass populations in the North East Atlantic could tip to positive due to the hypothetical opening of ecological niches with the decline of more sensitive species, Although photosynthesis of seagrass leaves is often stimulated at low pH in the laboratory (e.g. Cox *et al.*, 2015) which may indicate a potential reduction of carbon limitation by elevated CO_2, helping to ameliorate negative effects of other environmental drivers, such as warming, known to impact seagrass growth and survival (Brodie *et al.*, 2014). However, such stimulation was not observed in *Posidonia oceanica* in a long-term experiment performed in situ (Cox *et al.*, 2016).

3.3.2. Coral reefs

Tropical coral reefs harbor enormous biodiversity and play important roles in food security and coastal protection. Corals, the foundation species that create reefs, live close to their thermal thresholds and are negatively impacted by ocean acidification (Hoegh-Guldberg *et al.*, 2007). Anomalously high sea water temperatures compromise the photosynthetic capacity of the obligate endosymbionts of corals (Lesser, 1996), a disturbance that drives the breakdown of the association, the loss of coral color known as coral bleaching and often coral mortality. Ocean acidification diminishes the capacity of corals to calcify and increases the dissolution of the reef (Kleypas and Yates, 2009).

With a conservative lag time of 10 years between the atmospheric concentration of CO2 and changes in sea surface temperature, the atmospheric CO_2 level of 325 ppm reached in the early 1970s triggered the beginning of widespread coral bleaching and decline in coral health worldwide (Veron *et al.*, 2009). In the early 1980s, coral reefs in the Caribbean and eastern Pacific exhibited mass coral bleaching and temperature-related disease outbreaks in the Caribbean Sea (Glynn, 1984). The first global event occurred in 1997-1998 and resulted in mortality and loss of 16% of coral reefs (high confidence; Wilkinson, 2000, #22302). Further increases in atmospheric CO2 and ocean temperatures have continued to impact corals (high confidence; Gattuso *et al.*, 2015, #10535) manifesting in multiple widespread bleaching events that killed a large fraction of living corals in the Caribbean in 2005 (Eakin *et al.*, 2010) and global bleaching events and extensive coral mortality in 2010 (e.g. Moore *et al.*, 2012) and 2016 (Hughes *et al.*, 2017b) that both caused extensive coral mortality. The collective impact of climate related warming on reefs is now estimated at 50% loss of coral reefs globally since 1980, with 29% of the coral lost on the Australian Great Barrier Reef in 2019 alone (GBRMPA Media Report, May 2017).

If CO_2 levels continue to increase, there is now no doubt (exceptionally high confidence) that coral reefs will continue to be negatively affected by both warming induced bleaching and ocean acidification (high confidence) under both RCP2.6 and RCP8.5 scenarios. This statement is supported a diversity of models (e.g., Hughes *et al.*, 2017a; Hoegh-Guldberg *et al.*, 2014; Hoegh-Guldberg, 1999; Logan *et al.*, 2014; Donner *et al.*, 2005; van Hooidonk *et al.*, 2014; King *et al.*, 2017), experimental simulations and exposures (e.g., Dove *et al.*, 2013; Comeau *et al.*, 2013), and by numerous field studies (De'ath *et al.*, 2012; Silverman *et al.*, 2014; Albright *et al.*, 2016). For example, a recent analysis byVan Hooidonk et al. (van Hooidonk *et al.*, 2016) predicts that >75% of coral reef will experience annual severe bleaching (ASB) before 2070 under RCP4.5, and that RCP4.5 adds just 11 years to the global average ASB timing compared to RCP8.5. This point is reinforced by King *et al.* (King *et al.*, 2017) who show that 1.5 and 2.0°C of warming translate to a greater than 50 and 70% chance of annual bleaching on the Great Barrier Reef, respectively. Exemplifying the intensifying reef are the reports of bleaching two years a row in Hawaii (2014 and 2015; Rodgers *et al*., 2017, #85622) and on the Great Barrier Reef (2016 and 2017).

3.3.3. Mangroves and salt-marshes

Mangroves are critically important coastal habitat for numerous species. Climate change is likely to have a substantial impact on mangrove ecosystems (Ellison, 2015), specifically through sea level rise, changing ocean currents, increased storminess, increased temperature, changes in precipitation and increased CO_2 (McKee *et al*., 2012). Mangrove responses to increasing atmospheric CO_2 are however complex, with some species thriving while others decline or exhibit little or no change (Alongi, 2015). Temperature increase alone is likely to result in faster growth, reproduction, photosynthesis, and respiration, changes in community composition, diversity, and an expansion of latitudinal limits up to a certain point (Tittensor *et al*., 2010). Mangroves have already been observed to retreat with sea level rise (McKee *et al*., 2012), and large changes in sea level have led to mangrove ecosystem collapse (Ellison and Stoddart, 1991; Ellison, 1993). Sea-level rise threatens mangroves because they are sensitive to change in inundation frequency and duration and changes in salinity. Increases in flooding duration can result in mangrove death at seaward margins (He *et al*., 2007) and changes in species composition and ecosystem services (Ward *et al*., 2016).

Mangroves in microtidal areas and carbonate settings are particularly vulnerable to sea-level rise (Alongi, 2008). Further, a recent global analysis suggested that geomorphic settings affected vulnerability to sea level rise: back basin mangroves were less vulnerable than fringing mangroves due to species and sediment deposition differences (Sasmito *et al*., 2016). In many areas mangroves can adapt to sea level rise by landward migration, but these shifts threaten other coastal habitats such as salt marshes, which have other important biogeochemical and ecological roles (Hoegh-Guldberg and Bruno, 2010).

A large reservoir of below-ground nutrients, rapid rates of nutrient flux and microbial decomposition, complex and highly efficient biotic controls, self- design and redundancy of keystone species, and numerous feedbacks, all contribute to mangrove resilience to various types of disturbance. Mangrove response is species-specific and interacts with temperature, salinity, nutrient availability and patterns of precipitation. Many of these parameters are also subject to regional and local variation, as well as to human-induced pressures which changes over the coming decades are difficult to assess. A global review of climate impacts on mangroves showed extreme regional variation in mangrove communities, their biodiversity, threats, protection, and climatic influences (Ward *et al*., 2016). For example, these authors suggest that sea level rise is likely to have a lesser impact in areas with high sediment availability, uplifting or stable coasts, high productivity, and large tidal ranges (e.g., Amazon estuary and Parnaiba delta). However, mangroves are likely to be substantially threatened in areas with extensive coastal development (e.g., Asia, South and North America), very high rates of sea level rise (e.g., Indonesia and Mississippi delta), and low island mangroves (e.g., Pacific) (Ward *et al*., 2016).

Tidal marshes are also vulnerable to climate change, especially sea level rise (Kirwan and Megonigal, 2013). Some salt marshes can keep pace with sea level rise, but others, especially those cut off from their sediment delivery via levees and seawalls cannot (Day *et al*., 1995). Some suggest the sea level rise may lead to significant loss of tidal marshes and the key services they provide (Craft *et al*., 2009). Tidal marshes may drown when inundated and be replaced by upland species if inundated sufficiently (Raposa *et al*., 2016). Organogenic marshes and those in areas with limited sediment are likely to be more vulnerable (Hughes, 2004). As with mangroves, salt marsh survival depends on access to sediment to allow for vertical accretion to keep pace with sea level rise and the ability to move landward in response to rising seas (Kirwan and Megonigal, 2013). Increasing temperatures and decreased rainfall can dramatically affect tidal marshes (McKee *et al*., 2004). For example, large areas of marshes in the Mississippi Delta in 2000 died due to a strong La Nina event. This event resulted in lower water levels, prolonged drought, and high air temperatures, which raised soil salinities to toxic levels (Day *et al*., 2005). In the northern Gulf of Mexico, increased temperatures are predicted to result in a northward expansion of mangroves replacing salt marshes (Erwin, 2009). In the southeastern US, tidal saline wetlands contain a combination of mangrove forests and salt marshes whose relative abundance oscillates in response to the frequency and intensity of extreme winter events (i.e., freezing air temperatures). Mangroves are dominant in warmer areas and salt marshes are dominant in colder areas, and mangroves in the southeastern US have been expanding at the expense of salt marsh (Giri *et al*., 2011; Montagna *et al*., 2011; Armitage *et al*., 2015). Mangroves are expected to move poleward in response to decreases in the frequency and intensity of freeze events (Osland *et al*., 2016). Winter climate gradients that affect mangrove–marsh–salt marsh interactions are also present in Australia, New Zealand, South America, western North America, southeastern Africa, the Middle East, and Asia (Osland *et al*., 2016).

Factors such as tidal range or access to riverine sediment sources will determine vulnerability to sea-level rise, in addition to human impacts such as those that reduce sediment supply (Raposa *et al*., 2016). Oceanographic differences and local hydrodynamic factors can also affect exposure to (Sallenger Jr *et al*., 2012). Accretion, subsidence rates, and processes which influence marsh ability to grow vertically and/or to migrate inland affect vulnerability to sea level rise (Raposa *et al*., 2016). Human impacts such as nutrient pollution can destabilizes belowground biomass and increase decomposition, thus exacerbating salt marsh loss due to sea level rise (Deegan *et al*., 2012).

Some suggest that marsh vulnerability to sea level rise may be overestimated (Kirwan *et al*., 2016), while others project significant impacts (Spencer *et al*., 2016). Early estimates suggest that climate change may lead to a maximum global loss of 10–5% of mangrove forest for a sea level rise of 0.6 m (high-end IPCC projections in AR4), but must be considered of secondary importance compared with current annual rates of deforestation of 1 to 2% (Alongi, 2008). However, a recent global analysis assessed the impacts of sea level rise on global coastal wetland and found that a 50 cm of sea-level rise by 2100 is projected to result in a loss of 46–59% of global coastal wetland stocks (Spencer *et al*., 2016). A global coastal wetland loss of 78% is estimated under high sea level rise (110 cm by 2100). These authors project that under a low sea level rise (29 cm by 2100) losses do not exceed ca. 50% of the total stock. Further, their modeling confirms the idea that wetlands in micro-tidal regimes are more vulnerable to sea-level rise than those in macro-tidal environments.

3.3.4. Arctic biota

While Table 2 is focusing on Arctic biota, some comparative consideration of Arctic and Antarctic oceans is warranted. Climate impacts on polar marine biota are similar between the two polar areas, some differences arise due to different variabilities in environmental conditions such as temperature, current regime and nutrient as well as food supply. In general, climate change is projected to cause an increase in productivity at high latitudes (Pörtner *et al*., 2014). The Arctic ocean, being open to adjacent seas, experiences a wide range of influxes from lower latitudes and variable changes in ocean conditions. Even within the Arctic, ecosystems and their responses to climate change vary largely (Hunt *et al*., 2016), depending on the degree of warming, ambient variability and the advection of nutrients. Biomass of fish, birds and mammals in the Barents Sea benefits from advected heat, nutrients and plankton. Rapid sea ice loss due to Arctic warming poses serious risks to ice-associated biota (marine mammals, such as polar bears and seals, small crustaceans and ice algae), with cascading effects on the ecosystem. Retreat of sea ice may also affect the recruitment of Polar cod, its spawning and larval life being associated with the vanishing ice (Kohlbach *et al*., 2017). On the Pacific side primary productivity is also high but inflow of cold water during spring and summer constrains its exploitation by fauna. The Antarctic ocean does not experience such productivity increase due to its isolation by the Antarctic circumpolar current, presently shelf ecosystems such as the Ross Sea experience ice expansion and reduced production, a trend projected to continue for some decades. However, local stimulation of productivity by warming and ice melt may occur once warming finally develops (project to occur by about +3°C by 2100), leading to increased biomass of some metazoans (Smith Jr *et al*., 2014). Productivity is constrained by limited availability of iron. The Antarctic peninsula has experienced some warming and associated impacts (Convey *et al*., 2009) but has more recently undergone a cooling trend as part of natural variability (Turner *et al*., 2016). Ultimately, warming may exceed the low limits of thermal tolerance in Antarctic stenotherms, impacting key polar zooplankton, such as krill both directly and indirectly (through loss of sea ice habitat), large copepods, such effect is unexplored in pteropods - and finally fish. Similar trends likely develop in the Arctic, depending on the area, and have already begun in the more open systems on the Atlantic side, in parallel with the so-called Atlantification of e.g. the Eurasian Basin (Polyakov *et al*., 2017).

In both polar areas, pteropods are key links in ocean food webs between microscopic and larger organisms, including fish, birds and whales. The responses of pteropods to warming and deoxygenation has not been explored as extensively as the responses to ocean acidification. A high sensitivity to ocean acidification has been identified (Bednaršek *et al*., 2016). Ocean acidification at levels anticipated under RCP8.5 leads to a decrease in pteropod shell production (Comeau *et al*., 2009; Comeau *et al*., 2010; Lischka *et al*., 2011), an increase in shell degradation (Comeau *et al*., 2012; Lischka and Riebesell, 2012), a decrease in swimming activity when ocean acidification is combined with freshening (Manno *et al*., 2012), and an increase in mortality that is enhanced at temperature changes smaller than those projected for RCP8.5 (Lischka *et al*., 2011; Lischka and Riebesell, 2012). Shell dissolution has already been observed in high latitude populations (Bednaršek *et al*., 2012). Shell dissolution has been observed at aragonite saturation (Ωa) levels below 1.4 and is exacerbated at Ωa levels between 0.8 and 1 (Bednaršek and Ohman, 2015).

Effects on other polar calcifiers are poorly explored. Acidification will be exacerbated by freshening, especially in the Arctic, at the same time the effect size of ocean acidification is likely reduced with enhanced food supply (Ramajo *et al*., 2016). Further impacts are expected from increased freshening alone in coastal areas receiving discharge from melting glaciers and permafrost. Marine macrophytes, including kelp and eelgrass are expected to expand in a warming Arctic reflecting the increase in productivity (Krause-Jensen and Duarte, 2014) and offering refugia from ocean acidification to calcifiers, due to CO_2 uptake and elevated pH (Krause-Jensen *et al.*, 2016).

Krill (euphausid crustaceans) represent a critical link in the food web at higher latitudes, finally supporting mammals and birds. In the Antarctic distributional changes and decreases in krill abundance have already been observed associated with temperature increase (Atkinson *et al.*, 2004). The effect of changes in the extent of sea ice and associated loss of habitat structure is considered to be an indirect effect of warming. Temperature effects are predicted to be regional (Hill *et al.*, 2013). If the extent of sea ice is maintained, populations in cooler waters may experience positive effects in response to small increases in temperature. In contrast, populations in warmer areas may experience some negative temperature effects by 2100 under RCP2.6. Since all life stages are associated with sea ice, decreases in krill stocks are projected to follow the loss of sea ice habitat, potentially outweighing possible positive impacts of warming (Flores *et al.*, 2012).

Increases in sea surface temperature by 1 to 2°C have significant impacts on Antarctic krill. From Fig. 4 in Flores et al. (2012), severe disruptions of the life cycle are expected at a level of 2°C sea surface temperature rise and 500 µatm pCO_2. Therefore, high impact on populations would be reached approximately at the CO_2 level projected for 2100 by RCP4.5. Conditions in 2100 under the RCP2.6 scenario would be around the upper limit of the high risk range. Negative effects of ocean acidification on reproduction, larval and early life stages have been observed above 1250 µatm pCO_2, a value that is likely to be reached in parts of the Southern Ocean by 2100 under RCP8.5 (Kawaguchi *et al.*, 2013). Figure 1 in Flores *et al.* (2012) shows that the area with strongest sea ice decline partly overlaps with areas of high krill density (from the Peninsula to the South Orkneys). There has also been a significant warming trend in this area which may have forced populations southwards into less productive regions. Substantial declines in the viability of major krill populations in the Southern Ocean may occur within the next 100 years (Kawaguchi *et al.*, 2013), which could have severe consequences for dependent marine mammals and birds. Future projections indicate an up to 51% decline in the area of krill spawning habitat under business as usual by 2100 (Piñones and Fedorov, 2016). The genetic homogeneity of krill suggests that rapid adaptation through natural selection of more tolerant genotypes is unlikely (Bortolotto *et al.*, 2011).

Considering uncertainties about regional changes, some potentially positive effects and the relatively small number of studies, the level of confidence in future climate induced risks is medium under RCP2.6 and higher under RCP8.5. Other human pressures such as overfishing and pollution also threaten polar fauna (Sovacool and Siman-Sovacool, 2007). Despite high agreement amongst published findings, uncertainty remains surrounding the potential of polar fauna to adapt to changing environmental drivers. The latitudinal displacements observed across the oceans and the intrusion of boreal species into polar waters indicate that climate change may be too fast for higher organisms to adapt. Hence the confidence level is medium under RCP2.6. However, confidence increases to very high under RCP8.5 because it is almost certain that genetic adaptation to such large and rapid changes in pH and temperature will not be possible.

3.3.5. Finfish fisheries

Marine fishes are important predators and prey in ocean ecosystems, contributing substantially to coastal economies, food security and livelihood (FAO, 2016). Warming-induced shifts in the abundance, geographic distribution, migration patterns, and phenology of marine species, including fishes, were reported and projected with very high confidence in the IPCC AR5 report (Pörtner *et al.*, 2014). Empirical and theoretical evidence of range shifts in response to temperature gradients are reported across various taxa and many geographical locations, with observations suggesting that range shifts correspond with the rate and directionality of climate shifts —or 'climate velocity'— across landscapes (Pinsky *et al.*, 2013; Poloczanska *et al.*, 2013; Jones and Cheung, 2015). Observed range shifts associated with ocean warming may result in hybridization between populations through overlapping ranges, increasing the risks of genetic extinction and reducing the adaptability to environmental changes (Muhlfeld *et al.*, 2014; Potts *et al.*, 2014). Some taxa are incapable of keeping pace with climate velocities because of physical barriers, such as species in the Mediterranean Sea (Ben Rais Lasram *et al.*, 2010; Albouy *et al.*, 2012). Critical habitat for fishes such as coral reefs may be degraded or lost under climate change, increasing the risk of decrease in diversity and abundance of fishes associated to these habitats (Munday *et al.*, 2008; Cinner *et al.*, 2012). Warming-induced expansion of oxygen minimum zones and changes in net primary production will compress the available habitats for pelagic fish stocks and affect their productivity (Stramma *et al.*, 2012; Deutsch *et al.*, 2015). Projected future changes in temperature and other physical and chemical oceanographic factors are expected to affect the distribution and abundance of marine fishes, as elaborated by species distribution models with rate of shift similar to those observed at present day under the RCP8.5 scenario (Jones and Cheung, 2015). Limiting emissions to RCP2.6 is projected to reduce the average rate of range shift by 65% by mid 21st century (Jones and Cheung, 2015). Evidence of climate change altering species composition of marine fisheries is already apparent globally (Cheung *et al.*, 2013). Also, global fisheries production is significantly related to ocean net primary production and their changes are partly driven by temperature (Cheung *et al*., 2008; Stock *et al*., 2017). Simulations suggest that, as a result of range shifts, changes in net primary production and decrease in abundance of fish stocks, fisheries catch is likely to decline in tropical regions under warming (Cheung *et al*., 2010; Barange *et al*., 2014; Cheung *et al*., 2016; Stock *et al*., 2017). Projections also suggest that marine taxa in tropical regions are likely to lose critical habitat (e.g., coral reefs), leading to declines in fisheries productivity (Bell *et al*., 2013). In contrast, substantial increases are expected in potential fisheries catch in high latitude regions (Cheung *et al*., 2016; Stock *et al*., 2017) by mid-21st century or lower warming scenario (+1.5/+2°C). At high warming scenario (> +3.5°C), projections are much more uncertain as a result of differences in projected changes in net primary production between earth system models (Cheung *et al*., 2016). Overall, existing fish stocks are expected to decrease in catch while new opportunities for fisheries may emerge from range expansion of warmer-water.

Given the abundant evidence on the high sensitivity of fish stocks to warming and their direct impacts on fisheries across latitudinal regions, a score of 4 (high) s given to the sensitivity of finfish fisheries to warming. Given the uncertainties of potential adaptive capacity of finfish to warming, a rating score of 4* (high) on the confidence of the assessment is given.

While evidence suggests that adult fishes can survive high levels of CO_2, behavioral studies have found significant changes in species' responses under levels of CO_2 elevated above those of the present day level (Munday *et al*., 2014). Long-term persistence of these phenomena remains unknown. Finfish may also be impacted indirectly by ocean acidification through the foodweb (Pörtner *et al*., 2014). Some evidence for direct and indirect impacts of ocean acidification on finfish is available but varies substantially between species. Also, understanding about the scope of marine fishes' evolutionary adaptation to ocean acidification is limited. There is no published direct evidence of observed impacts of ocean acidification on finfish fisheries. Simulation models potential impacts of ocean acidification on fisheries by mid-21st century under the "business-as-usual" emission scenario (Ainsworth *et al*., 2011; Griffith *et al*., 2012; Lam *et al*., 2016). However, warming remains the primary climate driver affecting marine fisheries. Therefore, we assigned a moderate sensitivity (score = 3) of finfish fisheries to warming, with a low confidence score (2).

3.3.6. Finfish aquaculture

In this study, finfish aquaculture includes mariculture only (fish farming in the open ocean, an enclosed section of the ocean, or in tanks, ponds or raceways which are filled with seawater). Majority of finfish mariculture is from open system (e.g., net cage) or enclosed section of the ocean (FAO, 2016). Most of the fish farms operate in coastal regions. Thus, the current fish farm operations are exposed to changes in environmental conditions including warming, ocean acidification and sealevel rise (De Silva and Soto, 2009; Callaway *et al*., 2012; Bell *et al*., 2013). Specifically, growth and mortality of marine fishes are directly related to their thermal preference window and the environmental temperature (see finfish fisheries). Increased stratification from warming may also increase the risk of anoxia and hypoxia that impacts the survival of fishes in the farm (Pörtner *et al*., 2014). Particularly, increased extreme ocean warming may lead to mass mortality of cultured fishes (De Silva and Soto, 2009; Callaway *et al*., 2012). Ocean warming and the associated change in ocean conditions may increase the susceptibility of farmed fishes to diseases and parasites (Callaway *et al*., 2012). Moreover, most of the finfish in mariculture farm is carnivorous species (Naylor *et al*., 2000; Campbell and Pauly, 2013), and some components of their feed are from wild capture fish production (Troell *et al*., 2014); the availability of the latter is sensitive to warming (Merino *et al*., 2012). However, some farming practice such as aeration of water, e.g., may help reduce the sensitivity of marine fishes to warming. As a result, finfish aquaculture has a rating of sensitivity to warming as 4 (high) with a high level of confidence (4). Direct impacts of ocean acidification on finfish is relatively low and more uncertain (compared to shelf fish, see finfish fisheries above). Since feed is controlled by the farm, thus it may also reduce the sensitivity of mariculture to the indirect effects of ocean acidification to fish's food. Therefore, sensitivity of finfish aquaculture of ocean acidification is low (2) with a moderate level of confidence (3). Sea level rise may have limited impacts on open net cage fish farming. However, it may impact existing semi-enclosed fish farms e.g., traditional semi-enclosed fish farms in coastal wetland (De Silva and Soto, 2009; Callaway *et al*., 2012). Since these operations contributed a relatively smaller proportion of global fish production than open net cage which is much less sensitivity to sea level rise, a low sensitivity (2) is given for the overall finfish aquaculture to sea level rise with a high level of confidence (4).

3.3.7. Coastal protection

Coastal ecosystems (here, coral reefs, mangroves, salt marshes, and seagrass beds) play a critical role in coastal protection through wave attenuation and shoreline stabilization. A global meta-analysis of coastal habitats demonstrated that on average, they reduce wave heights between 35 and 71%: coral reefs reduce wave heights by 70%, salt-marshes by 72%, mangroves by 31% and seagrass/kelp beds by 36% (Narayan *et al*., 2016). Earlier analyses showed that mangroves can reduce wave height by between 13-66% over 100 m of mangroves (McIvor *et al.*, 2012), and seagrasses can attenuate wave height and energy with a percentage of wave reduction by as much as 50% using artificial seagrass (John *et al.*, 2015) and 40% with natural seagrass (Fonseca and Cahalan, 1992). A separate global analysis found that reefs reduce wave energy by an average of 97% (Ferrario *et al.*, 2014). Other ecosystems provide coastal protection, including macroalgae, oyster and mussel beds, and also beaches, dunes and barrier islands (stabilized by organisms; Defeo *et al.*, 2009; Spalding *et al.*, 2014, #59996), but there is less understanding of the level of protection conferred by these other organisms and habitats (Spalding *et al.*, 2014).

Although studies indicate some of these systems are already impacted by the effects of rising CO_2, or suggest they will be in the near future, levels of sensitivity are not well established, are highly variable, and in some cases their overall influence on coastal protection may be uncertain (i.e., species are replaced by functional equivalents in this context; Gedan and Bertness, 2009, #26650). Studies suggest that factors which are positively correlated to wave attenuation and shoreline stabilization include vegetation density, biomass production, and coastal habitat size (Shepard *et al.*, 2011).

Some of the coastal protection value of these ecosystems has already been lost as a result of impacts on coral reefs, mangroves, marshes, seagrasses and other ecosystems from sea temperature rise, sea level rise and local human impacts (e.g., coastal development and overexploitation). Recent papers demonstrate collapse in three-dimensional structure of reefs in the Caribbean (Alvarez-Filip *et al.*, 2009) and the Seychelles (Sheppard *et al.*, 2005), the second phase of which appears to be climate-related. Other studies show that some areas have not recovered from the 1997-98 and 2010 bleaching events and that some reefs have collapsed there (e.g. parts of the Seychelles). Researchers predict that 1/3 of reef-building corals face elevated extinction risk from climate change and local impacts (Carpenter *et al.*, 2008). A recent analysis showed that >75% of coral reef will experience annual severe bleaching (ASB) before 2070 under RCP4.5, and RCP4.5 only add 11 years to the global average ASB timing compared to RCP8.5 (van Hooidonk *et al.*, 2016). There is thus little doubt that the coastal protection function of some reefs has already been reduced. Further, overexploitation of predators increases grazing of corals which can lead to overgrowth of algae which can outcompete corals and thus result in reduced coastal protection (Mumby and Steneck, 2008).

