**Benthic-based contributions to climate change mitigation and adaptation**

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**Innovative solutions to improve the condition and resilience of ecosystems are needed to address societal challenges and pave the way towards a climate-resilient future. Nature-based solutions offer the potential to protect, sustainably manage, and restore natural or modified ecosystems whilst providing multiple other benefits for health, the economy, society and the environment. However, the implementation of nature-based solutions stems from a discourse that is almost exclusively derived from a terrestrial and urban context and assumes that risk reduction is resolved locally. We argue that this position ignores the importance of complex ecological interactions across a range of temporal and spatial scales and misses the substantive contribution from marine ecosystems, which are notably absent from most climate mitigation and adaptation strategies that extend beyond coastal disaster management. Here we consider the potential of sediment-dwelling fauna and flora to inform and support nature-based solutions, and how the ecology of benthic environments can enhance adaptation plans. We illustrate our thesis with examples of practice that are generating, or have the potential to deliver, transformative change and discuss where further innovation might be applied. Finally, we take a reflective look at the realized and potential capacity of benthic-based solutions to contribute to adaptation plans and offer our perspectives on the suitability and shortcomings of past achievements and the prospective rewards from sensible prioritization of future research.**

**This article is part of the theme issue ‘Climate change and ecosystems: threats, challenges and the role of nature-based solutions’.**

**1. Introduction**

The effects of anthropogenic activity and climate change are becoming so pervasive that there is wide recognition that human intervention is needed to both mitigate climate change and to promote adaptation [1]. In response, many countries are contemplating, or beginning to implement, ambitious adaptation plans [2] that include a portfolio of natural and nature-based solutions, an umbrella concept [3-5] that builds on approaches that collectively use the features and complex system processes of ecosystems to achieve multiple benefits for nature, the economy and society [6-8]. Although the concept of nature-based solutions is gaining momentum, and is undergoing a process of maturation [9-11], emphasis has largely been placed on context-specific actions aimed at improving broad, and often unspecified [12], aspects of urban regeneration [13], energy demand [14] or well-being [15], disaster management and resilience [16], carbon storage [17] or physical coastal protection [18-22]. Whilst these actions have merit because they can lead to beneficial outcomes, substantial scientific evidence for the interconnectivity of ecosystems [23-25], and an awareness that the provision of ecosystem services is not restricted to areas within arbitrarily defined boundaries [26], means that efforts to improve resilience to climatic related phenomena fall short of their potential as the default is to assume that ecosystem services are spatio-temporally constrained. Contributions from natural systems located beyond the immediate vicinity of highly populated areas tend to be overlooked [27]. In these instances, what is often forgotten is that the social and economic spatial scale at which positive outcomes are realized can extend beyond the physical spatial scale of ecosystem processes or habitats. Storm protection by saltmarshes and mangroves, for example, can provide protection from inclement conditions in the immediate vicinity, but can also benefit populations situated further inland by preventing storm surges, salination or inland flooding [28], thereby minimizing follow-on social and governance challenges that tend to accumulate in the wake of a storm. Failure to recognize the contribution of ecosystems beyond the focal area, at least in part, stems from a predisposition to consider familiar habitats that people routinely interact with as being key to the solution, whilst disregarding habitats that are more inconspicuous, seldom or indirectly accessed, or otherwise catalogued as unconnected. It is easier to comprehend, and therefore to effectively manage, interactions between ecosystems, or between social and ecological systems that are proximally located, and considerably more difficult to understand the multiple steps that may link distant systems. Yet the effects of climate change are global, and systems are linked across time and space, which together, demand a comprehensive response. As public scrutiny of the extent and effectiveness of political action increases [29] and the need to meet adaptation targets intensifies [30], the appetite to accelerate and scale-up instances of transformative change is growing [31] and provides impetus to explore the potential of underutilized or previously untapped natural resources.