There is concern since the 1980s that coral reefs will not be able to keep up with expected accelerating sea level rise over the 21st century (Buddemeier and Smith, 1988). There are however some uncertainty on this issue. Some recent studies suggest that sea level rise *per se* is likely to have negligible impacts on coral reefs' vertical growth because the projected rate and magnitude of sea-level rise by 2100 are within the potential accretion rates of most coral reefs (van Woesik *et al.*, 2015). Moreover, many reefs are currently subjected to tidal regimes of several meters (Anthony and Marshall, 2009). Other scholars however stress that the overall net vertical accretion of reefs may be much slower than the growth of individual coral colonies (Hubbard *et al.*, 2008). A key point though is that sea level rise will not act alone, and that the cumulative impacts of increasing sea surface temperatures, ocean acidification, disease and more generally the degradation of health states are likely to reduce reefs ability to keep pace with sea level rise (Yates *et al.*, 2017). Ocean acidification is likely to slow growth rates and reef accretion. Regarding ocean warming, and taking the example of the Maldives after the 2016 ENSO episode, Perry and Morgan (Perry and Morgan, 2017) provide pessimistic conclusions on coral reef's vertical growth potential over the 21st century. Some studies such as the one from van Woesik *et al.* (van Woesik *et al.*, 2015) in Palau, are more optimistic as they conclude that coral reefs will keep growing vertically in the case of stringent greenhouse gas emission mitigation scenarios (especially RCP2.6). However, the global society' ability to be on track to RCP2.6 is still far from certain, thus balancing the Woesik *et al.*'s conclusion. Another factor refers is that locally, sea level rise may increase sedimentary processes that potentially interfere with photosynthesis, feeding, recruitment, and other key physiological reef processes (Field *et al.*, 2011). Even small increases in sea level (e.g., 0.2 m) can increase turbidity on fringing reefs through increased re-suspension of fine sediment on reef flats and increased coastal erosion and transport of fine sediment to adjacent reefs.

Seagrasses have declined by 29% since the 19th century (Waycott *et al.*, 2009) due to human impacts (eutrophication, siltation, and development) have led to seagrass decline and are further stressed by climate impacts (Diaz-Almela *et al.*, 2007; Marbà and Duarte, 2010). Increasing temperature and heat wave events can adversely affect seagrass growth, survival and distribution (Koch *et al.*, 2013; Thomson *et al.*, 2015). Increasing temperatures may stimulate seagrass photosynthesis until an optimal value is reached which is followed by a rapid decline (Dhir, 2015). The ability of seagrass to cope with increasing temperature is determined by the thermal tolerance of individual species and environmental conditions. When thermal tolerance limits are exceeded, seagrass death can occur (Kaldy, 2014). A recent analysis demonstrated that increasing temperature (+4 °C above control conditions) was the most determinant stressor in seagrass survival (Repolho *et al.*, 2017). Ocean acidification is likely to benefit photosynthesis and growth rates of seagrass (Repolho *et al.*, 2017).

Salt marshes and freshwater tidal marshes have lost more than 50% of their historic global coverage, while 50% of mangroves have been lost in the last 50 years due to dredging, filling, dyking, drainage, trophic cascades, and invasive species (Spalding, 2010; Crooks *et al*., 2011; Donato *et al*., 2011). If these trends continue at current rates, a further 30–40% of tidal marshes and seagrasses and nearly all unprotected mangroves could be lost in the next 100 years (Pendleton *et al*., 2012). Increases in CO_2 and temperature may affect marshes and mangroves but responses likely will vary among species; decreased survival may occur in areas of increased aridity. Sea level rise is the primary climate impact affecting marshes and mangroves (see above). They can keep pace with sea level when sufficient sediment exists to maintain accretion or when landward migration is not constrained by steep topography or coastal development. However, mangroves in carbonate settings or microtidal environments are likely to be adversely impacted by sea level rise and large changes in sea level have led to mangrove ecosystem collapse (Ellison, 1993). A global review (Sasmito *et al*., 2016) demonstrated that accretion rates in basin and fringe mangroves are able to cope with RCP 2.6 over the next century, but can only keep pace with RCP 8.5 until 2055 (fringe mangroves) and 2070 (basin mangroves). These authors suggest that fringe mangroves in small islands (Caribbean, East Africa and parts of the Indo-Pacific) may be unable to keep pace with both low and high IPCC AR5 sea level rise scenarios. A recent global analysis of mangroves (Sasmito *et al*., 2016) showed that positive management interventions supported positive surface elevation gains compared to sea level rise, highlighting the important role of management in maintaining mangroves and their coastal protection values.

Impacts on coastal protection have already occurred but we lack data to extrapolate globally. However, the sensitivity of ecosystems that confer protection (reefs, salt marshes, seagrasses, and mangroves) to climate drivers are well documented (e.g., Sasmito *et al*., 2016; Waycott *et al*., 2009; van Hooidonk *et al*., 2016; Anthony *et al*., 2011). Coastal protection is conferred by a range of habitats and the co-dependency or interactions between them make projections difficult. For example, protection to seagrass beds conferred by coral reefs or the replacement of salt marsh with mangrove forest (Saunders *et al*., 2014; Alongi, 2015). Additionally, human-driven pressure on these ecosystems is inherently difficult to forecast decades from now due to the possible implementation of new policies and the effectiveness of management and climate mitigation efforts. Interacting effects of different symptoms of climate change such as increased temperature, sea-level rise, decreasing pH, salinity, nutrient availability, patterns of precipitation and occurrence of pathogens will all influence the physiological response of individual species and ecosystems and thus further reduce the predictability of responses at higher emissions. However, based on the current loss rates and impacts of climate change discussed above, it is likely that climate change will reduce the coastal protection benefits of these ecosystems. Confidence is thus medium under RCP2.6 and high under RCP8.5.

3.3.8. Bivalves fisheries and aquaculture

Bivalves are key components of coastal ecosystems and cultured commercially because of their high economic value (Ekstrom *et al*., 2015; Lemasson *et al*., 2017). Natural communities of bivalves often function as ecosystem engineers in particular reef-builders such as oysters andmussels (Gutiérrez *et al*., 2003). Bivalve reefs provide habitats for multiple other species resulting in high activities and biodiversity, and contribute to coastal protection. Bivalves are key to benthic-pelagic coupling, clearance of water and thus to nutrient recycling, and are an important food source for high consumers (birds, fishes). The economic value of bivalve fisheries (oysters, mussels and clams) is high and can locally be a major source of income (Ekstrom *et al*., 2015).

The sensitivities of bivalve fisheries and aquaculture to global warming and ocean acidification are high, while the direct impact of sea-level rise is very low. The effect of temperature on bivalves has been studied for decades and warming is expected to have a negative effect on survival, development, growth and conditions, not only of adults, but also of larvae and juveniles (Talmage and Gobler, 2011; Gazeau *et al*., 2014; Lesser, 2016). Organisms living at that thermal tolerance limit are in particular sensitive: summer heat waves can cause high mortality (Rodrigues *et al*., 2015). Ocean acidification has a strong negative impact on the calcification, growth and survival of bivalves (Gazeau *et al*., 2007; Gazeau *et al*., 2010; Talmage and Gobler, 2011; Kroeker *et al*., 2013; Waldbusser and Salisbury, 2014; Ekstrom *et al*., 2015; Lesser, 2016). Shellfish sensitivity varies among species, carbonate mineral phase (aragonite *vs*. calcite) and life stage. Synergetic effects of ocean acidification and temperature have been studied and these revealed a very high sensitivity of bivalves to the combination of warming and ocean acidification (Rodolfo-Metalpa *et al*., 2011; Talmage and Gobler, 2011; Kroeker *et al*., 2013; Lesser, 2016). Food abundance can, however, modify the response of bivalves to warming, ocean acidification and their combined effect (Lesser *et al*., 2010; Thomsen *et al*., 2013; Lesser, 2016). Moreover, bivalve communities can adapt over generations to become less sensitive (Thomsen *et al*., 2017).

4. Contribution of ocean solutions to minimize the impacts of key ocean drivers on ecosystems and ecosystem services (Table 3)

4.1. Rationale and methodological background

We assessed the potential effectiveness of ocean-based solutions to reduce the risk of impacts from climate change on marine ecosystems and their services, as well as the co-benefits and trade-offs for their conservation and sustainability. The focus was on selected ecosystems and ecosystem services that are vulnerable to climate change impacts (Gattuso *et al.*, 2015), including seagrass, coral reefs, mangroves and salt marshes, polar biota, finfish and bivalves fisheries as well as aquaculture and coastal protection provided by coastal ecosystems. These selections are for illustrative purposes and thus not exhaustive. Some important ecosystems and ecosystem services such as deep-sea ecosystems or recreation and cultural services, are not covered. The effectiveness of a solution to reduce climate change-related risk of impacts is based on the extent to which the solution can reduce exposure and sensitivity of the specific ecosystems and ecosystem services to climate drivers. Key climate-related drivers which are most relevant to marine and coastal ecosystems were considered: ocean warming, ocean acidification and sea level rise. The baseline level of expected exposure to climate drivers is assumed to be the level projected by 2100 under the RCP8.5 scenario. A solution can reduce climate impacts by reducing the stressors globally (e.g., by reducing the atmospheric CO_2 concentration) or locally (e.g., by cooling seawater around a specific ecosystem), and/or by reducing the sensitivity of the ecosystems or ecosystem services to climate drivers (e.g., through assisted evolution). A solution was considered effective if it can reduce the risk of impacts from climate change to level that is expected under RCP2.6.

We first assessed the potential effectiveness of each solution to minimize the risk of impacts from ocean warming, ocean acidification and sea-level rise on each ecosystem and ecosystem service considered. It was measured by a combination of the solution's potential to reduce the magnitude of the three drivers considered (Ep, scored 0 to 5; see Tables 1a and 1b for global and local effectiveness, respectively, including their related methodological background in SM31 and SM3.2) and the sensitivity of the ecosystem or ecosystem services to that climate driver (S, scored 0 to 5; see table 2 and methodological background in SM2.3). Specifically, the potential effectiveness to minimize the risk of impacts (Er) was calculated from the euclidean distance between Ep and S:

Er = 0 If Ep = 0
Er = NA If S = 0
Er = sqrt[S^2+(6-Ep)^2] If Ep > 0 and S > 0

Er was rescaled between 0 and 5 by setting a maximum value of Er at 5, and rounding the score to the nearest integer. Thus, a score of 5 indicates that the measure considered could potentially bring the impacts of a climate-related driver expected under RCP8.5 to a level at or lower than the one expected under RCP2.6, while 1 indicates that the degree of impact avoidance from those expected from RCP8.5 is very small, and 0 being no effect at all (or even exacerbate the impacts).

Secondly, we assigned a score to the potential effectiveness of each measure to reduce climate impacts on ecosystems and services by reducing other drivers or the sensitivity to other drivers (e.g. Assisted evolution), with 0 being no effect and 1 to 5 having a very low to very high potential effectiveness (Table 3, section SM3.4.2 below). A very high potential effectiveness here refers to the ability of the solution to reduce the risk of impact on the ecosystems and ecosystem services to a very low level (score of 1). For example, Alkalinization can promote calcification of coral reefs that could reduce the vulnerability to ocean acidification. Thus, a score of 2 (low) is given to the effectiveness of adding alkalinity in reducing the vulnerability of coral reefs to climate stressors. In another case, Eliminating overexploitation of fish stocks and coastal vegetation (e.g., mangroves) will enhance the productivity and adaptive capacity of fish stocks that can compensate for their climate vulnerability. Therefore, we have assigned a score of 5 for the effectiveness of Eliminating overexploitation as a solution to reduce climate sensitivity of finfish fisheries.

We also assessed the co-benefits on function and services as well as disbenefits of each measure on the selected ecosystems and ecosystem services. Co-benefits were evaluated based on the ability of solutions to enhance functions or services of the ecosystem considered, irrespective of their effects in reducing climate-related impacts. Disbenefits refer to negative impacts of the solutions on functions or services of the ecosystem considered. A score of 0, 1 to 5 was assigned for no, very low to very high co-benefits, respectively. This scale was reversed for disbenefits (i.e., 5 being very low and 1 being very high). A score of 5 for co-benefits means that the solution can also substantially mitigate non-climatic stressors, while a ranking of 1 for trade-offs means that the solution will degrade the ecosystem/ecosystem services beyond the expected climate impacts.

4.2. Results

Table 3 relates to the contribution of ocean-related solutions to minimize the impacts of key ocean drivers on ecosystems (seagrass habitats, coral reefs, mangroves and salt marshes, and Arctic biota) and ecosystem services (fin fisheries, finfish aquaculture, coastal protection by natural ecosystems, and bivalves fisheries and aquaculture). It is accessible here: http://www.obs-vlfr.fr/~gattuso/files/supplementary_tables.xlsx.

4.3. Justification of the scores of Table 3

4.3.1. Seagrass habitat

4.3.1.1. Renewable energy

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** The deployment of renewable energy devices in coastal areas is often associated with the restriction of the area designated for this use for other uses, such as fishing or others, which may provide protection to seagrass habitats.
- **Co-benefits -** If protected in the areas designated for marine energy parks, the services and functions associated with seagrass meadows, such as food supply, habitat for organisms and nutrient cycling would be exerted, delivering additional benefits.
- **Disbenefits -** Unintended consequences may include the removal of part of the seagrass bed when deploying the marine energy devices, in case they are deployed in seagrass meadows.
- **Caveats and limits -** Sound marine spatial planning is expected to avoid deployment of marine energy parks in seagrass meadows.

4.3.1.2. Vegetation (global and local)

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** It is assumed that all approaches addressing the causes of climate change and ocean acidification (reducing GHG emissions and increase carbon storage) are very highly effective to minimize the risks of impacts on seagrass habitats. Some, however, have drawbacks. The score considers both benefits and drawbacks. Conservation and restoration of seagrass meadows support and enhance CO_2 sequestration and avoid emissions by conserving carbon stocks (Duarte *et al*., 2013a; Marbà *et al*., 2015; Serrano *et al*., 2016). CO_2 sequestration has been overestimated because calcium carbonate cycling (a CO_2 source) is not considered (Macreadie *et al*., 2017b). Also, geophysical conditions of the sediment are, however, not always conducive to organic carbon stabilisation, ultimately leading to low storage in some seagrass communities (Belshe *et al*., 2017). The effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers is high, but the contribution to mitigate climate change will be modest (Pendleton *et al*., 2012).
- **Co-benefits -** Seagrass meadows provide important ecosystem services, including habitat provision and nursery grounds to support marine life and biodiversity, production to support marine food webs (Cullen-Unsworth and Unsworth, 2013; Dewsbury *et al*., 2016; Nordlund *et al*., 2016; Reynolds *et al*., 2016)Nordlund, global fisheries (Unsworth *et al*., 2018), and the capacity to maintain good water quality by removing nutrients, pollutants and pathogens (Lamb *et al*., 2017). Climate change adaptation, through the protection against storms and waves and the capacity of seagrass meadows to raise the seafloor, thereby adapting to sea level rise, offer arguably greater value than the contribution of restoration and conservation of marine vegetation to mitigate climate change does (Duarte *et al*., 2013b).
- **Disbenefits -** We are not aware of any reports of negative consequences of conservation and restoration of marine vegetation.
- **Caveats and limits -** Seagrass restoration requires significant resources and fails if not planned properly (van Katwijk *et al*., 2016). Because of the exponential nature of clonal growth, the benefits, in terms of CO_2 sequestration, of seagrass restoration projects accelerated over time and becomes significant only decades after the projects were initiated (Duarte *et al*., 2013a).

4.3.1.3. Fertilization

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** It is assumed that all approaches addressing the causes of climate change and ocean acidification (reducing GHG emissions and increase carbon storage) are very highly effective to minimize the risks of impacts on seagrass habitats. Some, however, have drawbacks. The rating considers both benefits and drawbacks. Marine productivity enhancement may lead to reduced pCO_2 partial pressures, thereby alleviating impacts to calcifiers associated with seagrass meadows in areas affected by marine Fertilization.
- **Co-benefits -** Co-benefits in terms of improved functions and services of seagrass meadows are expected to be minimal or non-existing.

- **Disbenefits -** Ocean fertilization can reduce submarine light penetration and shade seagrass habitats, if done in coastal environments. Likewise, establishing seaweed farms over seagrass meadows would reduce light penetration and impact on seagrass meadows.
- **Caveats and limits -** The areas likely targeted for marine fertilization, include the Southern ocean and the open North Pacific, which are high-nutrient, low-chlorophyll areas, but support no (Southern Ocean) or limited (open North Pacific) seagrass meadows.

4.3.1.4.3. Alkalinization

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** It is assumed that all approaches addressing the causes of climate change and ocean acidification (reducing GHG emissions and increase carbon storage) are very highly effective to minimize the risks of impacts on seagrass habitats. Some, however, have drawbacks. The rating considers both benefits and drawbacks. Alkalinization is unlikely to reduce impacts by other drivers than those climate-related. No other drivers affecting seagrass are known to be reduced by alkalinity.
- **Co-benefits -** No adverse effect reported in the literature.
- **Disbenefits -** Seagrass meadows are often CO_2-limited, so removal of CO_2 through alkalinity addition could affect seagrass productivity if CO_2 was depleted below threshold CO_2 levels for seagrass photosynthesis.
- **Caveats and limits -** No information in the original SM. The benefits, co-benefits, and disbenefits of alkalinization will remain hypothetical until further R&D and testing has been done. High uncertainty remains about the potential to scale this solution globally, and regarding potential unintended consequences.

4.3.1.5. Hybrid methods

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** in those cases where hybrid methods generate ocean alkalinity, see “Alkalinity” effectiveness, above. In those cases where hybrid methods produce and store marine CO2, this could be beneficial to seagrasses when CO2-limited.
- **Co-benefits -** In cases where hybrid methods produce ocean alkalinity see “Alkalinity” co-benefits, above.
- **Disbenefits -** Potential disbenefits include acidification if molecular CO_2 is the storage medium, trace metal and contaminant effects if these constituents are present with the carbonaceous material stored in the ocean. Potential for O2 reduction and acidification if organic matter is the storage medium of hybrid methods.
- **Caveats and limits -** The benefits, co-benefits, and disbenefits of many of the hybrid methods will remain hypothetical until further R&D and testing has been done.

4.3.1.6. Cloud brightening

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** No other drivers will be affected by cloud brightening.
- **Co-benefits -** Cloud brightening is unlikely to deliver additional benefits to seagrass ecosystems beyond those derive from reduced warming.
- **Disbenefits -** Seagrass growing at the light-imposed depth limit could be negatively affected if irradiance incident in the surface is decreased significantly.

4.3.1.7. Albedo enhancement

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Increased albedo is unlikely to affect other drivers than warming.
- **Co-benefits -** Increased albedo is unlikely to deliver additional benefits to seagrass ecosystems beyond those derive from reduced warming.
- **Disbenefits -** Seagrass growing at the light-imposed depth limit could be negatively affected if irradiance incident in the surface is decreased significantly.

4.3.1.8. Pollution reduction

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Eutrophication is believed to be the main driver of seagrass loss globally (Waycott *et al.*, 2009), leading to the loss of carbon sink capacity and risk of emissions of the carbon stored in their sediments. Hence, reducing nutrient inputs in eutrophied areas is expected to help conserve seagrass meadows, and recover meadows lost (Riemann *et al.*, 2016), with benefits in terms of conserving and restoring their carbon sink capacities and stocks.
- **Co-benefits -** Reduced pollutants, particularly nutrient, inputs to coastal areas would improve water quality and improve seagrass health and productivity, with the associated benefits, in terms of restoring ecosystem services delivered by seagrass meadows.
- **Disbenefits -** No unintended consequences on seagrass meadows are expected from reduced pollutant inputs.
- **Caveats and limits -** The treatment of pollutants is assumed not to involve the building of facilities that damage coastal ecosystems.

4.3.1.9. Restoring hydrology

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Seagrass meadows act as traps for allochthonous carbon, hence restoring hydrological regime may, in principle, increase their capacity to trap land-derived organic carbon in their sediments. However, there is no study yet conducted to evaluate this possibility.
- **Co-benefits -** Maintaining sediment delivery can help prevent coastal erosion and help maintain seagrass meadows, as well as support their capacity to trap sediments and support sediment accretion rates providing adaptation to sea level rise.
- **Disbenefits -** Increased sediment delivery maybe accompanied with increased turbidity, in which case seagrass meadows may be impacted, particularly at depth.
- **Caveats and limits -** We are not aware of any study demonstrating benefits or impacts of restored or reduced sediment delivery for seagrass meadows.

4.3.1.10. Eliminating overexploitation

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Removal of top predators has been shown to affect the capacity of seagrass meadows to store carbon, by releasing pressure on herbivores (Atwood *et al.*, 2015). Overexploitation of seagrass meadows may also cause physical disturbance, through fishing gear and/or boat propellers and anchors, which also leads to loss of the seagrass cover and associated carbon sink capacity and stocks.
- **Co-benefits -** Reducing overexploitation of seagrass meadows improves the health of these ecosystems and their capacity to supply services, including their role as habitat.
- **Disbenefits -** No unintended consequences have been reported.

4.3.1.11. Protection

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Marine protected areas including seagrass meadows enhance the scope for conservation of these habitats and, therefore, help avoid emissions from disturbed seagrass soils while maintaining their carbon sink capacity (Roberts *et al.*, 2017).
- **Co-benefits -** Protection of seagrass meadows help avoid losses from disturbance and ensure the continuity of the services these ecosystems provide (Roberts *et al.*, 2017), including global fisheries production (Unsworth *et al.*, 2018).
- **Disbenefits -** No unintended consequences have been reported.
- **Caveats and limits -** MPAs with adequate staff capacity have ecological effects (increase in fish populations) 2.9 times greater than MPAs with inadequate capacity but many MPAs fail to meet thresholds for effective and equitable management processes, with widespread shortfalls in staff and financial resources (Gill *et al.*, 2017). In addition, protection itself cannot avoid impacts from warming to vulnerable seagrass meadows once thresholds are reached (e.g., Jordà *et al.*, 2012).

4.3.1.12. Assisted evolution

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Assisted evolution has not been proposed for vulnerable seagrass, and is unlikely to work for seagrass at any reasonable scale.
- **Co-benefits -** Assisted evolution has not been proposed for vulnerable seagrass.
- **Disbenefits -** No assessment has been made.

4.3.1.13. Relocation and reef restoration

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Seagrass meadows are likely to benefit from restoration of seagrass meadows (self-evident) as well as those of adjacent habitats, which are often linked to seagrass meadows through nutrient, carbon and species exchange. Relocation could accelerate seagrass (*Z. marina*) colonization of a warming Arctic, which may, otherwise, be limited by propagule supply.
- **Co-benefits -** Restoration and relocation, where effective, would carry benefits in terms of the ecosystem services associated with seagrass meadows.
- **Disbenefits -** No unintended consequences of restoration have been reported. Possible impacts are not known, but likely to be modest or minimal, but need be assessed, particularly where relocation of seagrass meadows may be done at the expense of previously existing habitats.
- **Caveats and limits -** No experimental relocation of seagrass meadows has been conducted to-date.

4.3.2. Coral reefs

4.3.2.1. Renewable energy

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Ocean Thermal Energy Conversion (OTEC) is unlikely to be deployed in coral reefs. Any effects will be carry over effects from deployments in other locations like adjacent seagrass meadows. These will be cooling and reduced ocean acidification.
- **Co-benefits -** Co-benefits of possible bleaching reduction because OTEC brings up cool/more acidic/nutrified waters and structures attracts fish (fish aggregating devices).
- **Disbenefits -** Low because warming reduction is helpful to corals but also adverse effects from acidification and nutrients.
- **Caveats and limits -** OTEC leads to local cooling. If applied, wave, wind park and OTEC could have positive or negative effects. Wave parks may affect flows, sunlight, and fish aggregation patterns locally acting as dish attractant devices (Fish aggregating devices, FADs). Wind parks may offer substrates for potential recruitment and may also have fish benefits. on corals, thus generating habitat overcompensating for losses/ displacement of habitat during construction - increased sedimentation.

4.3.2.2. Vegetation (global and local)

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** CO_2 sequestration and storage and downstream indirect effects that limit ocean warming and slowing ocean acidification reduces bleaching and mortality risk on coral reefs
- **Co-benefits -** Highly influential on coastal protection and maintenance of ecosystem services, mangroves filter pollutants from coastal waters - this will promote coral health and inhibit algal growth. Mangrove and seagrasses provide nurseries for fish populations on coral reefs (Mumby *et al*., 2004).
- **Disbenefits -** No adverse effect reported in the literature.
- **Caveats and limits -** Conserving blue carbon habitats and their connections helps coral reefs - important chemical and biological interactions among habitats. Co-benefits high in terms of ecosystem services.

4.3.2.3. Fertilization

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Adverse impacts of nutrient enrichment on coastal and marine ecosystems are well documented (Ellison and Farnsworth, 1996; Hughes *et al*., 2003; Islam and Tanaka, 2004; Fabricius, 2005; Waycott *et al*., 2009; Duke, 2016). Fertilization has a serious negative effect on coral reefs (Carilli *et al*., 2009; Wooldridge and Done, 2009; Brodie *et al*., 2012) These negative effects will have immediate deleterious impacts on the health of the reef.
- **Co-benefits -** Artificial upwelling could have a cooling effect on coastal waters and reduce risk of bleaching on reefs, but these effects will be overshadowed by negative impacts of implemented with nutrient additions.
- **Disbenefits -** Reduced light levels will adversely affect calcification and coral reef growth and overgrowth by macroalgae can drive regime shifts ((Altieri *et al*., 2017).

4.3.2.4. Alkalinization

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Local amelioration and moderation of ocean acidification enhances net coral reef calcification (Albright *et al*., 2016) but the effect is likely to be small given that coral reefs thrive in highly variable ocean acidification settings that reflect the biological composition and health of benthic communities (Hofmann *et al*., 2010).
- **Co-benefits -** The ecosystem services associated with coral reefs will be sustained and other calcifiers may potentially benefit. These include molluscs, forams, and crustose coralline algae that represent critical coral settlement cues.
- **Disbenefits -** If calcium carbonate is mined from the reef itself this would have very negative consequences for the reef and all of the ecosystem services it provides.

4.3.2.5. Hybrid methods

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers** - in those cases where hybrid methods generate ocean alkalinity, could be highly effective in countering the effects on ocean acidification on corals (e.g.Albright *et al*., 2016) at least at local scales. see “Alkalinity”
- **Co-benefits -** In cases where hybrid methods produce ocean alkalinity and counter ocean acidification, co-benefits to corals and other shell formers are potentially significant at least at local scales (e.g.Albright *et al*., 2016).
- **Disbenefits -** Potential disbenefits include acidification if molecular CO_2 is the storage medium, trace metal and contaminant effects if these constituents are present with the carbonaceous material stored in the ocean. Potential for O2 reduction and acidification if organic matter is the storage C medium of hybrid methods.

- **Caveats and limits -** The benefits, co-benefits, and disbenefits of many of the hybrid methods will remain hypothetical until further R&D and testing has been done.

4.3.2.6. Cloud brightening

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Cloud brightening may help to stimulate global cooling (Latham *et al*., 2012). This could reduce thermal expansion and reduce the impacts of temperature related bleaching and reef degradation (Latham *et al*., 2013). This will sustain fortification against sea-level rise.
- **Co-benefits -** Sustaining coral reefs has many benefits in term of biodiversity and the full range of ecosystem services.
- **Disbenefits -** Will drive changes in precipitation, climate oscillations, and SST which will have unpredictable and potentially detrimental effects on coral reefs.
- **Caveats and limits -** More data needed to assess the balance of positive and negative impacts.

4.3.2.7. Albedo enhancement

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Unlikely to be deployed on coral reefs.
- **Co-benefits -** More research is necessary to ascertain impacts of coral reef habitats (Russell *et al*., 2012).
- **Disbenefits -** More research is necessary to ascertain impacts of coral reef habitats (Russell *et al*., 2012).

4.3.2.8. Pollution reduction

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Adverse impacts of nutrient pollution on coral reef ecosystems are well documented (Dubinsky and Stambler, 1996; Ennis *et al*., 2016; Salvat *et al*., 2016). Nutrient pollution and overfishing interact with temperature (Zaneveld *et al*., 2016) to exacerbate bleaching and related downward shifts in coral health. Poor water quality increases vulnerability to ocean acidification and thermal stress. All pollution compromises coral health and influences for carbon sequestration and storage as well as mediation of local ocean acidification conditions and sea-level rise. Coral reefs protect the coastline and reduce wave energy by an average of 97% (Ferrario *et al*., 2014). Poor water quality depresses calcification (Fabricius, 2005).
- **Co-benefits -** Improvements to water quality increases productivity and builds reef resilience as well as benefit adjacent seagrass and mangrove habitats. Reducing pollutants builds resilience on coral reefs and contributes to sustaining ecosystem services on reefs. Reef services include fisheries, tourism, recreation, carbon sequestration, water filtering, wave attenuation, stabilization of shoreline (Barbier *et al*., 2011).
- **Disbenefits -** No adverse effect reported in the literature.
- **Caveats and limits -** Investigating the last three major bleaching events, Hughes *et al*. (Hughes *et al*., 2017b) found that water quality had minimal effect on the unprecedented bleaching in 2016, suggesting that local protection of reefs affords little or no resistance to extreme heat.

4.3.2.9. Restoring hydrology

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Water flow modulates temperature induced bleaching and mortality (Bayraktarov *et al*., 2013) and response to ocean acidification in corals (Comeau *et al*., 2014).
- Maintaining optimal hydrological regimes will promote ecosystem health and sustain carbon sequestration, storage and function in local sea-level rise.
- **Co-benefits -** Will sustained ecosystem services on reefs. Reef services include fisheries, tourism, recreation, carbon sequestration, water filtering, wave attenuation, stabilization of shoreline (Barbier *et al*., 2011).
- **Disbenefits -** Given the sensitivity of corals to flow and water quality, control of hydrological and sediment regimes could result in greater unpredictability in flow and light conditions on the reefs that could have detrimental effects on reef health. This is speculative and intuitive as never been tested.

4.3.2.10. Eliminating overexploitation

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** The extraction of live coral, herbivorous fish and destructive fishing practices materials for building compromises reef health (Bozec *et al*., 2016) and vulnerability to thermal stress (Zaneveld *et al*., 2016) and influences for carbon sequestration and storage as well as mediation of local ocean acidification conditions and sea-level rise. Coral reefs protect the coastline and reduce wave energy by an average of 97% (Ferrario *et al*., 2014). Overfishing and nutrient pollution interact with temperature (Zaneveld *et al*., 2016) to exacerbate shifts in coral health. Bozec *et al*. (Bozec *et al*., 2016) find that the implementation of a size restriction of >30 cm provides a win:win outcome in the short term, delivering both ecological and fisheries benefits and leading to increased yield and greater coral recovery rate for a given harvest rate. Managing parrotfish is not a panacea for protecting coral reefs but can play a role in sustaining the health of reefs and high quality habitat for reef fisheries.

- **Co-benefits -** Controlling over-exploitation builds resilience on coral reefs and contributes to sustaining ecosystem services on reefs. Reef services include fisheries, tourism, recreation, carbon sequestration, water filtering, wave attenuation, stabilization of shoreline (Barbier *et al*., 2011).
- **Disbenefits -** Potentially difficult to enforce assertive management regimes with local communities with dependence on resource extraction.
- **Caveats and limits -** Presence of herbivores critical to coral reef function. However, investigating the last three major bleaching events, Hughes *et al*. (Hughes *et al*., 2017b) found that fishing pressure had minimal effect on the unprecedented bleaching in 2016, suggesting that limiting extraction afforded little or no resistance to extreme heat. However, local protection of fish stocks and improved water quality may, given enough time, improve the prospects for recovery.

4.3.2.11. Protection

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Protection in reserves leads to increased coral recruitment and fish biomass which potentially promotes coral reef recovery from coral bleaching and storms (Mumby *et al*., 2007; Gill *et al*., 2017). Protecting coral reefs has an impact on sea-level rise. Coral reefs reduce wave energy by an average of 97% (Ferrario *et al*., 2014) and have a local influence on ocean acidification conditions.
- **Co-benefits -** Ecological benefits of ecosystem protection (e.g., from MPAs) are well establishedFor example, increases in size, density, biomass, species richness within reserve boundaries (Lester and Halpern, 2008)and benefits from carbon sequestration, tourism, and coastal protection . Protected areas may also reduce user conflicts, enhance environmental awareness, and build social capital (Fox *et al*., 2012).
- **Disbenefits -** In general, social disbenefits of MPAs may include decreased food security, forced migration, loss of assets, loss of tenure, and increased poverty (Bennett and Dearden, 2014). No disbenefit reported in the literature as they pertain to reefs.
- **Caveats and limits -** Mesotrophic coral ecosystems (MCEs) are often considered to be buffered from many large-scale impacts known to affect shallow coral ecosystems, such as coral bleaching and cyclones. They are also relatively less affected by direct human impacts, such as overfishing and land-based runoff. MCEs were suggested to be refugia which could serve to reseed shallow-water coral reefs and that there is value to protect them (Baker *et al*., 2016). However, molecular evidence suggests that deep reefs are not universal refuges and that the reseeding potential varies among coral species (Bongaerts *et al*., 2017). Investigating the last three major bleaching events, Hughes *et al*. (Hughes *et al*., 2017b) found that water quality and fishing pressure had minimal effect on the unprecedented bleaching in 2016, suggesting that local protection of reefs affords little or no resistance to extreme heat. However, local protection of fish stocks and improved water quality may, given enough time, improve the prospects for recovery.

4.3.2.12. Assisted evolution

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Coral reefs contribute to CO_2 sequestration and storage and have a local influence on if scaled appropriately these approaches magnify capacity for both as well as have a will have a local impact on ocean acidification. These approaches are targeted at sustaining historical states on reefs or promoting assembly of “new” engineered systems meeting desired attributes and maintaining goods and services provided by the historical ecosystem (Jackson and Hobbs, 2009; Hobbs *et al*., 2011; Higgs *et al*., 2014). Genetic direction or climate optimization through selective breeding, microbiome modification and conditioning (plus more interventional approaches include genetic modification and synthetic biology) of corals to elevate thermal thresholds has the potential to enhance the survival of subsets of the communities.
- **Co-benefits -** These approaches have potential to sustains ecosystem services on reefs in the face of intensifying warming and ocean acidification (Rau *et al*., 2012; van Oppen *et al*., 2015; van Oppen *et al*., 2017).
- **Disbenefits -** Only a small subset of reef species could be made tolerant (Anthony, 2016; Anthony *et al*., 2017; van Oppen *et al*., 2017). Translocated plants and animals may carry pathogens or parasites affecting the health of native populations, be maladapted to other non-climate related changes, or may cause a change in genetic composition or population structure of native organisms, a loss of genetic diversity, or a breakdown of coadapted gene complexes (Laikre *et al*., 2010; van Oppen *et al*., 2015; Anthony *et al*., 2017). A counterargument here may be that with climate change and severe declines on the horizon, the spread and dominance of selected keystone species might be a better outcome than total loss (Anthony, 2016).
- **Caveats and limits -** Sustaining and enhancing natural marine ecosystem is in the conceptual stage but genetic direction (climate optimization) of stocks to elevate thermal thresholds has the potential to enhance the survival

of communities and perpetuate ecosystem services (Rau *et al*., 2012; van Oppen *et al*., 2015; van Oppen *et al*., 2017). These techniques are new to wild marine systems and have not implemented at scale.

4.3.2.13. Relocation and reef restoration

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers:**
  - The restoration and repopulation of denuded reefs is fundamental to sustaining coral reef systems (Rinkevich, 2014; Rinkevich, 2015), especially when receiving areas are failing to recruit juvenile corals.
  - Natural recovery can indeed be sufficient in the medium to long term (Edwards and Clark, 1999). Successful reef restoration requires addressing stressors adversely affecting coral reef health, thus has the potential to improve reef resilience and relocation may assist corals in occupying new climate niches.
- **Co-benefits -** The goal of coral reef restoration is to sustain ecosystems (Rinkevich, 2014; Timpane-Padgham *et al*., 2017). Restoring coral reefs potentially sustains some or all of the ecosystem services on reefs. Reef services include fisheries, tourism, recreation, carbon sequestration, water filtering, wave attenuation, stabilization of shoreline (Barbier *et al*., 2011).
- **Disbenefits -** Restoration often focuses on a few species that are chosen for ease of cultivation. This reduced diversity has undefined cascading effects on the provisioning of habitat for biodiversity and other ecosystem services. These are planted in a non-random fashion and if successful grow a landscape that lacks the topographic complexity of natural communities (e.g., Rinkevich, 2014; Rinkevich, 2017). This potentially influences capacity to deliver all historical ecosystems services.
- **Caveats and limits -** Relocation of coral stocks has the advantage of allowing corals to occupy new habitats (Beger *et al*., 2014) and environments that can be facilitated by artificial reef programs (Maya *et al*., 2016). Coral transplantation studies report rates of survival of coral transplants of 65% or more (Bayraktarov *et al*., 2017; Rinkevich, 2017) but low to moderate survival rates of coral transplants (6-35%) were found under elevated temperatures (Yap, 2004). Regardless of potential, coral farming and transplantation has been applied at relatively small scales to date.

4.3.3. Mangroves and salt marshes

4.3.3.1. Renewable energy

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Renewable energy (from marine wind, tides, currents, waves) can reduce carbon emissions, resulting in reduced warming, ocean acidification, and sea-level rise, thus potentially benefitting mangroves and salt marshes. Impacts of wind farms/hydropower on coastal habitats are not well established but limited evidence suggests both positive and negative impacts (e.g., negative impacts include changes to benthic and pelagic habitats, alterations to food webs, and pollution from increased vessel traffic or release of contaminants from seabed sediments). Potentially beneficial effects include potential de-facto marine reserve around wind turbines, as exclusion of boats would reduce disturbance from shipping (Bailey *et al*., 2014). Many marine renewable energy devices operate by removing kinetic energy from water (or air in the case of offshore wind). For devices at sea or in estuaries, the resultant reduction of energy may lead to downstream effects. Tidal energy devices may result in local acceleration and scouring in some cases, but have the potential to decrease tidal amplitude in downstream areas. Effects of wave energy devices may alter sediment transport and deposition as well as have an effect on beach processes, thus potentially impacting coastal habitats (Boehlert and Gill, 2010). Due to these potential effects, the effectiveness of this solution to reduce impacts on an ecosystem by reducing other drivers is likely to be very low.
- **Co-benefits -** Insufficient evidence exists to demonstrate co-benefits. Uncertainty score is based on agreement not evidence
- **Disbenefits -** Potential for unintended consequences exists and noted above.
- **Caveats and limits -** Any large-scale development in the marine environment comes with uncertainty about potential environmental impacts, most of which have not been adequately evaluated—in part because many of the devices have yet to be deployed and tested (Boehlert and Gill, 2010).

4.3.3.2. Vegetation (global) - see below for Local

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Restoration/conservation of marine vegetation has direct benefits to supporting their carbon sequestration benefits and reduced emissions from their degradation/destruction (Crooks *et al*., 2011; Howard *et al*., 2017). Conserved/restored vegetation supports sequestration and reduced warming (Mcleod *et al*., 2011; Howard *et al*., 2017). Protection and restoration of mangroves and salt marshes can reduce impacts from SLR as these habitats reduce wave height and energy. Salt marshes play an important role in wave attenuation and shoreline stabilization (Shepard *et al*., 2011) and can reduce the height of damaging waves in storm surge conditions by close to 20% (Möller *et al*., 2014).

Mangroves can reduce the height of wind and swell waves (Bao, 2011) and tsunami impacts (Alongi, 2008); wave height can be reduced by between 13-66% over 100 m of mangroves (McIvor *et al*., 2012).

- Due to the limited area of these habitats globally, their effectiveness to reduce impacts on ecosystems are low at the global scale. Global coverage of mangroves is about 13.8–15.2 million ha (Spalding, 2010; Giri *et al*., 2011). Global coverage of tidal marshes is up to 40 million ha, although only 2.2 million ha have been verified (Duarte *et al*., 2013b).
- **Co-benefits -** Significant co-benefits (Barbier *et al*., 2011; Shepard *et al*., 2011) including tourism, biodiversity, food security, water quality).
- **Disbenefits -** Unintended consequences unlikely but may occur if communities are not engaged in management planning/implementation and if local uses are not accounted for.
- **Caveats and limits -** Direct climate benefits available with many additional co-benefits. While benefits may be accrued quickly, full ecosystem recovery can take decades and requires long-term monitoring. Limited data on global extent of salt marshes.

4.3.3.3. Fertilization

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Low for nutrient addition; high for seaweed cultivation. While nutrient addition may stimulate photosynthesis, evidence suggests nutrient enrichment resulted in enhanced mortality of mangroves - benefits of increased mangrove growth in response to coastal eutrophication was offset due to mortality during drought, with mortality increasing with soil water salinity along climatic gradients (Lovelock *et al*., 2009). Nutrient enrichment in salt marshes has led to cracks in the banks of the tidal creeks and eventual collapse into muddy creek - long-term effect is conversion of vegetated marsh into mudflats (Deegan *et al*., 2012).
- **Co-benefits -** Co-benefits may occur with seaweed cultivation which has multiple benefits (improving water quality, fisheries, wave attenuation). Co-benefits are unlikely with nutrient addition and artificial upwelling as discussed above.
- **Disbenefits -** Nutrient enrichment of coastal areas is known to cause harmful algae blooms, which create low-oxygen conditions that kill off marine life and salt marsh disintegration and mangrove mortality (Lovelock *et al*., 2009; Deegan *et al*., 2012). May also cause increased growth in shoots and less growth in roots, thus less stabilization/sequestration potential in mangroves (Lovelock *et al*., 2009).
- **Caveats and limits -** Unintended consequences are likely to outweigh the potential benefits of nutrient addition and artificial upwelling.

4.3.3.4. Alkalinization (global) - see below for Local

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Large demand for carbonate mineral and water will likely limit its application to coastal sites (Rau, 2011) and is unlikely to address sea-level rise which is primary climate impact affecting mangroves/marshes (Kirwan and Megonigal, 2013; Ellison, 2015). Lab studies suggest the addition of alkaline substances releases conjointly toxic heavy metals (e.g., cadmium, nickel, chromium) leading to further perturbations that would likely impact ocean biogeochemical cycling and marine ecosystems including mangroves and marshes (González and Ilyina, 2016).
- **Co-benefits -** Co-benefits likely to be low - only relevant at local scales (Rau *et al*., 2012).
- **Disbenefits -** Addition of alkaline substances releases conjointly toxic heavy metals (e.g., cadmium, nickel, chromium) leading to further perturbations (González and Ilyina, 2016) and may result in adverse impacts in mangroves and salt marshes.
- **Caveats and limits -** Only relevant at local scales (Rau *et al*., 2012) and unlikely to benefit mangroves/salt marshes.

4.3.3.5. Hybrid methods

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** in those cases where hybrid methods generate ocean alkalinity, see “Alkalinity” effectiveness, above.
- **Co-benefits -** In cases where hybrid methods produce ocean alkalinity see “Alkalinity” co-benefits, above.
- **Disbenefits -** Potential disbenefits include acidification if molecular CO_2 is the storage medium, trace metal and contaminant effects if these constituents are present with the carbonaceous material stored in the ocean. Potential for O_2 reduction and acidification if organic matter is the storage medium of hybrid methods.
- **Caveats and limits -** The benefits, co-benefits, and disbenefits of many of the hybrid methods will remain hypothetical until further R&D and testing has been done.

4.3.3.6. Cloud brightening

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Research suggests that cloud brightening may help to stimulate global cooling (Latham *et al*., 2012) which could reduce thermal expansion and thus SLR impacts - however, changes to precipitation patterns and climate oscillations, and SST could change salinity regimes in coastal waters which could benefit or adversely affect mangroves. Cooling resulting from intervention may affect salt marsh/mangrove ranges which are sensitive to freezing temperatures. Changes in precip/temp changes can affect health of wetlands buffering sea-level rise - potential for pollution if not using sea salt (Shepherd, 2009).

- **Co-benefits -** More data are needed to determine co-benefits.
- **Disbenefits -** More data are needed to assess impacts (\e.g., precipitation patterns and climate oscillations, and sea surface temperature; \Latham et al., 2012, #95651} on mangroves/salt marshes.
- **Caveats and limits -** More data are needed (see above).

4.3.3.7. Albedo

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Intense cooling over small ocean regions could change circulation (e.g., El Nino and monsoon cycles), which could impede climate regulation; enhanced ocean upwelling could increase outgassing of CO_2. Local cloud albedo increases could result in changes in circulation, sea surface temperature gradients, nutrient upwelling, and El Nino which can have significant impacts on mangroves/salt marshes (Russell *et al.*, 2012).
- **Co-benefits -** Have not been verified regarding links to mangroves/seagrasses. Could drive range shifts (mangrove migration in response to cooler temperatures at boundaries of mangrove range) which could have positive or negative impacts.
- **Disbenefits -** More research is necessary to ascertain impacts on mangroves/salt marshes.
- **Caveats and limits -** Impacts to ocean circulation, temperature, nutrient upwelling and climate patterns (ENSO) may outweigh potential benefits.

4.3.3.8. Vegetation (local) - see above for Global

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Restoration/conservation of marine vegetation has direct benefits to supporting their carbon sequestration benefits and reduced emissions from their degradation/destruction (Crooks *et al.*, 2011; Howard *et al.*, 2017). Conserved/restored vegetation supports sequestration and reduced warming (Mcleod *et al.*, 2011; Howard *et al.*, 2017). Protection and restoration of mangroves and salt marshes can reduce sea-level rise locally as these habitats reduce wave height and energy. Salt marshes play an important role in wave attenuation and shoreline stabilization (Shepard *et al.*, 2011) and can reduce the height of damaging waves in storm surge conditions by close to 20% (Möller *et al.*, 2014). Mangroves can reduce the height of wind and swell waves (Bao, 2011) and tsunami impacts (Alongi, 2008); wave height can be reduced by between 13-66% over 100 m of mangroves (McIvor *et al.*, 2012).
- **Co-benefits -** Significant co-benefits (Barbier *et al.*, 2011; Crooks *et al.*, 2011) including tourism, biodiversity, food security, water quality).
- **Disbenefits -** Unintended consequences unlikely but may occur if communities are not engaged in management planning/implementation and if local uses are not accounted for.
- **Caveats and limits -** Direct climate benefits available with many additional co-benefits. While benefits may be accrued quickly, full ecosystem recovery can take decades and requires long-term monitoring. Limited data on global extent of salt marshes.

4.3.3.9. Alkalinization (local) - see above for Global

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Potential impacts to reduce warming and thus sea-level rise but low effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers (González and Ilyina, 2016) in mangroves and salt marshes. The effectiveness of Alkalinization to reduce impacts on coastal habitats are not well known but only relevant for coral/oyster reefs/seagrass, not helpful for mangroves/salt marshes. Lab studies suggest the addition of alkaline substances releases conjointly toxic heavy metals (e.g., cadmium, nickel, chromium) leading to further perturbations that would likely impact ocean biogeochemical cycling and marine ecosystem services (González and Ilyina, 2016). Large demand for carbonate mineral and water will likely limit its application to coastal sites (Rau, 2011).
- **Co-benefits -** Co-benefits likely to be low and only relevant at very local scales (Rau *et al.*, 2012).
- **Disbenefits -** Further evaluation is needed of the economics, potential scale, permanence, environmental cost/benefits, and societal acceptability (Rau, 2011). Addition of alkaline substances releases conjointly toxic heavy metals (e.g., cadmium, nickel, chromium) leading to further perturbations that would likely impact ocean biogeochemical cycling and marine ecosystem services (González and Ilyina, 2016).
- **Caveats and limits -** Potentially relevant at local scales (Rau *et al.*, 2012) but it is unclear how it would affect mangroves and salt marshes.

4.3.3.10. Pollution reduction

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** While reducing pollution into coastal ecosystems will not directly reduce the impacts of sea-level rise, which is the primary climate impact facing mangroves and salt marshes, it is likely to benefit the health of these ecosystems as a co-benefit based on the demonstrated adverse impacts of pollutants on these habitats (Lovelock *et al*., 2009; Deegan *et al*., 2012) and thus support their ability to sequester carbon.
- **Co-benefits -** Reducing pollutants in mangroves/seagrasses will improve ecosystem health and the benefits these systems provide (e.g., coastal protection, water quality, tourism, fisheries, etc.).
- **Disbenefits -** Unlikely to have adverse consequences.

4.3.3.11. Restoring hydrology

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Maintaining the hydrological regime is an important strategy to reduce the impacts of sea-level rise at local scales which is likely to benefit mangroves/salt marshes. Tidal flow and sediment circulation patterns are two key criteria to maintaining the ability of coastal wetlands to accrete vertically to keep pace with sea-level rise (Raposa *et al*., 2016; Sasmito *et al*., 2016), thus critical to maintaining their capacity for carbon sequestration.
- **Co-benefits -** Maintaining hydrological regimes can support carbon sequestration in coastal habitats in addition to other benefits (fisheries, tourism, water quality).
- **Disbenefits -** Restoring hydrological regimes may require removal of shoreline hardening and enforcing setbacks which could affect coastal property and may have social costs.
- **Caveats and limits -** Changes to hydrological and sedimentary regimes may promote the expansion of one blue carbon habitat at the expense of another (Macreadie *et al*., 2017a). Implementation of such measures should therefore be based on their potential net sequestration outcome, and should be preceded by a careful consideration of costs and benefits on a case-by-case basis (Verified Carbon Standard, 2015).

4.3.3.12. Eliminating overexploitation

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Reduced exploitation of mangroves will support their carbon sequestration benefits. Controlling the overexploitation of mangroves/salt marshes helps to both increase carbon uptake and reduce emissions released when they are degraded and destroyed. When healthy, blue carbon systems can sequester significant amounts of CO_2. Researchers estimate carbon storage in the top meter of soil to be approximately 280 Mg C ha^{-1} for mangroves, 250 Mg C ha^{-1} for tidal marshes, and 140 Mg C ha^{-1} for seagrass meadows, equivalent to 1,030 Mg CO_2eq ha^{-1} for estuarine mangroves, 920 Mg CO_2 eq ha^{-1} for tidal marshes, and 520 Mg CO_2 eq ha–1 for seagrass meadows. Adding the carbon in the plants, the mean carbon storage is 1,494, 951 and 607 Mg CO_2 eq ha^{-1} for mangroves, tidal marshes and seagrass meadows, respectively (Pendleton *et al*., 2012). A more recent global review found that estimates of carbon stocks in these systems range from 10.4–25.1 billion Mg C and wetland loss is estimated to be between 0.7–3% per year (depending on vegetation type and location), resulting in 0.23–2.25 billion Mg of CO_2 released (Howard *et al*., 2017). When degraded, these systems become significant sources of CO_2 emissions. For example, their annual loss accounts for up to 19% of carbon emissions from tropical deforestation globally resulting in economic costs of USD$6–42 billion annually (Pendleton *et al*., 2012).
- **Co-benefits -** Reducing overexploitation of mangroves and marshes helps to maintain the important ecosystem services they provide (Barbier *et al*., 2011).
- **Disbenefits -** Reducing overharvest may affect communities who depend on resource (e.g., mangrove timber) for fuel and/or firewood. Engagement with local stakeholders at the outset including all stages of planning and implementation, helps to ensure that their needs are incorporated into the project design and reduces the chance for leakage (e.g., protecting one mangrove forest which leads to deforestation of another) to occur (Wylie *et al*., 2016). Such efforts are critical as controlling overexploitation may involve reductions in valuable natural resources for local communities.
- **Caveats and limits -** Need to consider local human use needs and ensure community engagement in management efforts.