Oceans exert a major control on global climate [32] and they connect disparate ecosystems in ways that can shape how climatic forcing is expressed across entire terrestrial and marine regions [33]. They are also vast and, therefore, offer great potential to contribute to safeguarding the resilience of humanity [34], already absorbing greater than 90% of the excess energy in the climate system [35] and greater than 30% of anthropogenic CO2 emissions [32], as well as contributing negative feedbacks to counteract the effects of warming at higher latitudes [36]. Yet, with the exception of the use of habitat forming assemblages to counter coastal wave and wind action (e.g. sand dunes, coral reefs, reef-forming bivalves, seaweed and seagrasses, salt marsh vegetation, mangroves; reviewed in refs. [37-39]), the broader role of marine habitats in mitigating or avoiding other climate change impacts has received much less attention. Offshore soft sediment ecosystems, in particular, are not a prominent feature of the nature-based solutions narrative, despite the fact that much of the *prima facie* evidence for the effectiveness of eco-engineering to support mitigation measures emanates from, an albeit small proportion of, benthic habitats [40]. This oversight is surprising, as marine sediments cover an area greater than all other habitats on Earth combined [41] and can host impressive levels of biodiversity (coast, 803 species in 10 m2 [42]; deep sea, 798 species in 21 m2 [43]) that regulate biogeochemical cycling [44], climate active gases [45], ocean chemistry [46], and the long-term removal of carbon from the ocean-atmosphere system [47-48]. Indeed, the effects of warming [49], acidification [50], deoxygenation [51], sea-level rise [52], and their interactions [53], can be appreciably modified by the particle reworking and ventilatory behaviour of sediment-dwelling invertebrates and, depending upon the seasonal timing of extreme climatic events, their activities can either exacerbate, buffer or alleviate the long-term directional effects of forcing [54]. However, the capacity of benthic environments to continue to moderate change in this way is being challenged on an industrial scale by a multitude of human pressures [55] that can frustrate biodiversity-function relations [56-57]. This immediately raises the question of whether coastal and offshore benthic environments could be better managed to temper the effects of climatic associated events and minimize CO2 emissions at particular times of the year, or for a specific set of circumstances, and, if so, encourage processes of innovation that could usefully contribute to mitigation and adaptation pathways? To initiate this conversation, here we briefly review the potential for benthic systems to prevent, mitigate or enhance the impacts of climatic forcing, highlighting theory and practice that show most promise given the long-term effects anticipated prior to, and beyond, climate stabilization [58]. As the major responses of benthic systems to climate change have been extensively covered elsewhere [59], we restrict our review to the consideration of species-climatic forcing interactions that are amenable to management and most likely to make a difference to mitigation obligations.

**2. Harnessing the benthos**

Adaptation to climate risks that can no longer be avoided is fundamental to the global response to climate change, but it is clear that the articulation of adaptive measures is more exercised in safeguarding the continuity and economic viability of certain sectors through changes in practice (e.g. farming and fishing [60]), than it is in widening the adaptation search space to incorporate the influence of environment and ecology that can alter overall levels of resilience [61-62]. In the marine benthos, the latter might include the conservation, restoration or management of functionally important species and ecosystem processes [63], improving the growth and phenotypic/genotypic potential of commercial species (algae, crustaceans, molluscs and fish) under climate change [64], or the repositioning of aquaculture or fishing activity to regions that offer buffering capacity from warming or acidification [65-66]. There is also scope for using benthic environments to contribute to terrestrial based problems, such as supplementing cattle food with algal derivatives to lower methane production [67]. Most of these strategies are in their infancy, or not yet established, and, whilst the frameworks and principles of adaptation planning are routinely presented in the scientific literature, there are a limited number of examples where adaptation actions have been physically implemented and formally evaluated [68-69]. Moreover, the current repertoire of species, habitats and intervention possibilities considered is limited. Nonetheless, the literature base necessary to support the development of adaptation measures exists and is building for many species and habitats; for example, we have a good idea of the pace [70] and spatio-temporal expression [71] of climate change, which species are most vulnerable to ocean acidification and warming [72-73], what engineering materials [74] and habitat configurations [20,75] are most eco-beneficial, and the location of benthic communities likely to contribute most to nutrient and carbon dynamics [76]. We also have some understanding of the feedbacks associated with changes in species behaviour and species interactions in naturally assembled communities under future climate scenarios [57], and how context-specific system attributes and local management can moderate impact [54,77]. Despite the availability of the evidence, it has seldom been collated and expressed in this way for a benthic setting. It is our view that the assembly of such information, and other similar narratives, will be scientifically instructive and form an invaluable resource for decision-makers tasked with relocating people or business, establishing or diversifying sources of food or income, or when performing cost-benefit analyses prior to changing practice to improve sustainability.