4.3.3.13. Protection

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Protection of mangroves and salt marshes maintains their carbon sequestration potential and reduces the risk of emissions from their destruction (see stats above in overexploitation). A recent analysis of MPAs in Columbia and benefits to carbon storage in mangroves found that the contribution of the new network of MPAs to the annual capture rates is between 49 -94% additional to the contribution under the current protection scheme, which is equivalent to an approximate increase of the annual capture rates of between 6.00 thousand and 2.70 million $MgCO_2e$ (Zarate-Barrera and Maldonado, 2015).

- **Co-benefits -** Ecological benefits of ecosystem protection (e.g., from MPAs) are well established. For example, increases in size, density, biomass, species richness within reserve boundaries (Lester and Halpern, 2008)and benefits from carbon sequestration, tourism, and coastal protection. Protected areas may also reduce user conflicts, enhance environmental awareness, and build social capital (Fox *et al*., 2012).
- **Disbenefits -** Groups may be either empowered or disempowered when decision making authority and resource use rights are granted or denied, sometimes privileging one group over another (Mascia *et al*., 2010). Loss of access to natural resources may result in burdens on communities and livelihood shifts, and may result in inequitable distribution of benefits (Fox *et al*., 2012).
- **Caveats and limits -** Requires long term investment in MPA monitoring and management. MPAs with adequate staff capacity have ecological effects (increase in fish populations) 2.9 times greater than MPAs with inadequate capacity but many MPAs fail to meet thresholds for effective and equitable management processes, with widespread shortfalls in staff and financial resources (Gill *et al*., 2017).

4.3.3.14. Assisted evolution

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** New experiments are testing the impacts of genetic modification of corals (van Oppen *et al*., 2015). More data to assess the potential of assisted evolution for mangroves and salt marshes are needed.
- **Co-benefits -** Has potential to maintain valuable ecosystem services provided by mangroves and marshes (coastal protection, tourism, food security, water quality, etc.).
- **Disbenefits -** Artificially enhanced organisms might possess novel traits that give them a competitive advantage over the native population (e.g., invasives); translocated plants and animals may carry pathogens or parasites affecting the health of native populations, or may cause a change in genetic composition or population structure of native organisms, a loss of genetic diversity, or a breakdown of coadapted gene complexes (Laikre *et al*., 2010; van Oppen *et al*., 2015).
- **Caveats and limits -** More data are needed to demonstrate feasibility of assisted evolution - only relevant at local scales.

4.3.3.15. Relocation and reef restoration

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Relocation: Assisted migration is an emerging concept with potential benefits as a climate change adaptation strategy; existing data are limited regarding the Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers of assisted migration in mangroves and salt marshes. Examples are available from forestry (Williams and Dumroese, 2013) and coral reefs (Rau *et al*., 2012), but these studies have only recently been implemented so it is not yet possible to determine Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers. Restoration: Recent evidence suggests that restoration can be successful in increasing both biodiversity and ecosystem services (Bullock *et al*., 2011; Bayraktarov *et al*., 2016) for mangroves/marshes. Best practices for restoration success include: ensuring original source of degradation is addressed before restoration is implemented; restoring hydrological regimes/sediment flows; adequate site selection and techniques, etc.; (Bayraktarov *et al*., 2016; Narayan *et al*., 2016). A recent review (Bayraktarov *et al*., 2016) showed median survival was 51.3% for mangroves and 64.3.8% for salt marshes. Ecosystem services were reestablished following restoration including carbon sequestration, fisheries, tourism, water quality, coastal protection, etc.).
- **Co-benefits -** Relocation: Preventing local extinctions of mangroves/salt marshes will maintain the suite of services that they provide (food, climate regulation, coastal protection, water quality, etc). Restoration: Significant co-benefits achieved when coastal habitats are effectively restored (Barbier *et al*., 2011)
- **Disbenefits**
  - Relocation: While assisted migration has the potential to alleviate some of the risks posed by climate change to biodiversity and mangroves/salt marsh health and productivity, such as species extinction. However, there are possible risks in implementing assisted migration: invasive species, mortality and investment loss if the species or population is not well adapted to the local conditions, etc.
  - Restoration: Restoration activities may be ineffective or may lead to undesirable social impacts: endangered species establishment or resumption of natural flow regimes that involves flooding, loss of agricultural land, trespassing associated with increased recreational use of restored habitat (Buckley and Crone, 2008). Biodiversity and different ecosystem services might display contrasting trajectories during restoration, leading to conflicts and trade-offs - restoration actions focusing on a particular ecosystem service could lead to negative impacts on biodiversity or provision of other services, which needs to be considered during the planning process (Bullock *et al*., 2011).

- **Caveats and limits**
  - Relocation: More studies are needed to assess the potential of assisted migration for mangroves and salt marshes.
  - Restoration: Many examples of unsuccessful restoration efforts (Bayraktarov *et al.*, 2016).

4.3.4. Arctic biota

4.3.4.1. Renewable energy

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** All renewable energies could be deployed in Arctic locations (tidal energy, wave energy, wind energy). Space needed for wind farms or wave energy systems is available as habitat is largely undisturbed by fishing. Arctic biota are then possibly exposed to noise. Settlement potential is provided for seaweed, cold-water coral, molluscs on structures. Fish Aggregating Devices; Ocean Thermal Energy Conversion are not evaluated here. Measures effectively reducing the degree of warming would have the benefit of reducing the exposure of Arctic biota to meltwater.
- **Co-benefits -** Reduced climate change implies benefits for the maintenance of some, albeit reduced summer sea ice and associated habitat structure. Sufficient capacity would be needed to keep warming to below the threshold temperature eliciting the virtually complete disappearance of sea ice during summers. With diminishing ice, more open areas would become available for deployment of renewable energy infrastructure.
- **Disbenefits -** If infrastructure is deployed Arctic biota are then possibly exposed to noise; settlement potential is provided for seaweed, cold-water coral, molluscs on structures.

4.3.4.2. Vegetation (global and local)

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Historically, high polar areas are virtually void of marine vegetation, however, the Northern (in case of northern hemisphere) and Southern (in case of southern hemisphere) distribution limits of macroalgae and seagrasses are shifting poleward, at the same time when the equatorward distribution limits retreat to higher latitudes (e.g. Jueterbock *et al.*, 2013). The scope for increase in kelp and seagrass meadows is large in the Arctic, where extensive coastline (35% of the world's coastline) and more suitable conditions with climate change is expected to lead to increased macrophyte cover and production (Krause-Jensen and Duarte, 2014). A clear picture on the expansion of macrophytes as well as the space available for colonization in polar areas needs to be developed, depending on the degree of warming, and constrained by low light conditions during winter. Also it needs to be investigated how the area gained for colonization relates to the space lost at lower latitudes. At the same time, growth of non-calcifying macroalgae and seagrasses will be stimulated by elevated CO_2 levels; locally and in coastal areas some stimulation of CO_2 uptake by eutrophication may occur (Olischläger *et al.*, 2017). The mass balance of these effects needs to be evaluated.
- **Co-benefits -** Expansion of macroalgal canopy and kelp at high latitudes may enhance diversity and provide specific habitat. Enhanced CO_2 removal during warming (polar amplification) during the 24 h daylight periods in polar summer (Krause-Jensen *et al.*, 2016), thereby providing local protection from ocean acidification.
- **Disbenefits -** Drastic changes in the structure and functioning of the respective ecosystems are to be expected, including the displacement of endemic organisms and loss of polar characteristics.
- **Caveats and limits -** Changes in polar ecosystems and habitat due to shifting species composition and productivities. The area gained for seaweed colonization relates to the habitat lost at lower latitudes.

4.3.4.3. Fertilization

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** It needs to be investigated how the Fertilization gained in polar areas relates to the productivity lost due to enhanced stratification at lower latitudes. An overall small decline in global ocean productivity is expected (Pörtner *et al.*, 2014).
- **Co-benefits -** Expansion of vegetation (seaweed) area and enhanced CO_2 dependent growth and carbon storage at higher latitude is currently occurring, as well as an increase in primary productivity at high Arctic latitudes (Yool *et al.*, 2015). Further stimulation of ocean productivity by further nutrient addition would build on the climate induced trend, with unclear benefits, also due to the highly seasonal light availability.
- **Disbenefits -** Exacerbation of polar transformation, changing species distribution and ecosystem composition, loss of habitat to polar species. Nutrient addition may cause eutrophication of an already nutrient enriched system.
- **Caveats and limits -** The area gained for colonization relates to the space lost at lower latitudes.

4.4.3.4. Alkalinization

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Large scale Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers requires continuous effort which can only be secured by huge mining efforts on land, at the expense of losing terrestrial ecosystems or at least their integrity for both carbonates (e.g. Harvey, 2008) or olivine (silicate) (Hauck *et al.*, 2016).

- **Co-benefits -** Local to regional protection from negative impacts of ocean acidification. During olivine dissolution marine primary and export production benefit from fertilisation by silicic acid and iron (Hauck *et al.*, 2016), especially in sub-polar gyres.
- **Disbenefits -** Impacts of potentially excessive alkalinization on ecosystems remain largely unexplored (Cripps *et al.*, 2013; González and Ilyina, 2016).
- **Caveats and limits -** Success and dimension depends on willingness to sacrifice terrestrial ecosystems during mining activities.

4.3.4.5. Hybrid methods

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** in those cases where hybrid methods generate ocean alkalinity, see “Alkalinity” effectiveness, above.
- **Co-benefits -** In cases where hybrid methods produce ocean alkalinity see “Alkalinity” co-benefits, above.
- **Disbenefits -** Potential disbenefits include acidification if molecular CO_2 is the storage medium, trace metal and contaminant effects if these constituents are present with the carbonaceous material stored in the ocean. Potential for O2 reduction and acidification if organic matter is the storage medium of hybrid methods.
- **Caveats and limits** - The benefits, co-benefits, and disbenefits of many of the hybrid methods will remain hypothetical until further R&D and testing has been done.

4.3.4.6. Cloud brightening

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers at global scales is low at high latitudes and constrained to highly seasonal sun exposure (24 h daylight in summer). Specific regional benefits may still occur, e.g. reduction of polar amplification.
- **Co-benefits -** Increasing cloud albedo through cloud brightening (Latham *et al.*, 2012; Connolly *et al.*, 2014) may protect polar areas from excessive warming and thereby protect residual sea ice during polar, esp. Arctic summers. This would increase overall albedo and protect the large contribution of polar ice to global albedo (Pistone *et al.*, 2014).
- **Disbenefits -** Expanding cloud areas would reduce irradiation and, thereby, primary productivity during critical times of the year, in turn reducing overall, including fisheries productivity.
- **Caveats and limits -** Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers constrained to polar summers.

4.3.4.7. Albedo enhancement

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** As for cloud brightening Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers at global scales is low at high latitudes due to highly seasonal sun exposure. Regional benefits may be felt, e.g. reduced polar amplification. Protecting sea ice from melting or enhanced snow cover would largely benefit the albedo effects.
- **Co-benefits -** Increasing albedo may compensate for polar albedo losses, e.g. caused by expanding forestation or loss of sea ice (Pistone *et al.*, 2014). Increasing regional albedo may thereby contribute to protecting polar areas from excessive warming and thereby protect residual sea ice and associated albedo during polar summers.
- **Disbenefits -** Land surface area used for enhanced albedo may trigger land-use conflicts.
- **Caveats and limits -** Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers constrained to polar summers.

4.3.4.8. Pollution reduction

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Risk of oil and gas exploration and associated pollution is especially high due to strong seasonality and slow recovery of ecosystems. Accordingly, reducing pollution will be highly effective for conservation. Similarly, ocean acidification trends are especially strong at high latitudes. Accordingly, with ambitious global mitigation efforts the reduction of ocean acidification trends will be highly efficient at high latitudes. Reducing black carbon will benefit maintenance of albedo and thereby protect sea ice unless snowfall masks the effect of blackcarbon (Quinn *et al.*, 2011; Marks and King, 2013; Pedersen *et al.*, 2015).
- **Co-benefits -** Reducing pollution will be highly effective for marine conservation.
- **Disbenefits -** No adverse effect reported in the literature.

4.3.4.9. Restoring hydrology

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** .With increased precipitation, river flow and ice melt, delivery of water and sediment from watersheds may be improved. This may in turn improve oxygenation and nutrient supply to previously constrained systems. The net effect is considered small, due to previously low water temperatures...

- **Co-benefits -** With increased precipitation, river flow and ice melt, improved delivery of oxygen to Arctic ecosystems does not appear necessary and would have limited beneficial impact....
- **Disbenefits -** Nutrient supply to previously constrained systems may be enhanced reflecting eutrophication....
- **Caveats and limits -** Enhanced inflow of freshened sea water may support eutrophication of an already nutrient enriched system....

4.3.4.10. Eliminating overexploitation

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Some high latitude fish stocks are projected to become more resilient regionally, due to enhanced ocean productivity, but fish productivity may only be enhanced within a limited temperature range. Highly stenothermal polar species such as polar cod are projected to be marginalized (Kunz *et al*., 2016; Dahlke *et al*., 2017).
- **Co-benefits -** At high productivity it is easier to establish sustainable fisheries.
- **Disbenefits -** No adverse effect reported in the literature.
- **Caveats and limits -** With continued and unabated warming and acidification this is not a sustainable solution.

4.3.4.11. Protection

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Marine protected areas can enhance resilience to climate change and are especially useful at high polar latitudes (Wenzel *et al*., 2016) where climate changes more strongly (polar amplification), the vulnerability of aquatic animals (ectotherms) is high, resilience low and the velocity of recovery from disturbances equally low. This said, the impacts of climate change will develop nonetheless and establishing marine protected areas will buy time that may allow implementing effective mitigation measures.
- **Co-benefits -** Development of (new) ecosystem characteristics undisturbed by human interventions.
- **Disbenefits -**Protected areas often exclude human uses within their boundaries and may lead to forced migration or loss of assets and food security when communities are not engaged in planning and management (Bennett and Dearden, 2014).
- **Caveats and limits -** MPAs supported by appropriate staff capacity have positive ecological effects (such as increased fish populations) about 3 times greater than MPAs supported by inadequate staff capacity. Many MPAs do not meet requirements for effective management, due to insufficient staffing and financial resources (Gill *et al*., 2017).

4.3.4.12. Assisted evolution

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Not applied yet in Arctic areas, neither to wild species nor to aquaculture species as there are few aquaculture activities. The fact that evolutionary velocity is slow at cold temperatures may limit applicability of this approach in polar areas. If successful assisted evolution and biotechnology may be effective in aided development of resilience.
- **Co-benefits -** Efforts would need to focus on endemic Arctic species in how they can improve tolerance to especially elevated temperatures or ocean acidification. Such evidence is lacking....
- **Disbenefits -** If successful assisted evolution and biotechnology may support unwanted changes in ecosystem functions, considering that invasive species will also become increasingly involved in species interactions in the Arctic.
- **Caveats and limits -** If successful assisted evolution and biotechnology may reduce marginalization of stenothermal Arctic species, but also change ecosystem characteristics.

4.3.4.13. Relocation and reef restoration

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Not widely applicable to polar areas as this would mean assisted invasion of non-endemic species from lower latitudes to polar areas. Relocating species into polar areas represents invasion and may bring about impacts on endemic polar organisms as well as their marginalization or loss. Polar organisms have nowhere to retreat or migrate to as polar ecosystems represent the end of a cul-de-sac.
- **Co-benefits -** Might work for the expansion of seaweed biogeography into the Arctic with the benefit of enhanced removal and storage of CO_2.
- **Disbenefits -** Assisted migration may lead to the potential marginalization and loss of endemic species and habitat characteristics. These have nowhere to go as polar ecosystems represent the end of a cul-de-sac.
- **Caveats and limits -** Icebound habitat cannot be restored without ambitious mitigation and negative emissions. Potential marginalization and loss of endemic species and habitat characteristics due to assisted invasions.

4.3.5. Finfish fisheries

4.5.1. Renewable energy

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Renewable energy options in marine and coastal environment mainly involve harnessing wind, wave and tidal energy. Installations of these renewable energy facilities may provide artificial habitats (e.g., as artificial reefs) for fish stocks, potentially enhancing fish production (Inger *et al*., 2009) which may offset the negative effects of climate change on fish productivity. However, there is no evidence supporting the enhancement of fish stock production from renewable energy facilitates while the effectiveness of artificial reefs in enhancing net fish stock production may be limited or uncertain (e.g. Smith *et al*., 2016a), particularly under climate change. Therefore, a very low effectiveness rating score (1) with very low confidence (1) were assigned for both local and global scales.
- **Co-benefits -** Artificial habitats produced from structure supporting renewable energy facilities may enhance fish stock production, enhancing biodiversity and fisheries (Inger *et al*., 2009). Also, these facilities may become *de facto* structure that prevent trawling and other fishing activities in nearby area (Langhamer *et al*., 2010; Hammar *et al*., 2016). This may reduce impacts from trawling on marine species, and potentially improve the status of already depleted fish stocks or ecosystems. Concrete evidence supporting these co-benefits of marine renewable energy facilities is lacking. Moreover, the degree of these benefits may depend on the level of improved fishing restriction and the location of the facilities (Bergström *et al*., 2014; Hammar *et al*., 2016). Therefore, a low score (2) with low confidence (2) is given.
- **Disbenefits -** Marine organisms and ecosystems may be impacted during the construction and operation phase of marine renewable energy facilitates. These disturbance may include acoustic disturbance, dispersal of sediment, generation of electromagnetic fields, and direct habitat loss and mortality of organisms (Bergström *et al*., 2014; Hammar *et al*., 2016; Willsteed *et al*., 2017). These may affect fisheries productivity. Given the broad range of potential impacts, a moderate score (3) is given, although concrete evidence of impacts on fisheries production is limited. Thus, a low confidence score (2) is given.
- **Caveats and limits -** We assumed that renewable energy options in marine and coastal environment mainly involve harnessing wind, wave and tidal energy.

4.3.5.2. Vegetation (global and local)

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Coastal vegetations help facilitate nutrient cycling, providing energy to support upper trophic level in marine ecosystems for fisheries production. It also provides habitat that enhance biodiversity (Duarte *et al*., 2013b). Moreover, coastal vegetations are important habitats for critical life stages of exploited fish stocks e.g., feeding and spawning. Therefore, it is postulated that restoration and conservation of marine vegetation would enhance the growth and reproductive success of fish stocks under climate change. Abundance evidence is available for the ecological importance of coastal vegetation to exploited fish stocks (e.g., Seitz *et al*., 2013). However, direct evidence on the effects of coastal vegetation in moderating climate change impacts is limited. Also, with expected climate impacts under RCP8.5, fisheries species composition and potential catches would be substantially altered, particularly in tropical areas. It is not likely that restoration and conservation of vegetation alone would reduce climate risks to level expected under RCP2.6. Therefore, a moderate effectiveness and confidence scores (3) are given.
- **Co-benefits -** Restoration and conservation marine vegetation will contribute to the protection and enhancement of spawning, nursery and foraging habitats, thus providing benefits in enhancing fisheries production irrespective of climate change (e.g., Seitz *et al*., 2013). In fact, these vegetation are important to sustain fisheries production. Thus, the importance of co-benefits is very high (5) with very high confidence (5).
- **Disbenefits -** No adverse effect reported in the literature.
- **Caveats and limits -** Benefits to low latitude fisheries in minimizing climate impacts may be limited relative to mid to high latitude fisheries because of the large projected local extinction and decrease in fisheries catch potential in low latitude ecosystems (Pörtner *et al*., 2014; Cheung *et al*., 2016).

4.5.3. Fertilization

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Global modelling of the effects of ocean fertilization suggests that net primary production pattern (NPP) would be affected, with potential increases and decreases in different parts of the oceans (Russell *et al*., 2012). If net primary production increases, overall fish stock production may also increase, other things being equal (Cheung *et al*., 2008; Stock *et al*., 2017). Correlation that has been debated scientifically was drawn between the natural fertilization from volcanic eruption (Mt. Kasatoshi in 2008) and increase in Fraser River sockeye salmon (*Oncorhynchus nerka*) in 2010 (Parsons and Whitney, 2012). The increase productivity of some fish stocks may offset the impacts of climate change on fisheries production. However, the open oceans, where ocean fertilization will likely to operate, only contribute a smaller proportion of global fisheries production relative to the continental shelf. Also, because of the potential spatial variations in changes in NPP, the potential benefits of ocean fertilization on global fisheries production may also be limited. There has been no modelling or empirical studies that directly demonstrate the effects of artificial enhancement of ocean productivity on fisheries production, particularly under climate change. Therefore, a very low effectiveness rating (1) with very low confidence are given.

- **Co-benefits -** The potential increases in net primary production, and consequently, fisheries production may benefit fish stocks and fisheries (see the effectiveness section). However, because of the spatial differences in changes in productivity and the extent to which any increase in primary productivity would benefit upper trophic level production remains uncertain. Therefore, a co-benefiting rating of low (2) is given with low level of confidence.
- **Disbenefits -** Ocean fertilization may alter patterns of net primary production (see the effectiveness section). However, the depletion of other non-limiting nutrients may reduce the productivity of remote regions outside of the fertilization area, potentially reducing the productivity of the latter (Aumont and Bopp, 2006). This may result in re-distribution or overall decrease in fish production (Williamson *et al*., 2012). Increased export production may also increase the risk of ocean acidification and deoxygenation in deeper waters, adding uncertainty to the potential impacts on fisheries resources (Russell *et al*., 2012). As such, a moderate level of unintended consequences (3) is given with low level of confidence (2), as direct evidence of negative impacts of artificial enhancement of ocean productivity on fish stocks or fisheries is not available.
- **Caveats and limits -** Direct evidence linking artificial enhancement of ocean productivity and fisheries is rare.

4.3.5.4. Alkalinization

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Increased in alkalinity can reduce the rate of ocean acidification and the rate at which the saturation states of aragonite and calcite decrease locally (Keller *et al*., 2014). As this does not mitigate regional warming - the main drivers of climate impacts of finfish fisheries or increase the adaptive capacity of fish stocks and have little effect on mitigating other non-CO_2 drivers, therefore the effectiveness score is very low (1). Also, as literature on the effects of adding alkalinity on fish stocks and fisheries is limited, confidence level is considered to be low (2).
- **Co-benefits -** The use of olivine as chemical to increase ocean alkalinity would favour marine diatoms as a result of the increased silica content, but a decrease in dinoflagellates production. This may increase primary production available for fish production (Williamson *et al*., 2012). Therefore, we ranked very low co-benefits with low level of confidence.
- **Disbenefits -** Increases in export production from increased diatom production may lead to deoxygenation and ocean acidification in mid/deep waters. Also, if olivine is applied directly to seafloor, it may smother benthic organisms, reducing food supply to upper trophic level organisms in benthic habitats, including fish stocks. This may affect fisheries production. However, the extent to which these processes would affect fisheries production is uncertain. Because of the multiple pathways of potential unintended consequences, we assigned a moderate rating to unintended consequences with low level of confidence.
- **Caveats and limits -** Direct evidence assessing the effects of increasing alkalinity on fish stocks and fisheries is lacking.

4.3.5.5. Hybrid methods

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** To the extent that hybrid methods generate ocean alkalinity, see “alkalinity” effectiveness, above. No known direct or indirect benefits to fish stock or fisheries through moderating their sensitivity or adaptive capacity. Therefore, we have ranked very low for their effectiveness and low for confidence.
- **Co-benefits -** No evidence of direct or indirect co-benefit identified. Therefore, we have ranked a very low potential co-benefits with low level of confidence.
- **Disbenefits -** Potential leakage of CO_2, for example, in direct injection of CO_2 into the deep ocean, may impact deep-sea ecosystem and biogeochemical cycles (Seibel and Walsh, 2001; Seibel and Walsh, 2003), potentially altering deep-sea fisheries production. Hybrid methods producing organic matter as the C storage medium could, via diagenesis, locally generate seawater CO_2 and consume O_2, impacting potential fisheries production. Given the potential benefits appear to be very low, the potential impacts relative to these benefits thus are considered high although the confidence is low.
- **Caveats and limits -** Direct evidence assessing the effects of these hybrid methods on fish stocks and fisheries is lacking.

4.5.6. Cloud brightening

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** No evidence of effect in reducing the sensitivity or increasing the adaptive capacity of fish stocks or fisheries (Williamson *et al*., 2012).

- **Co-benefits -** No co-benefits identified.
- **Disbenefits -** Reduction in amount of light reaching the ocean may affect patterns of net primary production. Also, the extraction of surface ocean water for spraying may impact marine organisms, including fish eggs, larvae and other plankton (Williamson *et al*., 2012). Therefore, we ranked a high unintended consequences with low level of confidence.
- **Caveats and limits -** We could not find any study that investigate the effect of cloud brightening on marine ecosystem.

4.3.5.7. Albedo enhancement

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** No evidence of effect in reducing the sensitivity or increasing the adaptive capacity of fish stocks or fisheries (Williamson *et al*., 2012).
- **Co-benefits -** No co-benefits identified.
- **Disbenefits -** Possibly lead to shifts in pattern of temperature and net primary production (Williamson *et al*., 2012), impacting fisheries production. Therefore, we ranked a high unintended consequences with low level of confidence.
- **Caveats and limits -** We could not find any study that investigate the effect of cloud brightening on marine ecosystem.

4.3.5.8. Pollution reduction

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Pollutants e.g., PCBs, methyl-mercury can increase sensitivity of marine organisms to climate change (warming and deoxygenation) and ocean acidification (Alava *et al*., 2017). Also, eutrophication and the consequential hypoxic zones exacerbate ocean deoxygenation and acidification locally. The release of nitrous oxide and sulfur oxide from agriculture and fossil-fuel burning would also exacerbate local scale ocean acidification. It may also increase the chance of harmful algal bloom. Mitigating pollution can substantially help reduce sensitivity of fish stocks to climate change and ocean acidification. Therefore, a high effectiveness rating is given with high level of confidence.
- **Co-benefits -**This will also reduce all other direct/indirect non-climate related impacts of pollution on fish stocks and fisheries. Thus, it has a very high level of co-benefits with very high level of confidence.
- **Disbenefits -** No adverse effect reported in the literature.
- **Caveats and limits -** The effectiveness and co-benefits would be largest in area where pollution level is high.

4.3.5.9. Restoring hydrology

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Fish recruitment is often related to local current pattern (Boehlert and Mundy, 1988). Therefore, maintaining hydrological regime may safeguard the conditions for fish recruitment and thus increase the adaptive capacity of fish stocks to climate change. Since the effects will be dependent on the hydrological regime and specific engineering method used, we rank a low effectiveness with very high uncertainty.
- **Co-benefits -** Maintaining local current pattern may safeguard the conditions for fish recruitment. This would have benefit to fish stocks by protecting it from modification of water regime as a result of other human or natural processes. Therefore, there is a low level of co-benefits, although the level of confidence is low.
- **Disbenefits -** We do not find any direct evidence of unintended consequence. However, given the very low level of confidence, and that engineering of natural environment always poise risk to ecosystems, therefore, we assign a low level scoring of unintended consequence.
- **Caveats and limits -** Assuming that the solution mainly focuses on maintaining current water regime.

4.3.5.10. Eliminating overexploitation

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Eliminating overexploitation Increases capacity (genetic, population and community levels) of fish stocks and ecosystems to respond to climate change and ocean acidification (Perry *et al*., 2010; Planque *et al*., 2010). Increase abundance in protected area may increase spill over to compensate for loss in fisheries productivity from climate change and ocean acidification (Cheung *et al*., 2016). However, because of the high risk of impacts on low latitude fisheries, reducing overexploitation is not projected to fully compensate for the decrease in fisheries catch potential in these regions under high emission scenario (RCP8.5). Particularly, critical habitats for fish stocks that are sensitivity to climate change would still be impacted, affecting fisheries. Therefore, we assigned an overall high effectiveness rating, with high level of confidence.
- **Co-benefits -** Globally, 30-60% of fish stocks are overexploited (Pitcher and Cheung, 2013). Therefore, reducing over-exploitation will have direct co-benefit to restoring fish stock abundance, fisheries productivity, and ensuring long-term fisheries sustainability. Globally, such co-benefits would be as much as the effectiveness of this solu-

tion in addressing climate impacts. Therefore, we assigned a co-benefit score of very high with very high level of confidence.

- **Disbenefits -** No unintended biological consequences is expected from reducing over-exploitation on fisheries.
- **Caveats and limits -** The effectiveness in reducing risk of impacts from reducing over-fishing may vary between different regions and fisheries.

4.3.5.11. Protection

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Protective measures of ecosystems and habitats potentially increase biodiversity and abundance of fish stocks, as well as ensuring the functioning of their critical habitats. Thus this increases the capacity (genetic, population and community levels) of fish stocks and ecosystems to respond to climate change and ocean acidification. Increase abundance in protected area may increase spill over to compensate for loss in fisheries productivity from climate change and ocean acidification (Cheung *et al*., 2016). However, because of the high sensitivity of low latitude fisheries to climate change, the effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers of intervention may be lower in low latitude than in mid to high latitude. Therefore, we assign a high effectiveness rating to this solution with high level of confidence.
- **Co-benefits -** Protection contributes to enhancing productivity, biodiversity and sustainability of fisheries, if properly designed and implemented. Therefore, there is a very high level of co-benefits with high level of confidence.
- **Disbenefits –** Protected areas often exclude human uses within their boundaries and may lead to forced migration or loss of assets and food security when communities are not engaged in planning and management (Bennett and Dearden, 2014).
- **Caveats and limits -** The effectiveness of this measures are dependent the design and implementation of the MPAs. MPAs with adequate staff capacity have ecological effects (increase in fish populations) 2.9 times greater than MPAs with inadequate capacity but many MPAs fail to meet thresholds for effective and equitable management processes, with widespread shortfalls in staff and financial resources (Gill *et al*., 2017).

4.3.5.12. Assisted evolution

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** May help maintain critical habitats in low latitude (e.g., coral reefs) and their fisheries productivity. It may also help increase the tolerance to temperature and low oxygen for some fish stocks. However, there is no evidence for demonstrating the effective of this solution on wild fish stocks at a large scale currently. Thus, we considered a low effectiveness with very low level of confidence.
- **Co-benefits -** There is no identified co-benefit of this solution. Since information on this for fisheries is lacking, therefore, it has a low level of confidence.
- **Disbenefits -** Genetic modification of marine species may carry substantial known/unknown risk on the viability of the species and the impacts on other species and the environment (Knibb, 1997; Maclean and Laight, 2000; Devlin *et al*., 2006). For example, genetically modified species may outcompete conspecific that carries beneficial traits. It may also affect trophic interactions or biogenically modify habitats and the environment. Therefore, given the wide range of potential risk, and the low level of its effectiveness, the importance of unintended consequences is considered to be high, with moderate level of confidence.
- **Caveats and limits -** The practicality of this solution at the large scale has not been established yet.

4.3.5.13. Relocation and reef restoration

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Sensitivity of fish stocks to warming and ocean acidification may be lowered in higher quality and larger habitats (Bates *et al*., 2017). These habitats may be critical for life stages of fish stocks, or can increase ecosystem productivity, and thus fisheries production. However, because species are projected to shift away from low latitude regions, this intervention would have low effectiveness in maintaining fisheries production in tropical area. Also, there is limited evidence (observation or model projection) demonstrating the effectiveness on fisheries. Therefore, we consider this solution to have moderate effectiveness with low level of confidence.
- **Co-benefits -** Restoration can contribute to improving fish stock productivity and sustainability regardless of climate change and ocean acidification. Therefore, we consider a high level of co-benefits with high confidence.
- **Disbenefits -** Restoration may lead to large shift in ecosystem structure, which may have negative impacts on productivity of some existing fish stocks. Therefore, a low level of unintended conference with high level of confidence is considered.
- **Caveats and limits -** The effectiveness would depend on time-frame, as some restoration may take long-term which may reduce its effectiveness in addressing rapid climate change.

4.3.6. Fish aquaculture

4.3.6.1. Renewable energy

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** No known effect of reducing sensitivity or enhancing adaptive capacity of farmed fishes.
- **Co-benefits -** Structure supporting renewable energy may provide physical structure for offshore mariculture (Christie *et al*., 2014; Wever *et al*., 2015). Concrete evidence supporting such co-benefit of marine renewable energy facilities is lacking. Therefore, a low rating score (2) with low confidence (2) is given.
- **Disbenefits -** Cultured marine fishes in farms that are closed to the marine renewable site may be impacted during the construction and operation phase of marine renewable energy facilitates. These disturbance may include acoustic disturbance, dispersal of sediment and generation of electromagnetic fields (Bergström *et al*., 2014; Willsteed *et al*., 2017). Also, marine renewable facilities may compete for suitable sites for mariculture. Therefore, a moderate rating score (3) is given, although concrete evidence of impacts on fish mariculture production is limited. Thus, a low confidence score (2) is given.
- **Caveats and limits -** We assumed that renewable energy options in marine and coastal environment mainly involve harnessing wind, wave and tidal energy.

4.3.6.2. Vegetation (global and local)

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Coastal vegetation such as seagrass and kelp can reduce ocean acidification from absorption of CO_2 locally. It can also improve water quality from reducing exposure to bacteria pathogens (Lamb *et al*., 2017) and nutrients that contributes to hypoxic zones (Klinger *et al*., 2017). This can reduce the sensitivity of cultured fish in semi-open and open mariculture facilities to impacts from climate change and ocean acidification. However, this may not compensate fully the expected impacts of climate change on mariculture. Also, evidence that demonstrates the linkages between conservation of coastal vegetation and reduction in sensitivity of mariculture to climate change is limited. Therefore, we consider that this solution has a moderate effectiveness with moderate level of confidence.
- **Co-benefits -** Restoration and conservation of coastal vegetation will improves water quality for mariculture and thus can increase their productivity. Therefore, it has moderate level of co-benefits for aquaculture, with moderate level of confidence.
- **Disbenefits -** Restoration and conservation of coastal vegetation may not be compatible with certain types of aquaculture e.g., coastal shrimp farming. Therefore, we consider that it may have low unintended consequence relative to its benefits, with high level of confidence.
- **Caveats and limits -** Effectiveness, co-benefits and unintended consequences vary between different types of finfish aquaculture.

4.3.6.3. Fertilization

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Enhancement of productivity, especially through seaweed cultivation, may improve water quality for nearby aquaculture farm and reduce the sensitivity of farmed fishes to climate change and ocean acidification. Since this potential benefit is only limited to a certain type of productivity enhancement, and that it will only slightly reduce the sensitivity of farmed fishes to expected climate change and ocean acidification, therefore an effectiveness of very low is given, with low confidence.
- **Co-benefits -** Improvement of water quality would benefit aquaculture irrespective of climate change and ocean acidification. However, such co-benefit is limited to a certain kind of Fertilization, and should be in area close by the farm. Therefore, we assign a very low co-benefit with low level of confidence.
- **Disbenefits -** Adding nutrient to increase productivity in coastal waters may result in eutrophication and hypoxia, which would have large impacts on farmed fishes through reduced growth or increased mortality. Therefore, the Lack of unintended consequences is high, with moderate level of confidence.
- **Caveats and limits -** Aquaculture facility is open/semi-open and is located close to places where artificial Fertilization is conducted.

4.3.6.4. Alkalinization

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Increased in alkalinity can reduce the rate of ocean acidification and the rate at which the saturation states of aragonite and calcite decrease locally (Keller *et al*., 2014) . If applied around the farm, this may help reduce the impacts of ocean acidification of the cultured fishes. However, as this does not mitigate regional warming - the main drivers of climate impacts of fishes or increase the adaptive capacity of farmed fish and have little effect on mitigating other non-CO_2 drivers, therefore the effectiveness score is very low (1). Also, as literature on the effects of adding alkalinity on fishes is limited, confidence level is considered to be low (2).

- **Co-benefits -** The use of olivine as chemical to increase ocean alkalinity would favour marine diatoms as a result of the increased silica content, but a decrease in dinoflagellates production. This may increase primary production available for fish production (Williamson *et al*., 2012). As current finfish mariculture still depends on wild stock for fish feed, therefore, the potential increase in fish production may indirectly help increase and ensure supply of fish feed (Troell *et al*., 2014). Therefore, we ranked very low co-benefits with low level of confidence.
- **Disbenefits -** Increases in export production from increased diatom production may lead to deoxygenation and ocean acidification in mid/deep waters. This may affect farmed fishes if the solution intervention is done close to the fish farm and the lack of information about the effects of artificially increasing alkalinity on fish farms, we therefore assigned a low rating to unintended consequences with very low level of confidence.
- **Caveats and limits -** Direct evidence assessing the effects of increasing alkalinity on fish farm is lacking. Much of the assessment assume that the intervention is done close to the farm.

4.3.6.5. Hybrid methods

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** There is little direct or indirect benefits to farmed fishes through moderating their sensitivity or adaptive capacity. Therefore, we have ranked very low for their effectiveness and low for confidence.
- **Co-benefits -** No evidence of direct or indirect co-benefit identified. Therefore, we have ranked a very low potential co-benefits with low level of confidence .
- **Disbenefits -** Modification of water chemistry from these various interventions may affect the water quality of the farm, thus affecting fish production. Given the potential benefits are very low, the potential impacts relative to these benefits thus are considered high although the confidence is very low .
- **Caveats and limits -** Direct evidence assessing the effects of these other methods on fish farming is lacking .

4.3.6.6. Cloud brightening

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** No evidence of effect in reducing the sensitivity or increasing the adaptive capacity of farmed fishes (Williamson *et al*., 2012).
- **Co-benefits -** None reported in the literature.
- **Disbenefits -** Reduction in amount of light reaching the ocean may affect patterns of net primary production. Also, the extraction of surface ocean water for spraying may impact marine organisms, including fish eggs, larvae and other plankton (Williamson *et al*., 2012). This may affect fish production that supply feed to fish farm. Given the low effectiveness of this solution, we ranked a high unintended consequences with low level of confidence.
- **Caveats and limits -** Direct evidence assessing the effects of these other methods on fish farming is lacking.

4.3.6.7. Albedo enhancement

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** No evidence of effect in reducing the sensitivity or increasing the adaptive capacity of farmed fishes (Williamson *et al*., 2012).
- **Co-benefits -** None reported in the literature.
- **Disbenefits -** Reduction in amount of light reaching the ocean may affect patterns of net primary production. Also, the extraction of surface ocean water for spraying may impact marine organisms, including fish eggs, larvae and other plankton (Williamson *et al*., 2012). This may affect fish production that supply feed to fish farm. Given the low effectiveness of this solution, we ranked a high unintended consequences with low level of confidence.
- **Caveats and limits -** No evidence of effect in reducing the sensitivity or increasing the adaptive capacity of fish stocks or fisheries (Williamson *et al*., 2012).

4.3.6.8. Pollution reduction

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Pollutants (both organic and inorganic) affects water quality such as reduction in oxygen availability, increased in harmful contaminants which directly affects farmed fishes (Eng *et al*., 1989). Pollutants can increase sensitivity of marine organisms to climate change (warming and deoxygenation) and ocean acidification (Alava *et al*., 2017). Also, eutrophication and the consequential hypoxic zones exacerbate ocean deoxygenation and acidification locally. The release of nitrious oxide and surplur oxide from agriculture and fossil-fuel burning would also exacerbate local scale ocean acidification. It may also increase the chance of harmful algal bloom. Mitigating pollution can substantially help reduce sensitivity of farmed fish to climate change and ocean acidification. Therefore, a high effectiveness rating is given with high level of confidence.
- **Co-benefits -** This will also reduce all other direct/indirect non-climate related impacts of pollution on farmed fishes. Thus, it has a very high level of co-benefits with very high level of confidence.
- **Disbenefits –** No adverse effect reported in the literature.
- **Caveats and limits -** The effectiveness and co-benefits would be largest in area where pollution level is high.

4.3.6.9. Restoring hydrology

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Maintaining hydrological regime can help maintain water flow and thus dispersal of nutrients and other organic materials produced from open net cage, while ensuring that the farm water is well oxygenated. Therefore, this may reduce the sensitivity of the farmed fishes to local warming and ocean acidification. A moderate level of effectiveness with moderate level of confidence is given.
- **Co-benefits -** Maintaining hydrological regime can help maintain water flow and thus dispersal of nutrients and other organic materials produced from open net cage, while ensuring that the farm water is well oxygenated. This will be beneficial to the farm irrespective of climate change and ocean acidification. A moderate level of co-benefit with moderate level of confidence is given.
- **Disbenefits -** We do not find in the literature any direct evidence of unintended consequence. However, given the very low level of confidence, and that engineering of natural environment always poise risk to ecosystems, therefore, we assign a low level scoring of unintended consequence.
- **Caveats and limits -** Assuming that the solution mainly focuses on maintaining current water regime.

4.3.6.10. Eliminating overexploitation

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** One pathway of impacts of climate change and ocean acidification on finfish aquaculture is through the effects on wild caught fishes and invertebrates as feed for the farmed fishes (De Silva and Soto, 2009; Callaway *et al*., 2012; Troell *et al*., 2014). As reducing overexploitation is highly effective in reducing the sensitivity and increasing their adaptive capacity to climate change (see finfish fisheries above), this will ensure the supply of wild caught fish for feed (assuming that the composition of farmed species and their feed requirement remain the same as now). Thus, we assign a moderate effectiveness with moderate confidence on the effectiveness of reducing over-exploitation on reducing impacts of climate change on finfish mariculture.
- **Co-benefits -** Reducing over-exploitation may also improve ecosystem structure and functioning of coastal marine ecosystems (Jackson *et al*., 2001; Scheffer *et al*., 2005; Möllmann *et al*., 2008). Some of these ecosystem functions such as nutrient cycling, reduction in harmful algal bloom etc would also benefit fish farm. Reducing over-exploitation will also ensure sustainable supply of wild caught fish and invertebrate as ingredient of feed. Therefore, we assign very high co-benefit, and high level of confidence.
- **Disbenefits -** No adverse effect reported in the literature.
- **Caveats and limits -** The effectiveness and co-benefits would vary between types of finfish mariculture and the region.

4.3.6.11. Protection

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Protective measures of ecosystems and habitats potentially increase biodiversity and abundance of fish stocks, as well as ensuring the functioning of their critical habitats. Thus this ensure genetic variability of wild fish stocks. Fish farmers may be able to select more adaptable population as broodstock to help increase the adaptive capacity of farmed fishes to climate change and ocean acidification. Also, protection of key habitats and ecosystems can ensure its key ecosystem functions, one of which is regulating water quality, which would indirectly help reduce sensitivity of farmed fishes (in open and semi-open farm) to climate change and ocean acidification. However, because the effects are indirect and direct evidence on their contribution to reducing impacts of climate change on fish farm is limited, therefore we consider a low effectiveness with low level of confidence.
- **Co-benefits -** As noted above, protection may also address other human stressors on farmed fish, therefore, we assign a high level of co-benefits with moderate level of confidence.
- **Disbenefits -** No unintended biological consequences. However, the protected areas often exclude mariculture. Therefore, it may affect mariculture and thus we assign a low unintended consequence relative to benefit and with a moderate level of confidence.
- **Caveats and limits -** We assume that the protection is effective.

4.3.6.12. Assisted evolution

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Transgenic or selective breeding of farmed fishes are used in aquaculture already), and there is the potential to enhance the tolerance of farmed fishes to climate change and ocean acidification (Maclean and Laight, 2000; Callaway *et al*., 2012). However, direct application and evidence for application of these techniques to address climate change challenges to finfish mariculture are limited. Therefore, we assign a high effectiveness with moderate level of confidence.

- **Co-benefits -** There is little co-benefit of this solution, except that the new breed of farmed fishes may also have other traits that improve production. Since information is limited, therefore, it has a very low co-benefits with low level of confidence.
- **Disbenefits -** Genetically modified farm organisms may escape from mariculture facility and establish in the wild. Genetic modification of marine species may carry substantial known/unknown risk on the viability of the species and the impacts on other species and the environment (Knibb, 1997; Maclean and Laight, 2000; Devlin *et al.*, 2006). For example, genetic modified species may outcompete conspecific that carries beneficial traits. It may also affect trophic interactions or biogenically modify habitats and the environment. Therefore, given the wide range of potential risk, and the low level of its effectiveness, the importance of unintended consequences is considered to be high, with moderate level of confidence.
- **Caveats and limits -** Assuming that it is possible to select or modify the genetics of farmed fish to increase their tolerance to climate change and ocean acidification.

4.3.6.13. Relocation and reef restoration

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Relocation of farmed species to more suitable environment or repopulating farmed organisms with species or populations that are suitable to live in the new environmental conditions under climate change is one of the most effective ways to reduce impacts of climate change or ocean acidification on finfish aquaculture (De Silva and Soto, 2009; Callaway *et al.*, 2012). Such practice has been done by mariculture operation frequently. Therefore, we assign a very high effectiveness with very high confidence.
- **Co-benefits -** No adverse effect reported in the literature.
- **Disbenefits -** The newly introduced farmed species may improve a different set of environmental or ecological challenges e.g., the requirement of fish feed sourced from wild fish stocks, parasites, pathogens etc. Therefore, we assign a moderate level of unintended consequences with moderate confidence.
- **Caveats and limits -** Assuming that the relocated species will generate the same amount of production and/or profit.

4.3.7. Coastal protection by natural ecosystems

4.3.7.1. Renewable energy

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Renewable energy (from marine wind, tides, currents, waves) can reduce carbon emissions, resulting in reduced warming, Ocean acidification, and sea-level rise, thus benefiting coastal and marine ecosystems which support coastal protection (reefs, mangroves, salt marshes, seagrass). Impacts of wind farms/hydropower on coastal habitats that confer coastal protection benefits are not well established but limited evidence suggests both positive and negative impacts (e.g., negative impacts include noise levels, changes to benthic and pelagic habitats, alterations to food webs, and pollution from increased vessel traffic or release of contaminants from seabed sediments). Potentially beneficial effects include the development of artificial reefs from wind turbine foundations and potential de-facto marine reserve around wind turbines, as exclusion of boats would reduce disturbance from shipping (Bailey *et al.*, 2014). Many marine renewable energy devices operate by removing kinetic energy from water (or air in the case of offshore wind). For devices at sea or in estuaries, the resultant reduction of energy may lead to downstream effects. Tidal energy devices may result in local acceleration and scouring in some cases, but have the potential to decrease tidal amplitude in downstream areas. Effects of wave energy devices may alter sediment transport and deposition as well as have an effect on beach processes, thus potentially impacting coastal habitats (Boehlert and Gill, 2010)Boehlert. Due to these potential effects, the effectiveness of this solution to reduce impacts on an ecosystem by reducing other drivers is likely to be very low.
- **Co-benefits -** Insufficient evidence exists to demonstrate co-benefits.
- **Disbenefits -** Potential for unintended consequences exists and noted above.
- **Caveats and limits -** Any large-scale development in the marine environment comes with uncertainty about potential environmental impacts, most of which have not been adequately evaluated—in part because many of the devices have yet to be deployed and tested (Boehlert and Gill, 2010).

4.3.7.2. Vegetation (global) - see below for Local

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Conserved/restored vegetation supports sequestration and reduced warming, thus reducing sea-level rise over decadal timescales (Mcleod *et al.*, 2011; Howard *et al.*, 2017) Protection and restoration of mangroves, salt marshes and seagrasses can reduce sea-level rise as these habitats reduce wave height and energy. Salt marshes play an important role in wave attenuation and shoreline stabilization (Shepard *et al.*, 2011) and can reduce the height of damaging waves in storm surge conditions by close to 20% (Möller *et al.*, 2014). Mangroves can reduce the height of wind and swell waves (Bao, 2011) and tsunami impacts (Alongi, 2008); wave height can be reduced by between 13-66% over 100 m of mangroves (McIvor *et al*., 2012). Seagrasses also can attenuate the wave height and wave energy with a percentage of wave reduction by as much as 50% using artificial seagrass (John *et al*., 2015) and 40% with natural seagrass (Fonseca and Cahalan, 1992). Due to the limited area of these habitats globally, their effectiveness to reduce impacts on ecosystems which support coastal protection are low at the global scale.

- Global coverage of mangroves (13.8 to 15.2 x 106 ha; Spalding, 2010, #2414; Giri *et al*., 2011); tidal marshes (up to 40 million ha, although only 2.2 x 106 ha have been verified; Duarte *et al*., 2013, #7918); Seagrasses (17.7 to 60 x 106 ha; Charpy-Roubaud and Sournia, 1990, #43029; Duarte *et al*., 2005; Mcleod *et al*., 2011).
- **Co-benefits -** Vast amounts of co-benefits (fisheries, tourism, recreation, carbon sequestration, water filtering, wave attenuation, stabilization of shoreline) (Barbier *et al*., 2011).
- **Disbenefits -** Based on high co-benefits - restoration and conservation does not result in unintended consequences.
- **Caveats and limits -** While benefits may be accrued quickly, full ecosystem recovery can take decades and requires long-term monitoring. Limited data on global extent of blue carbon habitats.

4.3.7.3. Fertilization

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Adverse impacts of nutrient enrichment on coastal and marine ecosystems are well documented (Ellison and Farnsworth, 1996; Hughes *et al*., 2003; Islam and Tanaka, 2004; Fabricius, 2005; Waycott *et al*., 2009; Duke, 2016). Indirect effects possible as they can damage coastal systems which can sequesters and store carbon (see carbon uptake below); when degraded they can release emissions. This is likely to have a minor effect on reducing the impacts of sea-level rise globally on coastal habitats.Increased productivity can focus energy on leaves vs. roots thus reduced sea-level rise protection - effects on growth are specific specific and determined by local conditions (e.g., salinity, flooding duration, etc) (Krauss *et al*., 2008; Lovelock *et al*., 2009). Nutrient additions may adversely affect salt marshes and erode carbon deposits. Mangroves may benefit slightly but salt marshes and corals would be adversely affected.
- **Co-benefits -** Unclear benefits as Lovelock *et al*. (2009) demonstrate adverse impacts of nutrient additions and responses depend up species differences and local conditions.
- **Disbenefits -** Potential for unintended consequences are high as eutrophication is a leading cause of decline in coastal habitats (Waycott *et al*., 2009; Spalding, 2010).
- **Caveats and limits -** Seaweed cultivation will have coastal protection benefits (Barbier *et al*., 2011) but other solutions (nutrient additions) have greater potential for unintended consequences (Waycott *et al*., 2009; Spalding, 2010).