Whilst exemplars of adaptation are in short supply for offshore marine systems, interventions to mitigate against the effects of climate related change are more common, but conclusions are mixed and lack consensus [78]. In the marine benthos, most work has involved the management of nutrients to control the export and sequestration of carbon (reviewed in ref. [79]) and has focused around the use of saltmarsh, macroalgae, mangroves, seagrass and shellfish. Notably, these include the dominant primary producers in coastal habitats which, following detachment, can be sequestered in offshore sediments, including the deep sea [80], a fraction that is often missed from global budgets. However, the provenance and fate of vegetated ecosystems are largely unknown because the contribution of different primary producers to organic carbon and nutrient pools in depositional marine environments has not been distinguished [81]. In coastal and shelf regions, longline mussel farming is emerging as a tool to remove nutrients and counteract the negative effects of eutrophication, whilst also providing food, local employment and other environmental and economic benefits [82]. Early indications are that full-scale mitigation cultures can achieve a higher impact on basin-scale water quality parameters than equivalent land-based measures [83], but mussel farms are not necessarily a cost-effective option relative to other abatement measures [84]. They also generate additional environmental impacts, such as excessive enrichment of the seafloor through faecal pellet production, that require supplementary remedial solutions which, ironically, could be tackled by introducing bioturbating fauna to enhance organic matter decomposition [85]. An alternative mitigation mechanism is restoration of mussel, oyster or other bivalve populations, as shellfish reefs contain significant pools of carbon, facilitate atmospheric CO2 drawdown via filtration and biodeposition [86-87], and also seem to reduce coastal flood risk cost relative to complementary grey (structural) or policy measures [88]. The success or otherwise of such ventures is, however, often viewed through the lens of a small subset of response variables. Should a more holistic view of farmed or restored shellfish reefs be quantified and monetized, expenditure on such mitigation options may promote public subsidy and hasten investment and trading mechanisms that will lead to their growth [89]. Indeed, concepts such as living shorelines, where multiple habitats are engineered together to provide multiple benefits, are rapidly emerging (e.g. the coastal CO2 removal belt in Korea [69]), but maximizing habitat structure does not necessarily result in higher levels of function or enhanced multiple benefits as is so often assumed [90].

Interventions to mitigate the consequences of climate change hold much promise in offshore sediment systems, as concepts of ecological succession, habitat recovery [91-93] and ecosystem engineering [94-95] are particularly well developed (figure 1), and the functional role of fauna are well known and can be applied generically [96]. This presents the possibility of controlling bioturbation to prevent carbon loss or enhance carbon sequestration, modify sediment erosion thresholds, or generate hotspots of climatically beneficial activity through the introduction or removal of specific species from targeted functional groups [85]. Emissions of carbon dioxide, nitrous oxide and methane linked to the formation of biogenic mounds have been resolved at a local level by modifying tidal flushing regimes to deter mound-building species and by direct control of specific populations [97-98]. Manipulations such as these tend to focus on positive species interactions that reinforce ecosystem processes [38,99], but there are also examples of using negative species interactions to improve restoration outcomes. For example, the antagonistic relationship between the sediment-destabilising lugworm *Arenicola marina* and the sediment-stabilizing seagrass *Zostera noltii* can be moderated by adding a shell layer below seagrass transplants to reduce lugworm density and restore sediment stability to preferentially support the proliferation of seagrass, thereby reducing ocean acidification through growth related CO2 removal [100]. Indeed, there are numerous examples in the literature that are reinterpreting species interactions within a climate solutions framework but, while most offer intuitive and credible actions, they lack ambition in terms of being of sufficient scale to make meaningful contributions to climate mitigation. Larger scale interventions will require different approaches that move beyond individual species. It is known that sediment dwelling invertebrates are important in modulating carbon mineralization pathways [101], and that they promote the turnover and influence the fate of carbon [102] at large scales and in response to climate fluctuations [103]. It follows, therefore, that as ocean warming is set to increase stratification and decrease nutrient availability of mid-ocean surface waters, decreases in carbon sequestration linked to reduced particulate organic carbon export from the euphotic zone to the deep ocean could be moderated through the adjustment of deposit feeding communities [104] or via iron fertilization [105]. The latter exploits the persistence of high-nitrate, low-chlorophyll conditions in the surface waters of several large regions of the world, where various micronutrients required for photosynthesis are in low concentration. Release of limiting nutrients, such as iron, results in phytoplankton blooms that quiesce and then fall to the seafloor. Whilst high levels of carbon drawdown have been documented over the short-term (reviewed in ref. [106]), iron fertilization may only be worthwhile if sustained over millennial timescales [107]. It is already clear, however, that the process can generate other negative climate and ecosystem consequences, including the production of additional greenhouse gases, increased oxygen consumption leading to hypoxia, toxic algal blooms and fundamental changes to benthic ecosystem structure [106,108-109]. Indeed, evaluations of other large scale climate engineering methods, such as artificial ocean upwelling, alkalinization and solar radiation management, yield similar lists of secondary effects that have not been fully appraised [110]. Further, as has been shown for the renewable energy and energy extraction sectors, both positive and negative effects can extend for hundreds of kilometres from the point of origin [111] and are likely to go undetected in the absence of appropriate monitoring programmes [112-113].

Much of the effort diverted to establishing mitigation opportunity has so far been directed at long term sustainability, but with the advent of more intense and more frequent extreme climatic events it is equally important to develop short-term coping strategies. Evidence is emerging that the protection of designated areas of marine habitat can form a significant component of local and global adaptation strategies [114] by increasing the resilience of species to extreme events. Unexploited invertebrate species within a protected area grow larger and are more resistant to deviations in temperature, and they can provide larval spillover across the edges of the reserves to expedite recovery in areas that have been affected [115]. Reserves free from bottom fishing activity also tend to establish habitat forming assemblages, which can be important in forming refugia for stress susceptible species by altering the surrounding microclimate [77]. For instance, macrophyte photosynthetic activity buffers calcifying organisms from ocean acidification [116], whilst the canopy of dense stands attenuate flow, shade light and reduce temperature for the associated community. Analogous phenomena occur within soft sediment communities, where tube building polychaetes attenuate flow and stabilize the sediment [117] and infaunal bioirrigation behaviour alleviates oxygen, biogeochemical and temperature variation within the sediment profile [49,57]. However, the relief that facilitative activities can exert under times of stress are recognized and generally accepted, but have seldom been interrogated within an extreme event context [118]. Post-event interventions, such a transplanting species or building corridors to connect populations, lack examples of application, but form plausible temporary solutions for benthic environments that should be further explored and investigated.