4.3.7.4. Alkalinization (global) - see below for Local

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Unlikely to address sea-level rise, which is primary climate impact affecting mangroves/marshes (Kirwan and Megonigal, 2013; Ellison, 2015) which provide significant coastal protection benefits, thus low effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers (González and Ilyina, 2016). The effectiveness of Alkalinization to reduce impacts on coastal habitats are not well known. Lab studies suggest the addition of alkaline substances releases conjointly toxic heavy metals (e.g., cadmium, nickel, chromium) leading to further perturbations that would likely impact ocean biogeochemical cycling and marine ecosystem services (González and Ilyina, 2016). Adding alkalinity may help buffer corals from ocean acidification, but unclear how this would impacts their coastal protection function. Large demand for carbonate mineral and water will likely limit its application to coastal sites (Rau, 2011).
- **Co-benefits -** Co-benefits likely to be low as only relevant at local scales (Rau *et al*., 2012).
- **Disbenefits -** Further evaluation is needed of the economics, potential scale, permanence, environmental cost/benet, and societal acceptability (Rau, 2011). Addition of alkaline substances releases conjointly toxic heavy metals (e.g., cadmium, nickel, chromium) leading to further perturbations that would likely impact ocean biogeochemical cycling and marine ecosystem services (González and Ilyina, 2016).
- **Caveats and limits -** Only relevant at local scales (Rau *et al*., 2012) and unclear how it would affect coastal protection.

4.3.7.5. Hybrid methods

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** To the extent that hybrid methods reduce ocean warming and generate ocean alkalinity, they may reduce stress on coral reefs which provide coastal protection. However, the effectiveness of hybrids to moderate the sensitivity or adaptive capacity of mangroves and salt marshes to climate drivers (esp. sea level rise) is low.

- **Co-benefits** - In cases where hybrid methods produce ocean alkalinity and counter ocean acidification, co-benefits to corals are potentially significant at local scales (e.g. Albright *et al.*, 2016), thus supporting coastal protection benefits of reefs. Unlikely to support mangroves and salt marshes unless hybrid methods improve circulation, thus allowing sediment accumulation and reduced flooding and erosion.
- **Disbenefits -** Potential disbenefits include acidification if molecular CO_2 is the storage medium, trace metal and contaminant effects if these constituents are present with the carbonaceous material stored in the ocean. Potential for O_2 reduction and acidification if organic matter is the storage C medium of hybrid methods. Potential leakages of CO_2, for example, in direct injection of CO_2 into the deep ocean, may impact biogeochemical cycles (Seibel and Walsh, 2001; Seibel and Walsh, 2003), thus potentially affecting coastal ecosystems. Hybrid methods producing organic matter at the C storage medium could, via diagenesis, locally generate seawater CO_2 and consume O_2. Seaweed fertilisation may result in eutrophication and hypoxia, affecting coastal ecosystems.
- **Caveats and limits -** The benefits, co-benefits, and disbenefits of many of the hybrid methods will remain hypothetical until further R&D and testing has been done.

4.3.7.6. Cloud brightening

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Research suggests that cloud brightening may help to stimulate global cooling (Latham *et al.*, 2012) which could reduce thermal expansion and thus sea-level rise impacts. However, changes to precipitation patterns and climate oscillations, and sea surface temperature could affect the ability of coastal habitats to protect shorelines. Changes in precip/temp changes can affect health of wetlands buffering sea-level rise. Potential for pollution if not using sea salt (Shepherd, 2009).
- **Co-benefits -** More data are needed to determine co-benefits.
- **Disbenefits -** More data are needed to assess impacts (e.g., precipitation patterns and climate oscillations, and SST) (Latham *et al.*, 2012).
- **Caveats and limits -** More data are needed to assess impacts (e.g., precipitation patterns and climate oscillations, and SST) (Latham *et al.*, 2012).

4.3.7.7. Albedo enhancement

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Intense cooling over small ocean regions could change circulation (e.g., El Nino and monsoon cycles), which could impede climate regulation; enhanced ocean upwelling could increase outgassing of CO_2. Local cloud albedo increases could result in changes in circulation, sea surface temperature gradients, nutrient upwelling, and El Nino which can have significant terrestrial ecosystem impacts, especially through changes to regional precipitation regimes (Russell *et al.*, 2012) which could adversely affect coastal protection function of coastal ecosystems.
- **Co-benefits -** Have not been verified regarding coastal protection benefits.
- **Disbenefits -** More research is necessary to ascertain impacts of coastal habitats (Russell *et al.*, 2012).
- **Caveats and limits -** Impacts to ocean circulation, temperature, nutrient upwelling and climate patterns (ENSO) may outweigh benefits.

4.3.7.8. Alkalinization (local) - see above for Global

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Potential impacts to reduce warming and thus sea-level rise but low effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers (González and Ilyina, 2016) in coastal protection. The effectiveness of Alkalinization to reduce impacts on coastal habitats are not well known but only relevant for coral/oyster reefs/seagrass, not helpful for mangroves/salt marshes. Lab studies suggest the addition of alkaline substances releases conjointly toxic heavy metals (e.g., cadmium, nickel, chromium) leading to further perturbations that would likely impact ocean biogeochemical cycling and marine ecosystem services (González and Ilyina, 2016). Adding alkalinity may help buffer corals from ocean acidification, supporting reef (oyster/coral) calcification and growth, but unclear how this would impact their coastal protection function. Large demand for carbonate mineral and water will likely limit its application to coastal sites (Rau, 2011).
- **Co-benefits -** Co-benefits likely to be low and only relevant at very local scales (Rau *et al.*, 2012).
- **Disbenefits -** Further evaluation is needed of the economics, potential scale, permanence, environmental cost/benet, and societal acceptability (Rau, 2011). Addition of alkaline substances releases conjointly toxic heavy metals (e.g., cadmium, nickel, chromium) leading to further perturbations that would likely impact ocean biogeochemical cycling and marine ecosystem services (González and Ilyina, 2016).
- **Caveats and limits -** Potentially relevant at local scales (Rau *et al.*, 2012) but unclear how it would affect coastal protection. Benefits potentially through enhanced reef growth - oyster/coral reefs and seagrass calcifiers will benefit - some net reduction in CO_2 uptake.

4.3.7.9. Pollution reduction

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Highly effective at local scales- pollutants can acidify coastal waters at higher rates than CO_2 alone (Kelly *et al*., 2011).Sulfur dioxide precipitation, hypoxia, eutrophication, and emissions and runoff from acidic fertilizers can exacerbate the impacts of ocean acidification. Therefore, controlling coastal pollutants such as nitrogen and sulfur oxides can reduce ocean acidification at local scales (Mcleod *et al*., 2011). While reducing pollution into coastal ecosystems will not directly reduce the impacts of sea-level rise, coastal habitats such as mangroves, seagrasses, marshes, and coral reefs provide valuable coastal protection benefits (e.g., Ferrario *et al*., 2014; Möller *et al*., 2014; Narayan *et al*., 2016; Ward *et al*., 2016). Controlling pollutants which damage these ecosystems will help to maintain ecosystem health, and the coastal protection services that they provide. Pollution also has been shown to decrease the coral bleaching threshold, thus can help to maintain reef health and coastal protection services in the face of increasing sea level (Wiedenmann *et al*., 2013; Ferrario *et al*., 2014).
- **Co-benefits -** Numerous co-benefits of reducing pollutants into coastal water provided by healthy coastal ecosystems (Barbier *et al*., 2011)
- **Disbenefits -** Reducing pollutants is unlikely to have adverse effects.
- **Caveats and limits -** While some suggest nutrient addition will improve coastal carbon sequestration by enhancing mangrove/salt marsh productivity, the balance of evidence points to a likely decrease in carbon storage under nutrient addition (Macreadie *et al*., 2017a). Experimental evidence shows net losses of carbon either through plant mortality and gaseous efflux (e.g. in mangroves; Lovelock *et al*., 2009, #102777; Lovelock *et al*., 2014), or through erosion and loss of sediment (e.g. in salt marshes; Deegan *et al*., 2012, #102185). While more research is needed to quantify the long-term effects of nutrient loading on net carbon flux, particularly in tidal marshes and mangroves, the few existing studies suggest that nutrient reduction programs may have a favorable effect on carbon sequestration (Macreadie *et al*., 2017a).

4.3.7.10. Vegetation (local) - see above for Global

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Conserved/restored vegetation supports sequestration and reduced warming, thus reducing sea-level rise over decadal timescales (Mcleod *et al*., 2011; Howard *et al*., 2017). Protection and restoration of mangroves, salt marshes and seagrasses can reduce sea-level rise locally as these habitats reduce wave height and energy. Salt marshes play an important role in wave attenuation and shoreline stabilization (Shepard *et al*., 2011) and can reduce the height of damaging waves in storm surge conditions by close to 20% (Möller *et al*., 2014). Mangroves can reduce the height of wind and swell waves (Bao, 2011) and tsunami impacts (Alongi, 2008); wave height can be reduced by between 13-66% over 100 m of mangroves (McIvor *et al*., 2012). Seagrasses also can attenuate the wave height and wave energy with a percentage of wave reduction by as much as 50% using artificial seagrass (John *et al*., 2015), and 40% with natural seagrass (Fonseca and Cahalan, 1992). Their effectiveness to reduce impacts on ecosystems which support coastal protection is very high.
- **Co-benefits -** Vast amounts of co-benefits (fisheries, tourism, recreation, carbon sequestration, water filtering, wave attenuation, stabilization of shoreline) (Barbier *et al*., 2011).
- **Disbenefits -** Based on high co-benefits - restoration and conservation does not result in unintended consequences.
- **Caveats and limits -** While benefits may be accrued quickly, full ecosystem recovery can take decades and requires long-term monitoring.

4.3.7.11. Restoring hydrology

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Maintaining the hydrological regime is an important strategy to reduce the impacts of sea-level rise at local scales. Tidal flow and sediment circulation patterns are two key criteria to maintaining the ability of coastal wetlands to accrete vertically to keep pace with sea-level rise (Raposa *et al*., 2016; Sasmito *et al*., 2016). Highly effective to support coastal protection values of mangroves and salt marshes, unlikely to affect corals and their coastal protection function.
- **Co-benefits -** Maintaining hydrological regimes can support carbon sequestration in coastal habitats in addition to other benefits (fisheries, tourism, water quality).
- **Disbenefits -** Restoring hydrological regimes may require removal of shoreline hardening and enforcing setbacks which could affect coastal property.
- **Caveats and limits -** Changes to hydrological and sedimentary regimes may promote the expansion of one blue carbon habitat at the expense of another (Macreadie *et al*., 2017a). Implementation of such measures should therefore be based on their potential net sequestration outcome, and should be preceded by a careful consideration of costs and benefits on a case-by-case basis (Verified Carbon Standard, 2015).

4.3.7.12. Eliminating overexploitation

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Reducing the overexploitation of mangroves, coral reefs, and seagrasses can reduce the effects of sea-level rise locally. These habitats reduce wave energy. Coral reefs reduce wave energy by an average of 97% (Ferrario *et al*., 2014). Salt marshes also play an important role in wave attenuation and shoreline stabilization (Shepard *et al*., 2011) and can reduce the height of damaging waves in storm surge conditions by close to 20% (Möller *et al*., 2014). Mangroves can reduce the height of wind and swell waves (Bao, 2011) and tsunami impacts (Alongi, 2015); wave height can be reduced by between 13-66% over 100 m of mangroves (McIvor *et al*., 2012). Seagrasses also can attenuate the wave height and wave energy with a percentage of wave reduction by as much as 50% using artificial seagrass (John *et al*., 2015), and 40% with natural seagrass (Fonseca and Cahalan, 1992). Other ecosystems provide coastal protection, including macroalgae, oyster and mussel beds, and also beaches, dunes and barrier islands (stabilized by organisms; Defeo *et al*., 2009; Spalding *et al*., 2014, #59996). Therefore, the protection of these habitats helps to ensure that their coastal protection value is secured.
- **Co-benefits -** See above for multiple co-benefits.
- **Disbenefits -** Reducing overharvest may affect communities who depend on resource (e.g., mangrove timber) for fuel/firewood. Engagement with local stakeholders at the outset including all stages of planning and implementation, helps to ensure that their needs are incorporated into the project design and reduces the chance for leakage (e.g., protecting one mangrove forest which leads to deforestation of another) to occur (Wylie *et al*., 2016). Such efforts are critical as controlling overexploitation may involve reductions in valuable natural resources for local communities.
- **Caveats and limits -** Need to consider local human use needs and ensure community engagement in management efforts.

4.3.7.13. Protection

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Protection of coastal habitats have significant coastal protection benefits (see references in Eliminating overexploitation above).
- **Co-benefits -** Ecological benefits of ecosystem protection (e.g., from MPAs) are well established. For example, increases in size, density, biomass, species richness within reserve boundaries (Lester and Halpern, 2008)and benefits from carbon sequestration, tourism, and coastal protection. Protected areas may also reduce user conflicts, enhance environmental awareness, and build social capital (Fox *et al*., 2012).
- **Disbenefits -** Groups may be either empowered or disempowered when decision making authority and resource use rights are granted or denied, sometimes privileging one group over another (Mascia *et al*., 2010). Loss of access to natural resources may result in burdens on communities and livelihood shifts, and may result in inequitable distribution of benefits (Fox *et al*., 2012).
- **Caveats and limits -** Requires long term investment in MPA monitoring and management. MPAs with adequate staff capacity have ecological effects (increase in fish populations) 2.9 times greater than MPAs with inadequate capacity but many MPAs fail to meet thresholds for effective and equitable management processes, with widespread shortfalls in staff and financial resources (Gill *et al*., 2017).

4.3.7.14. Assisted evolution

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** New experiments are testing the impacts of genetic modification of corals (van Oppen *et al*., 2015) and more data are needed to determine their ability to cope with climate impacts, and maintain their ecosystem services (e.g., coastal protection).
- **Co-benefits -** Has potential to maintain valuable ecosystem services provided by reefs, mangroves, seagrasses, and marshes in addition to coastal protection (tourism, food security, source of medicines, cultural/spiritual values, water quality, etc.).
- **Disbenefits -** Artificially enhanced organisms might possess novel traits that give them a competitive advantage over the native population (e.g., invasives); translocated plants and animals may carry pathogens or parasites affecting the health of native populations, or may cause a change in genetic composition or population structure of native organisms, a loss of genetic diversity, or a breakdown of coadapted gene complexes (Laikre *et al*., 2010; van Oppen *et al*., 2015).
- **Caveats and limits -** More data are needed to demonstrate feasibility of assisted evolution - only relevant at local scales.

4.3.7.15. Relocation and reef restoration

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers**

  - Relocation: More data are needed to assess the effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers of assisted migration but conservation scientists now recognize that it may be necessary to secure vulnerable species and the benefits that they provide (Hoegh-Guldberg *et al.*, 2008; van Oppen *et al.*, 2015). Successful restoration of coastal habitats that support coastal protection has been demonstrated (>8 kha of mangroves planted in Vietnam).
  - Restoration: Potential to be highly effective in maintaining coastal protection benefits (restoration of mangroves/marshes) when implemented based on best practices (ensure source of degradation is addressed before restoration is implemented; restore hydrological regimes/sediment flows; adequate site selection and techniques, etc.) (Bayraktarov *et al.*, 2016; Narayan *et al.*, 2016).
- **Co-benefits**
  - Relocation: The assisted migration of corals (van Oppen *et al.*, 2015), mangroves, seagrasses, and salt marshes may be necessary to maintain the diverse ecosystem services that they provide.
  - Restoration: Significant co-benefits achieved when coastal habitats are effectively restored (Barbier *et al.*, 2011).
- **Disbenefits**
  - Relocation: One of the most serious risks associated with assisted colonization is the potential for creating new pest problems at the target site. Introduced organisms can also carry diseases and parasites or can alter the genetic structure and breeding systems of local populations (Hoegh-Guldberg *et al.*, 2008). Further social impacts must be assessed (e.g., financial or human safety constraints, for example, may make a species' introduction undesirable; Hoegh-Guldberg *et al.*, 2008, #88763). Current data demonstrate how introduced species that provide coastal protection services can become invasive and outcompete native populations (e.g., invasive mangroves in Florida and Hawaii). Assisted migration faces numerous ethical, economical, legal, political, and ecological issues (Schwartz *et al.*, 2012).
  - Restoration: Restoration activities may be ineffective or may lead to undesirable social impacts: endangered species establishment or resumption of natural flow regimes that involves flooding, loss of agricultural land, trespassing associated with increased recreational use of restored habitat (Buckley and Crone, 2008).
- **Caveats and limits**
  - Relocation: Uncertainties about future climate conditions, risks associated with moving species and populations outside their current ranges, and existing policies have hampered preliminary studies and formal actions (Williams and Dumroese, 2013).
  - Restoration: Many examples of unsuccessful efforts with median survivals of 64.5% for coral reefs, 38.0% for seagrass, 51.3% for mangroves, 64.8% for salt marshes, and 56.2% for oyster reefs (Bayraktarov *et al.*, 2016).

4.3.8. Bivalves fisheries and aquaculture

4.3.8.1. Renewable energy

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** The infrastructures for extracting wind, wave or tidal energy may provide an artificial habitats for bivalves (Buck *et al.*, 2017). These facilities may prevent bottom-trawling fisheries and other fisheries nearby so that wild populations of bivalve may profit. Aquaculture may profit from this if a mode of cooperation between shellfish farmers and energy companies can be defined (Jansen *et al.*, 2016).
- **Co-benefits -** The artificial habitats provided by the renewable energy installations may function as substrate resulting in bivalve reefs. These artificial reefs may provide larvae for downstream habitats that can be harvested. Moreover, these artificial reefs of suspension feeders will provide many ecosystem functions such as water clearance, food for higher trophic levels, etc (Jansen *et al.*, 2016).
- **Disbenefits -** Installations for renewable energy may lower water mixing rates or current velocities with negative consequences for suspension feeding bivalves and sponges. Moreover, high density reefs of bivalves on the engineered structures may cause high faecal pellets deposition at the seafloor and consequently lead to low oxygen conditions.
- **Caveats and limits -** The possibility to combine exploitation of these renewable energy installations with shellfish aquaculture determines the overall benefit (Buck *et al.*, 2010; Jansen *et al.*, 2016).

4.3.8.2. Vegetation (global and local)

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Coastal vegetations provide coastal protection, enhance nutrient cycling, provide organic carbon for consumers, and a habitat for bivalves (Peterson and Heck, 2001). Canopies may trap sediment material causing problem for suspension feeders.

Consequently, restoration and conservation of coastal vegetated systems is expected to reduce impact from sediment disturbances and eutrophication.
- **Co-benefits -** The production and export of organic matter from vegetated systems may provide an energy resource for bivalves (Graniero *et al*., 2017).
- **Disbenefits -** Restoration and conservation of coastal vegetations may come at the expense of unvegetated (intertidal) habitats where bivalves are living and more easily cultured and harvested. However, vegetated areas account for a very small fraction of the coastal zone and we therefore consider this have a very low unintended consequence.
- **Caveats and limits -** Effectiveness, co-benefits and unintended consequences vary between different types of vegetations and between aquaculture and bivalve fisheries.

4.3.8.3. Fertilization

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Enhancing phytoplankton productivity will stimulate food supply to suspension feeders and many benthic communities are primarily food supply limited (Herman *et al*., 1999). More food supply will stimulate populations growth and will make them less sensitive to other stressors such as ocean acidification and warming (Lesser *et al*., 2010; Lesser, 2016).
- **Co-benefits -** Enhanced food supply because of elevated ocean productivity will stimulate potential for shellfish aquaculture and the functioning benthic bivalve communities. The latter has consequences for biodiversity of organism living in these habitats (Gutiérrez *et al*., 2003).
- **Lack of dis-benefits -** Increased primary production and carbon supply can lead to oxygen depletion and local ocean acidification because of respiration.
- **Caveats and limits -** The link between ocean primary productivity and shellfish aquaculture and fisheries depends on their spatial arrangement.

4.3.8.4. Alkalinization

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Local addition of alkalinity will enhance calcification by bivalves and thus makes less sensitivity to other stressors. Release of iron/silica from olivine weathering may locally stimulate diatoms, a high quality food for most bivalves (Meysman and Montserrat, 2017)
- **Co-benefits -** Enhanced calcification following alkalinization of seawater will strengthen reefs and thus the communities depending on these ecosystem engineers (Gutiérrez *et al*., 2003).
- **Disbenefits -** The effects of excess alkalinization on bivalves is not well known. Harvesting bivalve shells for alkalinization elsewhere may disturb local carbon balances.
- **Caveats and limits -** The mode and duration of alkalinity additions determine the efficiency, co-benefits and unintended consequences.

4.3.8.5. Hybrid methods

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Hybrid methods that lower global warming will potentially impact shellfish metabolism. Hybrid methods involving alkalinization will enhance calcification.
- **Co-benefits -** More data are needed to assess co-benefits
- **Disbenefits -** More data are needed to assess negative impacts.
- **Caveats and limits -** No direct evidence is available.

4.3.8.6. Cloud brightening

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Cloud brightening with seawater will lower global warming with potentially a very small effect on shellfish metabolism.
- **Co-benefits -** More data are needed to assess co-benefits.
- **Disbenefits -** By changing the light climate, primary production and thus food supply to suspension feeders may decline in some areas.
- **Caveats and limits -** No direct evidence is available.

4.3.8.7. Albedo enhancement

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Increasing albedo will lower global warming with potentially a very small effect on shellfish metabolism.
- **Co-benefits -** More data are needed to assess co-benefits but unlikely of major importance.
- **Disbenefits -** By changing the light climate, primary production and thus food supply to suspension feeders may decline in some areas.
- **Caveats and limits -** No direct evidence is available.

4.3.8.8. Pollution reduction

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Cultural eutrophication is one of the causes of hypoxia and respiration induced ocean acidification (Cai *et al*., 2011). Reducing nutrients inputs may thus be beneficial for bivalve fishing and aquaculture.
- **Co-benefits -** Reducing nutrient inputs would be beneficial for bivalve communities suffering from eutrophication induced problems. This would consequently also be beneficial for related ecosystem functions (Levin *et al*., 2009).
- **Disbenefits -** Reducing nutrient input might lower biomass yield in oligotrophic systems.
- **Caveats and limits -** Removal of contaminants would be beneficial for bivalves and their consumption by humans.

4.3.8.9. Restoring hydrology

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Suspension feeding bivalves living near coastal may profit from measures to maintain or improve hydrology (Herman *et al*., 1999).
- **Co-benefits -** Maintaining hydrological conditions will sustain bivalve fisheries and aquaculture.
- **Disbenefits -** If hydrological measures are accompanied by higher suspended matter loads this may be detrimental to filter feeders (Herman *et al*., 1999)
- **Caveats and limits -** Too much freshwater supply may be problematic for marine bivalves (Parada *et al*., 2012).

4.3.8.10. Eliminating overexploitation

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Reducing overexploitation of benthic fishes will cause less disturbance of benthic systems and might in that way result in more shellfish to be harvested (Jennings *et al*., 2001). Reducing overexploitation of wild shellfish will increase capacity of shellfish to respond to climate change and ocean acidification.
- **Co-benefits -** Reducing shellfish exploitation will be beneficial for ecosystem functioning and for larvae (and thus aquaculture)
- **Disbenefits -** No adverse effect reported in the literature.
- **Caveats and limits -** Will vary by system and per species.

4.3.8.11. Protection

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Protection of coastal and benthic ecosystems will increase bivalve recruitment and thus lower the sensitivity of bivalves and shellfish aquaculture.
- **Co-benefits -** Protection of bivalve communities and their reefs will be beneficial to their ecosystem functions.
- **Disbenefits -** No adverse effect reported in the literature.
- **Caveats and limits -** Protection may come at the expense of areas for shellfish aquaculture.

4.3.8.12. Assisted evolution

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Transgenic or selective breeding of farmed species are used in aquaculture already, and there is the potential to enhance the tolerance of farmed fishes to climate change and ocean acidification (Maclean and Laight, 2000; Callaway *et al*., 2012). However, direct application and evidence for application of these techniques to address climate change challenges to mariculture are limited.
- **Co-benefits -** There is little co-benefit of this solution, except that the new breed of farmed organisms may also have other traits that improve production.
- **Disbenefits -** Genetically modified farm organisms may escape from mariculture facility and establish in the wild. Genetic modification of marine species may carry substantial known/unknown risk on the viability of the species and the impacts on other species and the environment (Knibb, 1997; Maclean and Laight, 2000; Devlin *et al*., 2006) For example, genetically modified species may outcompete conspecific that carries beneficial traits. It may also affect trophic interactions or biogenically modify habitats and the environment. Therefore, given the wide range of potential risk, and the low level of its effectiveness, the importance of unintended consequences is considered to be high, with moderate level of confidence.
- **Caveats and limits -** Assuming that it is possible to select or modify the genetics of farmed species to increase their tolerance to climate change and ocean acidification.

4.3.8.13. Relocation and reef restoration

- **Effectiveness of solution to reduce impacts on an ecosystem by reducing other drivers -** Relocation of farmed species to more suitable environment or repopulating farmed organisms with species or populations that are suitable to live in the new environmental conditions under climate change is one of the most effective ways to reduce impacts of climate change or ocean acidification on finfish aquaculture (De Silva and Soto, 2009; Callaway *et al*., 2012). Such practice has been done by mariculture operation frequently. Therefore, we assign a very high effectiveness with very high confidence.

- **Co-benefits -** No adverse effect reported in the literature.
- **Disbenefits -** The newly introduced farmed species may improve a different set of environmental or ecological challenges e.g., the requirement of fish feed sourced from wild stocks, parasites, pathogens etc. Therefore, we assign a moderate level of unintended consequences with moderate confidence.
- **Caveats and limits -** Assuming that the relocated species will generate the same amount of production and/or profit.

5. Cost effectiveness of ocean-based measures

5.1. Cost effectiveness for global measures (*cf.* Table 1a)

5.1.1. Renewable energy

Hawken (Hawken, 2017) provides a list of net costs, integrated for the period 2020 to 2050, of various Renewable energy methods. The net cost expresses the amount of money required to implement renewable energy solutions compared to the cost of repeating business-as-usual (e.g. the difference in cost between an offshore wind farm and a coal power plant). For the purpose of this study, only the ocean-based measures (offshore wind turbines, as well as wave and tidal energy) were considered and the corresponding range of US\$/t CO_2, calculated, averaged and scored as described in Table SM3.5.1 below.

Table SM3.5.1 *Assessment of Renewable energy's cost effectiveness. All values are integrated over the period* 2020 to 2050.

	Offshore wind turbines	**Wave and tidal energy**
Reduction of atmospheric CO_2 equivalent (Gt)	14.1	9.2
Net cost (billions US\$)	572.40	411.84
US\$/tCO_2	40.6	44.8
Range (US\$/tCO_2)	40.6 - 44.8	
Average (US\$/tCO_2)	42.7	
Score	4	

5.1.2. Vegetation (global)

We examined three categories of coastal vegetated areas: mangroves, salt marshes and seagrass habitats. The The Vegetation measure covers restoration and conservation of coastal vegetation to enhance CO_2 uptake and avoid further emissions. We only address here the cost effectiveness of restoration (Table SM3.5.2).

- The range of cost of each sub-category was derived from two sources. Table S1 (restoration projects which have already been implemented for mangroves, salt-marshes and seagrass habitats) in Bayraktarov et al. (Bayraktarov *et al*., 2016) and restoration projects targeting mangroves and salt-marshes in Narayan et al. (Narayan *et al*., 2016);
- These ranges (costs concerning overall, developed and developing countries) are expressed in US\$/ha in restoration projects targeting mangroves and salt-marshes (Bayraktarov *et al*., 2016) and in US\$/m^2 (Narayan *et al*., 2016). We first converted the aforementioned costs to US\$/t CO_2. We have to mention that the authors of these articles provided a different amount of reported restoration projects' cost, as well as their median. However, they do not include discrete data (i.e. cost of each project). For this reason, we did not use the median, as there is possibility of data to overlap. On the contrary, despite of the differences in underlying assumptions and corresponding ranges, we combined the two references to create one range of cost for each vegetated area ;
- Siikamäki et al. (Siikamaki *et al*., 2012) provide information on the amount of CO_2 stored in one ha of each of these coastal vegetated areas. This constituted the key component of our conversion.

Table SM3.5.2. *Assessment of Vegetation's (global) cost effectiveness. Conversion from C to* CO_2 *using a ratio* CO_2/C *of 3.67.*

	Mangroves	**Salt marshes**	**Seagrass habitats**	**Source**
Cost (US$/ha)	0.69×10^2 - 0.828×10^6	3.22×10^2- 86.40×10^6	66.54×10^2 - 4.106×10^6	Bayraktarov *et al.* (2016)
tCO_2/ha	17.14×10^2	14.42×10^2	2.62×10^2	Siikamaki *et al.* (2012)
Conversion to US$/$tCO_2$	4×10^{-2}- 0.483×10^3	22×10^{-2}- 59.908×10^3	2537×10^{-2}- 15.654×10^3	
Cost (US$/ m^2)	5×10^{-2} - 0.064×10^2	10^{-2} - 0.33×10^2	-	Narayan *et al.* (2016)
tCO_2/m^2	17.14×10^{-2}	14.42×10^{-2}	-	Siikamaki *et al.* (2012)
Conversion to US$/$tCO_2$	29×10^{-2}- 0.038×10^3	6.9×10^{-2}- 0.229×10^3	-	
Range (US$/t CO_2)	4×10^{-2}- 0.483×10^3	6.9×10^{-2}- 59.908×10^3	2537×10^{-2}- 15.654×10^3	Bayraktarov *et al.* (2016) Narayan *et al.* (2016) Siikamaki *et al.* (2012)
Average (US$/$tCO_2$)	0.24×10^3	30×10^3	7.84×10^3	
Score	1	1	1	
Average score	1			

5.1.3. Fertilization

A wide range of ocean fertilization costs are available. Ocean fertilization used to be considered as cheap measure, as low as US$2/tCO2 sequestered (reviewed in Markels and Barber, 2002; Boyd, 2008; Fuss *et al.*, 2018). These low initial estimates omitted to consider some costs and were based on unrealistic assumptions. As a result, they were subsequently revised upwards. Rickels *et al.* (2012) and Harrison (Harrison, 2013) estimated the cost of iron fertilization at US$22-119 and 457 per t CO_2 sequestered. Fertilization using macronutrient was estimated at US$20/t CO_2 (Jones, 2014; Fuss *et al.*, 2018). The range of all estimates is 2-457 US$/t CO_2, with a mid-point of 229.5 US$/t CO_2. The cost effectiveness was then scored as very low (score of 1).

5.1.4. Alkalinization (global)

Renforth and Henderson (Renforth and Henderson, 2017) provide in their Table 3 the cost of various ocean alkalinity carbon storage technologies. These costs are largely speculative at this stage. In a previous study, Renforth et al. (2013) indicated a range of 72-159 US$/t CO_2 taken up by the ocean. This range reflects the extraction, calcination, hydration, and surface ocean dispersion costs in a global scale (including transportation). In the case of direct addition of alkaline minerals to the ocean (i.e., without calcination), a range of 20-50 US$/t CO_2 was derived from Harvey (2008), Koehler *et al*. (2013) and Renforth and Henderson (2017). In Table SM3.5.3, the resulting range is thus 10-190 US$/t CO_2 and the score is 3.

Table SM3.5.3. *Assessment of Alkalinization's (global) cost effectiveness.*

Technology	**Cost (US$/t$CO_2$)**
Ocean liming (Oxy-fuel flash calciner: limestone)	126
Ocean liming (Endex CFC: limestone)	100
Ocean liming (Oxy-fuel flash calciner: dolomite)	95
Ocean liming (Endex CFC: dolomite)	72
Ocean liming (Solar calciner: limestone)	159
Ocean addition of alkaline minerals (carbonates or silicates)	20 – 50; Average: 35
Electrochemical weathering ($CaCO_3$)	14-190; Average: 102
Accelerated weathering of limestone	10-40; Average: 50
Range (US$/t$CO_2$)	10-190
Average (US$/t$CO_2$)	85.14
Score	3

5.1.5. Hybrid methods

Table SM3.5.4. *Assessment of Hybrid methods' cost effectiveness.*

Method	**Cost (US$/t CO_2)**	**Source**
Marine biomass fueled BECCS (assumed equivalent in cost to land biomass fueled BECCS)	38-98 Average: 68.5	Smith *et al*. (2016)
Biomass energy with accelerated weathering of limestone in seawater for CO_2 capture and storage as ocean alkalinity	18-128 Average: 73	Rau and Caldeira (1999)
Carbon-negative H_2 production with ocean alkalization	86	Rau *et al*. (2013)
Marine-biomass-sourced biochar (assume cost similar to land-sourced biochar)	12-135 Average: 73.5	McGlashan *et al*. (2012)
Storage of crop waste in ocean sediments	93	Strand and Benford (2009)
DAC with ocean CO_2 storage	25-309 Average: 167	Lackner *et al*. (2012) Holmes and Keith (2012) Zeman (2014)
Range (US$/t tCO_2)	12-309	
Average (US$/t tCO_2)	93.5	
Score	3	

5.1.6. Cloud brightening

Here, the assessment was based on a cost provided by Shepherd et al. (2009) [US$ 0.2 x 10^9/ (W/y/m^2)]. To compare this cost with the other methods included in Table 1a, we had to convert the unit from US$/(W/$m^2$) to US$/t CO_2. For this reason, we divided the difference of radiative forcing between RCP2.6 and RCP8.5 (240 W/m^2), from 2020 to 2100 (Riahi *et al*., 2007; Van Vuuren *et al*., 2007; Moss *et al*., 2010), by the cumulative anthropogenic emissions between these two RCP scenarios (1400 Pg C) throughout these years (Jones *et al*., 2013). This ratio was then converted to (W/m^2)/t CO_2 and multiplied by the initial cost. Finally, we obtained a cost described in US$/t CO_2 and scored the method accordingly. Explicitly the calculations are described in Table SM3.5.5.

Table SM3.5.5. *Assessment of the cost effectiveness of cloud brightening.*

Initial cost [US\$ / (W/y/m²)]	0.2×10^9
Difference in integrated radiative forcing (W/m²) from 2020 to 2100	240
Anthropogenic emissions (Pg C) from 2020 to 2100	1,400
Ratio_1 [(W/m²)/PgC]	0.1717
Anthropogenic emissions (t CO_2) from 2020 to 2100 **Ratio of $CO_2/C=3.67$*	$1{,}400 \times 10^9 \times 3.67$
Ratio_2 [(W/m²)/t CO_2]	$240/(1{,}400 \times 10^9 \times 3.67)$
Cost [Initial cost x Ratio_2] (US\$ /t CO_2)	0.00934
Score	5

5.1.7. Albedo enhancement

To the best of our knowledge, no information on cost is available. This measure was therefore not scored. It has however been suggested that the fuel efficiency of commercial shipping might be improved if bubbles were produced beneath ships' hulls (Crook *et al*., 2016).

5.2. Cost effectiveness for local measures (*cf.* Table 1b)

5.2.1. Alkalinization (local)

Feng et al. (Feng *et al*., 2016) consider costs of a regional dispersion of CaO- based Artificial Ocean Alkalinization (AOA), which were inferred from Renforth *et al. (2013)*. The regions examined in the simulations of Feng et al. (Feng *et al*., 2016) are the Great Barrier Reef, the Caribbean Sea and the South China Sea. Data were converted from US\$/t CO_2 to US\$/ha by taking into account the cumulative amount of atmospheric CO_2 sequestered by AOA in the year 2009, as well as the surface area of these regions. Subsequently, we obtained a cost range and an average for each region and finally an overall average and a score for the method. Calculations are shown in Table SM3.5.6.

Table SM3.5.6. *Assessment of Alkalinisation's (local) cost effectiveness.*

	Great Barrier Reef	**Caribbean Sea**	**South China Sea**
Cost (US$/year)	51×10^6 - 112×10^6	107×10^6 - 237×10^6	117×10^6 - 258×10^6
t CO_2 sequestered in 2099	56.32×10^9	119.28×10^9	129.83×10^9
Conversion to US$/t$CO_2$	0.9-2	0.9-2	0.9-2
Surface area (km^2)	17×10^6	3.9×10^6	5.2×10^6
tCO_2 sequestered/ km^2	3.31×10^3	30.58×10^3	24.82×10^3
tCO_2 sequestered/ ha ** 1 km^2=10^2 ha*	33.1	305.8	248.2
Conversion to US$/ha	29.8-66.2	275.2-611.7	224.7-499.4
Average (US$/ha)	48	443.45	362.05
Average (US$/ha)	284.5		
Score	3		

5.2.2. Vegetation (local)

The Vegetation measure covers restoration and conservation of coastal vegetation to enhance CO_2 uptake and avoid further emissions. We only address here the cost effectiveness of restoration. The costs were extracted from the same sources as for the assessment of Vegetation (global). The approach followed is described in Table SM3.5.7.

Table SM3.5.7. *Assessment of vegetation's (local) cost effectiveness.*

	Mangroves	**Salt marshes**	**Seagrass habitats**	**Source**
Cost (US$/ha)	0.69×10^2- 0.828×10^6	3.22×10^2- 86.40×10^6	66.54×10^2 - 4.106×10^6	Bayraktarov *et al.* (2016)
Cost (US$/m^2)	5×10^{-2} - 0.064×10^2	10^{-2} - 0.33×10^2	-	Narayan *et al.* (2016)
Conversion to US$/ ha	5×10^2- 6.4×10^4	10^2 - 33×10^4	-	
Range (US$/ha)	0.69×10^2- 0.828×10^6	3.22×10^2- 86.40×10^6	66.54×10^2 - 4.106×10^6	Bayraktarov *et al.* (2016) Narayan *et al.* (2016)
Average (US$/ha)	0.41×10^6	43.2×10^6	2.06×10^6	
Score	1	1	1	
Average score	1			

5.2.3. Pollution reduction

Not scored because the cost of pollution control is vastly different depending how far depollution goes.

5.2.4. Restoring hydrology

Data for this category is available from NOAA's tidal restoration projects (NOAA Restoration Center and NOAA Coastal Services, 2010). These projects were implemented to address issues of drought or for sanitary purposes. Consequently, these estimates include costs unrelated to the scope our study, such as wastewater treatment. Furthermore, costs of restoring hydrology would greatly differ depending on the coastal system considered and cost of labour. This measure was therefore not scored due to the lack of adequate information.

5.2.5. Eliminating overexploitation

No data available.

5.2.6. Protection

The costs were derived from McCrea *et al.* (2011) and were the total establishment costs of Marine Protected Areas (MPAs), in 2005 USD with purchasing power parity (ppp) in order for the differences between developed and developing economies to become smoother. The costs in this study vary non - linearly with the MPA size. The costs of establishing the thirteen MPAs were given in US$ per km^2. First, we arranged them by increasing value as per below (Table SM3.5.8.) and subsequently we obtained the median and scored accordingly.

Table SM3.5.8. *Assessment of protection's cost effectiveness.*

MPAs*	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
Total establishment cost (US$/km^2)	41	96	116	1.79	3.91	4.45	4.6	6.89	8.95	40	47.5	71.74	1,117,358
Total establishment cost (US$/ha)	0.41	0.96	1.16	17.9	39.1	44.45	46	68.91	89.5	400	475	717.4	11,173.58
Median (US$/ha)	46.03												
Score	5												

* ***1:*** *Mariana Trench MNM (USA),* ***2:*** *PMNM (USA),* ***3:*** *Seaflower MPA (Colombia),* ***4:*** *Pilar MPA (Philippines)* ***5:*** *MISSTA MPA (Philippines),* ***6:*** *Nha Trang Bay MPA (Vietnam),* ***7:*** *Villahermosa MS (Philippines),* ***8:*** *Tambunan MPA (Philippines),* ***9:****Talisay MPA (Philippines),* ***10:*** *Bibilik MPA (Philippines),* ***11:*** *Bonaire NMP (Netherlands Antilles),* ***12:*** *Saba MPA (Netherlands Antilles),* ***13:*** *CHICOP (Tanzania).*

5.2.7. Assisted evolution

No data available.

5.2.8. Relocation and reef restoration

In this category only the restoration project costs of coral and oyster reefs were considered, using data from Bayraktarov et al. *(2016)* and Narayan et al. (2016). The calculations are described in Table SM3.5.9.

Table SM3.5.9. *Assessment of restoration's cost effectiveness.*

	Coral reefs	**Oyster reefs**	**Source**
Cost (US$/ha)	76.47×10^2 - 143×10^6	44.90×10^2 - 2.17×10^6	(*160*)
Cost (US$/m^2)	2 - 74.90×10^2	1.07×10^2 - 3.16×10^2	(*277*)
Conversion to US$/ha (*1 m^2=10^{-4} ha*)	2×10^4 - 74.90×10^6	1.07×10^6 - 3.16×10^6	-
Range (US$/ha)	76.47×10^2 - 143×10^6	44.90×10^2 - 3.16×10^6	(*160, 277*)
Average (US$/ha)	71.5×10^6	1.6×10^6	
Score	1	1	
Average score	1		

6. Global governability of ocean solutions (Table 5)

Governance can be generally defined as "an effort to craft order, thereby to mitigate conflict and realise mutual gains" (p. 500, Williamson, 2000). Governance is needed or fruitful because actors are often interdependent in the sense that actions taken by one actor may lead to benefits or disbenefits for other actors. For example, an actor emitting greenhouse gas (GHG) affects all other actors by contributing to global warming. Governance arrangements such as laws, courts, property rights, norms, conventions, etc. arise to constrain human behaviour in face of these interdependencies, and through this, mitigate conflict and realise mutual gains (North, 1990; Williamson, 2000; Ostrom, 2005). For example, a formal climate treaty that caps emissions, or an informal social norm to eat less meat, constrain human emission behaviour and thus help to realise the mutual gain to reduce global warming.

Here, we assess the governability of ocean solutions, defined as society's capability to govern the implementation of solutions (Kersbergen and Waarden, 2004; Kooiman *et al.*, 2008), solving conflicts and harnessing mutual benefits. Such governability depends on both the specific form of biophysical interdependencies between the actor at hand (i.e., how costs and benefits are distributed across involved and affected actors), and the existing institutional arrangements that influence behaviour in the face of these interdependencies (Ostrom, 2005). For example, governability is higher, when actors share social norms or mental models, because then they are more likely to reach agreement/consensus and develop governance arrangements (Ostrom, 2000).

For environmental problems, interdependence is caused by environmental processes that distribute the benefits and disbenefits of actions taken by one actor to other actors. This makes governance of environmental problems specifically challenging, because environmental processes generally involve large uncertainties, cover long distances and cross administrative boundaries (Vatn, 2005; Magnan *et al.*, 2015), and thus may introduce global interdependencies as in the case of climate change. To understand these challenges, a vast environmental governance literature, in particular the *realist-materialist* branch thereof, has characterized environment-related interdependencies between actors and the associated governability, at both local (Ostrom, 2005; Vatn, 2005; Ostrom, 2009) and global scales (Kaul *et al.*, 1999; Barrett, 2007). Well-known classes of governance challenges are the provisioning of public goods (PG) and common-pool resources (CPR), which will be subsumed here under the label *collective goods*. Actor's interdependencies in collective goods have been further characterized by a range of other contextual variables such as jointedness in supply, effectiveness of the solution, predictability of the effects of an action, frequency of the action, etc. (Hagedorn, 2008; Ostrom, 2009; Hinkel *et al.*, 2014).

Here we apply this realist-materialist literature to assess the global governability of the ocean-based solutions considered in this paper. By global governability we refer to the capability of the global community of nation states and international no-state actors to mitigate conflicts and realize mutual gains in face of ocean-based solutions for climate change. We focus on supranational aspects of governability because the climate problem is a global problem, which requires cooperation and coordination between sovereign nation states and international non-state actors. The unique and defining feature of such governance above the level of nation states is the lack of a sovereign global entity that could regulate, monitor and enforce the implementation of solutions, which makes global governance specifically challenging (Kaul *et al.*, 1999; Barrett, 2005; Walker *et al.*, 2009). This is not to say that solving climate change problem does not include sub-national governance challenges. Addressing these would, however, require detailed analysis of sub-national actors, their interdependencies and diverse institutional arrangements for each country considered, which is beyond the scope of a single, global scale-focused paper. Hence, sub-national actors, national laws, rules and other governance arrangements are not considered here.

Our assessment of governability is based on the peer-reviewed literature on governance in general and ocean governance in particular, and proceeds as follows. First, we select biophysical and institutional factors that have been empirically found to influence governability in a positive or negative way (subsection 6.1). Next, we characterize supranational governability of each solution according to each dimension (subsection 6.2). Finally, we combine the individual dimensions into an governability index which assigns a score between 1 and 5 to each solution (SM6.3 and Table SM6.3.1 for a synthesis). Subsection 6.4 presents the final results (Table 5).

6.1. Dimensions of governability

6.1.1. Bio-physical dimensions

The biophysical interdependence between nation states depends on how environmental processes distribute benefits and disbenefits of ocean based solutions across actors on two levels:

- ***Global level*** - Solutions have global benefits by addressing global drivers. For example, marine Cloud brightening aims at enhancing the production, longevity and brightness of stratocumulus clouds in order to change climate features at the regional to global scale. Also, maintaining mangrove ecosystems sequesters carbon and thus contributes to the provisioning of the global benefit of reducing climate change.
- ***Local level*** - Solutions may have local benefits or disbenefits by addressing local drivers and impacts on ecosystems, or having negative local side effects. For example, switching to renewable energies may have the local co-benefit of reducing air pollution. Also, restoring hydrological flows could lead to disbenefits on shipping potential or hydropower generation.

Many of the solutions analysed here have effects on both global and local levels. For example, restoring ecosystems brings a range of local benefits, while, at the same time, may sequester carbon and hence contribute to the global effect of reducing greenhouse gas concentrations.

The variables to characterise the various biophysical and economic dimensions of governability were selected iteratively by i) first scoring each solution against possible variable taken from the literature, ii) disregarding those that did not show a significant difference in value across the solutions, and finally iii) removing variables that were redundant. Each solution was scored against each variable using a scale from 0 to 1. The final governability score was then obtained as a weighted average of the scores multiplied by 5 (see Table SM6.3.1 for a synthesis).

Global level

- ***Can the solution make a sizeable contribution to reduce global drivers (i.e. potential effectiveness of solution)?*** Solutions that are perceived not to be very effective reduce the likelihood of cooperation amongst actors and hence governability (Ostrom, 2007). The value of this variable was computed by dividing the "effectiveness" of solutions scored in Tables 1a and 1b by 5.
- ***Predictability of the effects of a solution*** - The predictability of the effects of a solution increases governability, because it increases the expectation of actors that the effort invested in the solution will pay off (Hagedorn, 2008; Ostrom, 2009). The value of this variable was computed by dividing the "confidence levels" described in Tables 1a and 1b by 5.
- ***Absence of an Olsonian actor*** - If a nation state or a small group of nation states, so-called "Olsonian" actors (Olson, 1971; Bisaro and Hinkel, 2016), can derive more benefits from providing a good than the associated cost of implementation, this state (or small group of states) has a strong incentive for providing the good unilaterally (or mini-laterally). For pure collective goods, such as reducing greenhouse emissions, this increases the solution's governability (Olson, 1971; Barrett, 2007). If, however, significant disbenefits are associated with a solution, as it is, e.g., the case for SRM and some CDR measures, the presence of an Olsonian actor can also reduce governability, because the Olsonian actor may go ahead in providing the good without the permission of other possibly adversely affected actors, which is stressed in the literature on geoengineering governance (e.g., Williamson and Bodle, 2016; Preston, 2013; Rabitz, 2016). Following this latter literature, we assign a score of 0 to a solution if an Olsonian actor is present and a score of 1 otherwise.
- ***The type of collective good*** describes whether the collective good at hand is a PG, which means that its provisioning is dominated by supply-side measures, or a CPR, which generally means that its provisioning is dominated by demand-side measures (Ostrom *et al.*, 1994). An example of the former is providing the global good of a "safe climate" through removing GHG from the atmosphere. An example of the latter is providing the global good of a "safe climate" by burning less fossil fuels. Demand-side challenges (CPR) are generally more difficult to govern, because cooperation necessarily means to sacrifice individual gains (here, burning fossil fuels), which provides a strong incentive for each individual actor not to cooperate. In supply-side challenges (PG), cooperation does not automatically lead to an individual loss. A dilemma nonetheless exists because of the risk of getting a lower payoff when co-operating and others defect. Following this literature, we assign a score of 0 if the solution is a CPR and a score of 1 if it is a PG.

Local level

- ***The presence of local benefits*** (i.e. reduced local impacts that are not induced via a reduction of global drivers) increases the incentive of nation states to implement measures and hence increases global governability, while the presence of local disbenefits acts in the opposite direction. We assign a score of 1 to a solution if local benefits are present and 0 otherwise.
- ***The absence of local disbenefits***, similarly to the presence of local benefits, increases governability. We assign a score of 1 to a solution if local disbenefits are absent and 0 otherwise.
- ***Predictability of the benefits and disbenefits of a solution*** - Same rationale than for the Global level (see above). As for the global level, the value of this variable was computed by dividing the "confidence levels" described in Tables 1a and 1b by 5.
- ***Are the local net benefits (benefits minus disbenefits) outweighing the local cost of implementation?*** This variable full fills a special role in the assessment, because it determines whether global social dilemma associated with the provisioning and use of global PG and CPR exist or not. If *local net benefits (benefits minus disbenefits) outweigh the local cost of implementation*, then there is a local rationale for action and hence no global social dilemma exists, which increases the solution's governability significantly. Governance between nation states is much more challenging than within nation states, because in the former case there is no sovereign international entity that could regulate, monitor and enforce the implementation of solutions (Kaul *et al.*, 1999; Barrett, 2005; Walker *et al.*, 2009). We assign a scores of 1 to a solution if local net benefits are higher than local costs of implementation, 0 if this is not the case and 0.5 for intermediate situations.

One other dimension of governance emphasized in the literature but disregarded here is the geoengineering-related "moral hazard" (Hale, 2012). This refers to the risk that public decision-makers, as well as private or civil society actors, may reduce their mitigation effort because they believe that SRM, for example, can function as insurance against climate risk (McLaren, 2016). The fear is that "the mere mention of a technical solution to warming temperatures might weaken political efforts at reducing greenhouse gas emissions" (Preston, 2013). Other scholars argue that SRM especially, with all its negative side-effects, could also be seen as a threat itself, leading to greater effort to mitigate (Burns *et al*., 2016). Irrespective of the direction of this effect, we disregard this dimension of governability because it can not be attributed to a single measure, but rather is associated to all measures together in that the presence of geo-engineering measures increases (or decreases) the governability of all other mitigation measures.

6.1.2. Institutional dimensions

We characterize the institutional aspects of governability in terms of two dimensions, the first one pertaining to formal and the second one to informal institutional arrangements.