**3. Bright spots in the benthos**

The pace of climate change demands the rapid adoption of pathways to transformative change, best achieved by drawing on existing experiences from a diversity of practices, worldviews, values, and regions. Examples of good practice that are positive, sustainable, and scalable exist and are well documented [31], but examples from marine systems are scarce, constrained in scope, and are often viewed independently from other systems. Moreover, the vast majority of exemplar studies stem from coastal protection projects that follow a ‘rebuild by design’ philosophy, where the risk of wave and flood exposure is minimized by establishing a wide area or buffer zone that consists of multiple habitat types (e.g. low vs high salt marsh habitat, shrubland, mud flat, beach, dune, reefs, barrier islands) designed and configured to provide multi-layered protection whilst enhancing environmental, economic and social benefits [20]. Reliance on this limited set of marine examples, however, may mean that we are missing out on the capacity to fully harness the potential for change in the way benthic systems are governed to help with rapid adaptation to, and mitigation of, climate change. Some efforts can be quite elaborate and consider multiple components of the ecosystem or involve multiple ecosystems [20,69,119], but success or otherwise often relates to the directional change in a limited number of parameters and does not involve the necessary follow up to fully assess the wider consequences of action [112,113]. Nevertheless, there are a number of scalable benthic based solutions that are subsidiary to these larger projects, but have merit as they have characteristics that may reduce ecological footprints, improve resource management and biodiversity conservation, increase the sustainability of food production or improve equitable access to resources [31]. For example, suspension feeding bivalves optimized to mitigate eutrophication and nutrient loading are cost-efficient relative to land-based measures whilst providing local employment and, in some cases, a harvestable product [120-121]. Shrimp and fish are being farmed in closed recirculation systems on land with no discharge, achieved using biodegradable biopolymers to absorb waste products [122]. Such systems provide food security as well as economic and social benefits, such as social cohesion, educational value and livelihood enrichment [123]. Similarly, bioengineered breakwaters and living shorelines are emerging with multiple benefits, such as reducing flood risks and mitigating the loss of intertidal and shallow water biodiversity whilst offering recreational value [20].

**4. Getting it right**

We have argued that benthic communities offer a variety of social, economic and environmental opportunities as society adapts to climate change. Yet, realizing these benefits requires management to, firstly, establish the most likely consequences of climate-related change, and secondly, to do so across a broad range of spatial and temporal scales. To date, the role of sediment communities in climate mitigation has largely been considered as part of a wider debate about the negative consequences of human activities, such as bottom fishing, where it has been convenient to include discussion about using marine protected areas as climate refugia [114,124]. Such an approach does not put climate change at the heart of the design and, whilst implementation of an MPA may be practical at large scales (greater than hundreds of kilometers), plans will need to be sympathetic to needs of multiple users if they are to be accepted and effective in the long term. This problem is illustrated by the findings of a recent model concerning the adaptation of benthic species’ to climate change, which found that locating MPAs in cool refugia was a relatively unsuccessful strategy [125]. Rather, establishing MPAs that allow sufficient larval dispersal between warmer and cooler areas is more likely to facilitate natural adaptation. Current regional conservation plans typically protect areas that exhibit low levels of vulnerability to climate change and disregard how species may redistribute as climate change advances [126].

Climate change adaptation is, of course, a major rationale for the surge of interest in benthic habitat restoration [4]. Yet theory over how such restoration should be planned remains in its infancy. There are two key siting considerations, which may prove to be incompatible and involve strong tradeoffs. The first is simply where should restoration be placed to maximise its sustainability? Answering this question is not entirely straightforward because it depends on the outcome of the interactions of multiple components of the system [127], as well as the effect of habitat configuration [75, 128] and environmental setting [129-130]. The second asks where restoration can have the greatest spillover benefits to connected ecosystems [131]. Such benefits include the spillover of larvae to replenish damaged habitats elsewhere, but the extent to which this occurs has not been widely determined [132], especially in the deep ocean [133]. Lagrangian models of connectivity have been combined with network theory to identify local populations that play an exceptionally important role in resupplying other locations. For example, it is estimated that 3% of reefs comprising Australia’s Great Barrier Reef can resupply corals to almost half of the entire ecosystem within a single summer spawning event [134]. Identifying such population sources and the networks of dispersal provides an entry point to tailoring restoration where it can be most effective, but *a priori* assumptions about dispersion capability and habitat suitability are not always verified and can lead to surprises that require restoration plan adjustments [135]. In both cases, the majority of the research has focused on biological and ecological considerations; there has been much less focus on social-ecological or governance considerations.