- ***Existing formal governance arrangements with global relevance*** **-** This includes both international governance arrangements such as international treaties, as well as national, bilateral or minilateral arrangements that have a global effect. Existing formal governance arrangements may increase governability by providing a framework for negotiating stronger global regulations (e.g., the UNFCCC), for example. Governance arrangements can also decrease governability by hindering progress in implementing solutions. Here we score governability on this dimension by listing the major relevant governance arrangements and assessing these in terms of their combined enabling or constraining effects. This considers, e.g., whether arrangements are (1) binding or nonbinding; (2) include enforcement mechanisms, and (3) how comprehensively they cover relevant countries. We score solutions with a 1 if existing formal arrangements enable the implementation of a given ocean solution, 0 if they disable implementation and 0.5 if they are neutral.
- ***Degree of normative consensus*** **-** This dimension refers to the informal institutional arrangements of shared moral and social norms amongst actors from governmental, non-governmental and private sectors. A broad normative endorsement of solutions amongst all groups of actors fosters co-operation and hence increases governability, whereas controversial normative positions decreases governability (Abbott and Snidal, 1998). In the former case we score solutions with 1 and in the latter cases with 0. Intermediate cases receive a 0.5.

6.2. Justification of the scores given

Most of the scores for the biophysical dimensions of governability are directly taken from the scores of the other Tables, as explained above in Section 6.1. This includes sizable contribution, predictability, local benefits and disbenefits. References that justify these scores can thus be found in the corresponding sections of this Supplementary Material. The subsections following below provide justification based on existing literature for those dimensions not covered in the other sections.

6.2.1. Global good is a CPR or a PG

All measures are scored as providing global public goods except Renewable energy and Reducing overexploitation which are scored as "common pool resource" (CPR). Reducing overexploitation of marine resources is a classical CPR. Renewable energy is also a CPR, because it is a mitigation measure that is more costly than burning fossil fuels. Hence switching to renewable energy means tempering the use of the global carbon budget (i.e. the common pool) which is a subtractable resource. Conversely, implementing a geo-engineering measure consists in providing the global public goods of increasing the global carbon budget.

6.2.2. Absence of an Olsonian actor

For most measures no Olsonian actor that could provide the global collective good unilaterally (or minilaterally) is present. Generally, there can not be an Olsonian actor for local solutions. For the global solutions, the unilateral provision of the good may be possible in the case of adding alkalinity, land-ocean hybrids and cloud brightening.

6.2.3. Local net benefits > local cost of implementation

Scoring was conducted based on scores from other tables (e.g., local co-benefits and disbenefits, to obtain local net benefits; and costs, see above, section 5.2) and available literature. For example, protection through the establishment of marine protected areas (MPAs) can provide local benefits through larval and adult spillover and contribution to fisheries that exceed local disbenefits of reduced extent of fishing grounds (Halpern *et al*., 2009). In MPAs that are effectively managed and enforced, the combined economic benefits from, e.g., fisheries and tourism, have been found to greatly exceed the costs of management and enforcement of the MPA (Sala *et al*., 2013).

6.2.4. Enabling and constraining institutions and degree of normative consensus

The information given below provides the basis for solution-specific scoring of supranational governability with regard to two institutional considerations: “existing governance structures and arrangements with international relevance” and “degree of normative consensus”, as defined above (Section 6.1.2). The dates given for international conventions, agreements, etc. either relate to initial signing or establishment, or to dates of specific decisions (as mentioned) by Parties. The color code in the measure-specific tables below is meant to make it easier to get a quick-glance view of whether consideration of these factors results in a higher or lower governability score (from deep green to deep red). The context of these scores is developed in subsection 6.3. See also Table 5 (subsection 6.4).

6.2.5. Renewable energy

Existing **governance structures and arrangements** with international relevance (Combined enabling and constraining score: 0.75)	Enabling	The Paris Agreement (*469*) of the UN Framework Convention on Climate Change (*470*) requires net zero emissions of greenhouse gases within 30-80 years, hence global-scale replacement of fossil fuel energy sources by renewables or nuclear power. National policy actions (e.g. via feed-in tariffs) have stimulated technological advances and mass production, hence incentivising wider global use of renewables. Finance to assist renewable energy development available via Global Climate Fund (GCF), World Bank and other mechanisms.
	Constraining	National fossil fuel subsidies remain in many countries. Some concerns re potential environmental impacts for tidal power schemes and wind turbines.
Degree of **normative consensus** (Score 1)		Marine renewables generally have high societal acceptability, and considered less problematic than for those on land.

6.2.6. Vegetation (global and local)

Existing **governance structures and arrangements** with international relevance (Combined score: 1.0)	*Enabling*	Many international institutions promote the conservation and restoration of coastal vegetation, either explicitly or in the context of wider protection of natural habitats and ecosystems. These structures include the **Ramsar Convention** on Wetlands of International Importance (1971); the **Convention on Biological Diversity** (CBD, 1992), with its Aichi Biodiversity Targets (2010) and Strategy Plan for Biodiversity 2011-2020; the **Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services** (IPBES, 2012); the UN Strategic Development Goals, particularly **SDG 14** (2015); the **UN Framework Convention on Climate Change** (UNFCCC, 1992) and its **Paris Agreement** (2015) and the **UN Environment Programme** (UNEP, 1972). Non-governmental activities with relevant international influence include the **International Union for the Conservation of Nature** (IUCN) **The Nature Conservancy** (TNC), the **World Wildlife Fund** (WWF), and many others.
	Constraining	No major constraining institutional structures or arrangements
Degree of **normative consensus** (Score 1)		Generally high societal acceptability.

6.2.7. Fertilization

Existing **governance structures and arrangements** with international relevance (Combined score: 0)	*Enabling*	Regulatory mechanism for relevant open-ocean research developed by **London Convention/London Protocol** (LC/LP; proposal for Protocol amendment, 2013), with requirement for environmental impact assessment.
	Constraining	Prohibition of iron fertilization to enhance marine productivity other than for research (above) under **London Convention** (LC, 1972) and its associated **London Protocol** (LP, 1996), with relevant LP decisions in 2008-2013. Other, non-binding, decisions that strongly discourage ocean Fertilization have been made by the **UN General Assembly** (2008), the **Convention on Biological Diversity** (CBD, 2008), and the **Intergovernmental Oceanographic Commission** (IOC, 2009). In addition, the **Antarctic Treaty** and its associated **Madrid Protocol** (1991) prohibits such action in most of the Southern Ocean [where it would need to be implemented in order to achieve global-scale potential climatic benefits].
Degree of **normative consensus** (Score 0)		Initial small-scale experiments on ocean fertilization (in 1990s) were non-controversial. Subsequently (since about 2007), strong concerns raised by NGOs, governments and intergovernmental bodies re potential for adverse impacts, with identified need for global-scale regulatory control (above). An unauthorised iron-addition experiment was carried out in the NE Pacific in 2012; this action was widely criticized for contravening emerging governance arrangements.

6.2.8. Alkalinization (global & local)

Existing **governance structures and arrangements** with international relevance (Combined score: 0.25)	*Enabling*	No specific mechanisms
	Constraining	The **London Convention/London Protocol** (LC, 1972; LP, 1996) prohibits the unlicensed dumping at sea of wastes and 'other matter'. Marine geoengineering (in general terms, in addition to iron fertilization) included through proposed Protocol amendment (2013). Several decisions of Parties to the **Convention on Biological Diversity** (CBD) on climate geoengineering (e.g. in 2010, 2012 and 2015) are also relevant; however, these do not explicitly mention interventions based on adding alkalinity to the ocean.
Degree of **normative consensus** (Score 0)		Concerns regarding potential adverse environmental impacts, on land as well as at sea - but not widely discussed.

6.2.9. Hybrid method

Existing **governance structures and arrangements** with international relevance (Combined score: 0.25)	*Enabling*	**London Protocol** provides regulatory framework for sub-seafloor CO_2 storage in international waters. Otherwise, the addition to the ocean of hybrid carbon storage forms other than CO_2 (e.g., organics, bicarbonate, carbonate) have not been widely considered.
	Constraining	Direct CO_2 injection into the ocean prohibited by **London Protocol.** Other methods may be constrained by more general LP decisions relating to marine-based climate geoengineering. To the extent that carbon captured via hybrid methods is stored in the marine environment in forms other than molecular CO2: The **London Convention/London Protocol** (LC, 1972; LP, 1996) prohibits the unlicensed dumping at sea of wastes and 'other matter'. Several decisions of Parties to the **Convention on Biological Diversity** (CBD) on climate geoengineering (e.g. in 2010, 2012 and 2015) are also relevant; however, these do not explicitly mention interventions based on adding carbonaceous materials to the ocean. When carbonaceous materials are added to national/coastal waters, local and national laws will apply.
Degree of **normative consensus** (Score 0)		In most cases lack of experimentation, practice and general awareness of hybrid methods means consensus has not formed and would be premature without more evidence of the methods' benefits and disbenefits and likelihood of deployment.

6.2.10. Cloud brightening

Existing **governance structures and arrangements** with international relevance (Combined score: 0.25)	*Enabling*	No specific mechanisms
	Constraining	Decisions of the **Convention on Biological Diversity** (CBD) on climate geoengineering (e.g. in 2010, 2012 and 2015) are relevant, but do not explicitly mention interventions based on marine cloud brightening. Weather modification risks and impacts have been considered, in general terms, by the **World Meteorological Organisation** (WMO); such actions are prohibited in a military context by the UN Environmental Modification Convention (1977).
Degree of **normative consensus** (Score 0)		Large-scale application likely to results in national winners and losers at regional scale; hence need for negotiation of loss and damage mechanisms to cover risk of adverse impacts occurring across national boundaries. High public concern (in some countries) regarding '**chemtrail conspiracy**'; i.e. that secret testing and/or implementation of weather modification is already underway.

6.2.11. Albedo enhancement

Existing **governance structures and arrangements** with international relevance (Combined score: 0)	*Enabling*	No specific mechanisms
	Constraining	Decisions of the **Convention on Biological Diversity** (CBD) on climate geoengineering (e.g. in 2010, 2012 and 2015) are relevant, but do not explicitly mention interventions based on marine albedo through long-lived foams. The addition of the chemicals (surfactants) involved would currently be prohibited by the **London Convention/ London Protocol** (LC/LP); such action may also be regulated by the **Convention on the Prevention of Pollution from Ships** (MARPOL, 1973, 1978) of the **International Maritime Organization** (IMO). The potential for adverse impacts on fisheries, sea mammals, seabirds and other marine life would be of concern to the **UN Food and Agriculture Organization** (FAO), and many other bodies with interests in marine bioresources, marine ecosystem services and marine protection.
Degree of **normative consensus** (Score 0)		Not widely discussed. Nevertheless, likelihood of very low societal acceptability, due to high risk of very many damaging environmental and economic consequences, including effects on coastal tourism.

6.2.12. Pollution reduction

Existing **governance structures and arrangements** with international relevance (Combined score: 1.0)	*Enabling*	Global reduction in marine pollution a specific target of ocean-related **UN Sustainable Development Goal** (SDG 14; 2015). Also encouraged by regulatory action by the **Convention on the Prevention of Pollution from Ships** (MARPOL, 1973, 1978) of the **International Maritime Organization** (IMO), and by the **London Convention/ London Protocol** (LC/LP). Other relevant arrangements and bodies with interests include the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR), the Stockholm Convention on Persistent Organic Pollutants, and the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP, sponsored by the UN, UNEP, FAO, UNESCO-IOC, UNIDO, WMO, IMO, IAEA and UNDP).
	Constraining	No major constraining institutional structures or arrangements
Degree of **normative consensus** (Score 1)		High societal acceptability of measures to reduce marine pollution.

6.2.13. Restoring hydrology

Existing **governance structures and arrangements** with international relevance (Combined score: 0.5)	Enabling	No major enabling institutional structures or arrangements
	Constraining	No major constraining institutional structures or arrangements
Degree of **normative consensus** (Score 0.5)		Limited information to assess. Wide range of potential actions involved: some may be locally controversial.

6.2.14. Eliminating overexploitation

Existing **governance structures and arrangements** with international relevance (Combined score: 1.0)	*Enabling*	Global reduction in overexploitation of fisheries and other marine bioresources (e.g. relating to coral reefs) is a specific target of ocean-based **UN Sustainable Development Goal** (SDG 14; 2015). Also actively promoted by **UN Food and Agriculture Organization** (FAO, 1945), and many other bodies, including international fishery commissions for open-ocean stocks (e.g. tuna and salmon); the **UN Convention on Law of the Sea** (UNCLOS, 1956); the **Convention on Biological Diversity** (CBD, 1992) of the **United Nations Environment** (UNEP, 1972); the **Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services** (IPBES, 2012); the **International Union for the Conservation of Nature** (IUCN, 1948); and the **Global Ocean Commission** (2013).
	Constraining	No major constraining institutional structures or arrangements
Degree of **normative consensus** (Score 1)		The desirability of reducing overexploitation can be considered non-controversial, with very high societal acceptability.

6.2.15. Protection

Existing **governance structures and arrangements** with international relevance (Combined score: +1)	*Enabling*	Establishment of marine protected areas at global scale initially promoted by **International Union for Conservation of Nature** (IUCN) through its 4th World Parks Congress, with subsequent endorsement and formal development by many bodies and structures, including the **UN World Summit on Sustainable Development** (2002), the **Convention on Biological Diversity** (CBD) and its Aichi Biodiversity Targets (2010) and Strategy Plan for Biodiversity 2011-2020; the **UN Framework Convention on Climate Change (UNFCCC);** the **Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services** (IPBES, 2012); the **UN Strategic Development Goals**, particularly SDG 14 (2015); the **UN Environment Programme** (UNEP, 1972); and the **UN Educational, Scientific and Cultural Organization** (UNESCO; Man and the Biosphere initiative). Close linkage with goals of **Ramsar Convention** on Wetlands on International Importance and **Antarctic Treaty.** Many relevant non-governmental organisations and activities, operating on global scale; e.g. The Nature Conservancy, World Wildlife Fund, Conservation International, Pew Trusts.
	Constraining	No major constraining institutional structures or arrangements
Degree of **normative consensus** (Score 1)		The development of marine protected areas and similar conservation initiatives generally has high societal acceptability. Nevertheless, there can be opposition from the fishing industry and local communities if livelihoods are threatened.

6.2.16. Assisted evolution

Existing **governance structures and arrangements** with international relevance (Combined score 0.25)	*Enabling*	No known major enabling institutional structures or arrangements
	Constraining	The **Cartagena Protocol on Biosafety** (2000) of the **Convention on Biological Diversity** (CBD) provides non-binding guidance to limit adverse environmental impacts of genetically-modified organisms. Aspects of the **Convention on International Trade in Endangered Species of Wild Fauna and Flora** (CITES) are also relevant.
Degree of **normative consensus** (Score 0)		The release of genetically-modified organisms into the natural environment is inherently controversial, with generally low societal acceptability.

6.2.17. Relocation and reef restoration

Existing **governance structures and arrangements** with international relevance (Combined score: 0.75)	*Enabling*	Habitat restoration considered a component of climate mitigation by **UN Framework Convention on Climate Change (UNFCCC).** Aim of at least 15% restoration of degraded habitats (marine and terrestrial) by 2020 identified in **Aichi Biodiversity Target 15** of **Convention on Biological Diversity** (CBD). Development of marine protected areas is the main factor enabling habitat restoration, with support from **Ramsar Convention, International Union for the Conservation of Nature** (IUCN) and many others.
	Constraining	Aspects of the **Convention on International Trade in Endangered Species of Wild Fauna and Flora** (CITES) may constrain relocation initiatives.
Degree of **normative consensus** (Score 1)		Moderate-scale restoration of natural marine ecosystems and the services they provide is mostly non-controversial. Nevertheless, conflicts of interests may arise with large-scale restoration and/or relocation, depending on the changes of use that have occurred, e.g. in salt marsh reclamation.

6.3. Aggregating dimensions into a scalar governability score

Collapsing the different dimensions of governability into a single score is challenging. Generally, there is few literature that makes individual dimensions of governability comparable and if so this is done in the context of carefully designed comparative case studies that look at very similar issues (Bisaro and Hinkel, 2016). The aggregated governability scores presented here should thus be regarded as indicative.

We assigned to each solution a score between 0 and 1 for each of the above named dimensions, with 0 meaning that the dimension affects governability in a negative way and 1 meaning it affects it in a positive way. We then compute a weighted average of the scores of the individual dimensions (see Table SM6.3.1 below for a summary) and multiply the result by 5 in order to attain a value in the same range as the other aspects of global potential. Due to the lack of any argument on how to assign different weights to different dimensions, we weighted most of the dimensions equally with however two exceptions. (1) The first exception refers to the dimension of whether local net benefits of a solution (benefits minus disbenefits) outweigh local costs of implementation. According to the *realist-materialist* literature, this dimension is by far of greatest importance for global governability. If the local (i.e. national) net benefit of a solution are smaller than the local costs of implementation, then global social dilemmas of provisioning of a global collective good with the associated free-riding (PG) and over-exploitation (CPR) incentives discussed above arise. If, however, the local net benefits of a solution are estimated higher than the local costs of implementation, then these negative incentives disappear, because there is a pure local rationale for implementing solutions and the global collective good is provided as a co-benefit. Hence this dimension takes the role of distinguishing between two basic types of governance challenges, one in which states need to sacrifice something in order to contribute to the global public good and the other one in which the collective good is provided as a co-benefit to local action. We thus assigned a weight of 5 to this dimension, which means that it contributes to more than a quarter (28%) to the total governability score (see Table SM6.3.1 below). (2) The second exception refers to the two purely institutional dimensions of the assessment grid, i.e. formal and informal institutions. We assigned a weight of 3 to each of them, in order to offset the weight of biophysical dimensions (i.e. more numerous criteria).

Table SM6.3.1. *Weights applied to compute the aggregated governability score for each solution.*

Dimensions of governability			
Biophysical dimensions	**Global characteristics**	Sizeable contribution	Value computed by dividing the "effectiveness" of solutions scored in Tables 1a and 1b by 5
		Predictability	Value computed by dividing the "confidence levels" described in Tables 1a and 1b by 5
		Absence of Olsonian actor	Score of 0 if an Olsonian actor is present, and a score of 1 otherwise
		Global good is a PG	Score of 0 if the solution is a CPR and a score of 1 if it is a PG
	Local characteristics	Local benefits	Score 1 if local benefits are present, and 0 otherwise
		Predictability	Value computed by dividing the "confidence levels" described in Tables 1a and 1b by 5
		Absence of local disbenefits	Score of 1 to a solution if local disbenefits are absent and 0 otherwise
		Local net benefits > local cost of implementation	Scores 1 if local net benefits are higher than local costs of implementation, 0 if this is not the case, and 0.5 for intermediate situations
Institutional dimensions	**Formal institutions**	Enabling institutions	Score 1 if existing formal arrangements enable the implementation of a given ocean solution, 0 if they disable implementation, 0.5 if they are neutral
		Constraining institutions	
	Informal institutions	Degree of normative consensus	Score 1 when broad normative endorsement of solutions amongst all groups of actors, score 0 when controversial normative positions, score 0.5 in intermediate situations

6.4. Results

Table 2. *International governability of ocean solutions: rationale and final scores*. See: http://www.obs-vlfr.fr/~gattuso/files/supplementary_tables.xlsx.

Note that the final scores for international governability are also reported in Tables 1a and 1b.

Color legend:

- Green mean positive influence on governability (values >= 0.75)
- Red means negative influence on governability (values <= 0.25)
- Yellow means intermediate influence on governability (values >0.25 and <0.75)
- Grey means not applicable or unknown. An example of not applicable is "renewable energy" which has a 1 for lack of local benefits, hence no local benefit is listed in the cell below. Unknown corresponds to "Land-ocean hybrids" measures which are very diverse and cannot be allocated a single score.

SM4. Principal component analysis

To get a synthetic view of the attributes of the various ocean-based solutions, data were run through a principal component analysis (PCA) and grouped through hierarchical ascending clustering (HAC). The Euclidean distance between the raw scores of all solutions for all attributes was computed. PCA usually uses scaled values (centered on the mean, divided by the variance). Here, using the raw scores meant that (i) the value that we, as humans, place on an increase of 1 in the score is the same for all attributes and at any point in the scoring scale (e.g. a difference between 1 and 2 in readiness is as important as a difference between 4 and 5 in the effectiveness to moderate warming); (ii) attributes whose scores vary little among solutions have low weight in the analysis. This Euclidian distance matrix was then used to compute the PCA space. The quality of the representation of the attributes and solutions on each principal component was quantified by their squared cosine. The squared cosines for principal components 1 and 2 used in Figure 6 were summed to get the global representativity in the plane they define.

The relevance of the principal components to discriminate solutions was judged from their associated eigenvalues, which were compared to the mean eigenvalue (Kaiser-Guttman criterion) and a broken-stick model. Four principal components were retained and used for clustering. The clustering algorithm used Euclidean distance and Ward's aggregation method, in order to highlight synoptic groups. The number of groups was defined based on the aspect of the resulting tree, which unambiguously separated three main groups before a succession of short branches in each group.

The analysis was performed on the full dataset and on a reduced dataset in which attributes were averaged per ecosystem and ecosystem services. The results were very similar and only the simpler version was kept for clarity. All analyses were performed in R 3.4 (R Development Core Team, 2017) with packages FactoMineR 1.36 for PCA (Lê *et al.*, 2008), tidyverse 1.1.1 for data manipulation (Wickham, 2017), and ggplot2 2.2.1 for graphics (Wickham, 2016).

This principal components analysis was used to reduce the eight dimensions of our assessment dataset defined by the scoring criteria to two latent dimensions that explain most of the variance in the assessment data. Each latent dimension can be interpreted by looking at the criteria which contribute most to it. The first one explains 44% of total variance (Fig. SM5.1), with global governability, technological readiness and co-benefits, as well as, to a lesser extent, the duration of the effect and the level of disbenefits, contributing most to it. The second latent dimension explains 21% of total variance and reflects the potential effectiveness of the measures to reduce acidification and, to a lesser extent, warming, and their impacts on ecosystems and ecosystem services.

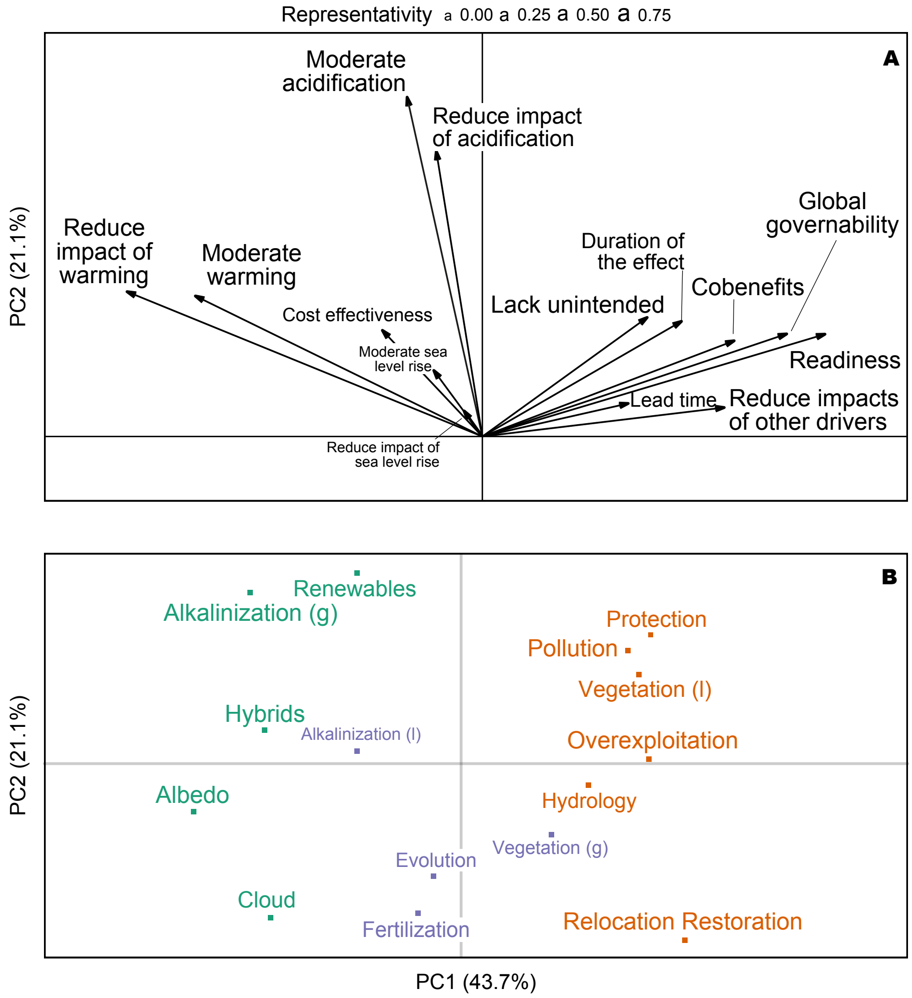

Fig. SM4.1. Principal components analysis (PCA) of the attributes of ocean-based solutions. (**A**) Correlations among criteria, some being averaged across ecosystems and ecosystem services. When two arrows point in the same direction, the criteria are correlated: the scores of most solutions are similar for these two criteria (e.g. both warming-related criteria, co-benefits and readiness). When they point in opposite directions, criteria are anti-correlated (e.g. moderate warming and global governability). When they are perpendicular, criteria are uncorrelated (e.g. acidification-related criteria and readiness). (**B**) Positions of solutions in the PCA. Solutions on the right have high scores in the criteria that point to the right and low scores in the attributes that point to the left; a similar reasoning can be made for any direction in this space. Solutions are clustered into three groups, through hierarchical clustering based on their position in the PCA space, and coloured accordingly. The first two principal components explain 65% of the variance in the attributes of ocean-based solutions. Attributes or solutions that are not well represented in this space are shown in smaller font (representativity = "Repr." varies between 0 and 1). See SM5 for details on the PCA approach, and SM3 and 4 for additional information on the assessment.

SM5. References

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