An important point about ‘getting it right’ is that increased investment in management, both to support practical application of interventions and to maintain appropriate post-intervention monitoring and evaluation [112,113], is likely to be critical as climate impacts strengthen. Yet, there are a variety of reasons why governments might be tempted to reduce investments into the management of benthic ecosystems [136]. These include a lack of clarity about appropriate solutions, perceived futility of local interventions, short-termism in extracting a declining resource, the perception that management is unsuccessful because ecosystem state continues to decline (which can be addressed by using appropriate counterfactuals for the system state with less management), and difficulties with suitability of legislation that is not always formulated adequately to protect the benefits most valued by people [137]. The out-of-sight and data deficient [138] nature of much of the marine environment, coupled with differences in perspectives between terrestrial and marine ecologists [139], compounds these problems. Our focus on benthic ecosystem functions can be translated into ecosystem services by focusing on the benefits that benthic restoration would provide for people [140]. However, we should also be careful not to oversell the utility of taking an ‘ecosystem services’ approach to the selection and management of benthic ecosystem functions. In many cases, alternative ecosystem service values are so disparate that they can only be reconciled through somewhat arbitrary rescaling of values. For example, an insightful analysis of the value of benthic habitat for fisheries versus wave energy generation required fisheries values to be multiplied by a factor of 50 in order to create a ‘level playing field’ [141].

**5. Thinking big**

Whilst many of the examples of nature-based solutions concern proof of concept studies over relatively small spatial scales, it is clear that for the potential of these interventions to be fully realized, they must be implemented over the range of interacting scales within which marine social-ecological systems function (figure 2). The process of scaling up may be fiscally or politically challenging but, more fundamentally, the survey and monitoring required to formulate a nature-based solution can be highly intensive and time consuming [142]. Remote sensing techniques (including satellite, airborne, boat and autonomous vehicle-based sensors; figure 2a) have been shown to be highly effective for large scale monitoring of benthic communities and habitats, including coral reefs [143] and large expanses of the deep ocean [144]. These techniques also provide the opportunity to link across scales, for example from individual to community to regional and beyond, recognizing that one scale of monitoring will unlikely be able to capture all data required to assess the changing nature of our benthic habitats. Many of the factors (e.g. physical process, infrastructure, climate and weather) that influence the decision of what type of intervention to make and where to site it can be remotely sensed [145] and we argue that in doing so, we are able to better map onto the physical impacts and socio-economic scales related to climate change (figure 2b). As an example, remote sensing has been used in conjunction with ground truthing surveys for example to design Marine Protected Areas [146]. The large spatial coverage and high temporal frequency of collection (figure 2a), makes remote sensing techniques an ideal tool for the routine survey and identification of benthic communities and habitats, including ongoing monitoring of nature-based solutions at management and policy relevant scales.

**6. Research priorities**

Opportunities for enhanced socio-ecological resilience and planning and more informed decision-making within the benthic arena seem rife, but there is a need to (i) formulate basic science in support of best practice, including the interrogation of realized levels of risk reduction and routine follow-up checks that can identify maladaptive outcomes, and (ii) establish effective participatory processes with implicated stakeholders that maximise engagement and lead to the co-design of solutions [147]. Realization of a coherent plan is embryonic, in part because of compartmentalized funding streams and the interdisciplinary nature of the problems society now faces, but also because the case for the benthos has not been strongly articulated. It can be especially hard, for example, to identify relevant stakeholders when systems are distantly located and the links required to connect from the system to the stakeholders are multiple. Whilst we acknowledge the challenges that lie ahead, decision-makers nevertheless need credible and relevant information to inform regional and national responses to climate change. Hence, for the benthos, we see an immediate and urgent need to:

1. *Establish, extend and diversify knowledge about the contributions that benthic communities make in relation to greenhouse gases, carbon sequestration and storage and other climate change related measures.*

Whilst we have good information on how species in coastal habitats can contribute to aspects of climate change mitigation, focus is constrained to a limited number of unspecified climatic driven problems and the role of offshore and deep ocean benthic communities is woefully under-represented.

1. *Divert effort away from replication of known species and ecosystem responses to climate change and, instead, seek novelty by identifying species and ecosystem effects on climatic variables with a view to identifying scalable benthic-based mitigation measures.*

Specific pathways from species and ecosystem properties to mitigative effects need to replace generic assumed benefit. Such an exploration will need to understand and integrate how social and economic drivers influence what is acceptable to people, and the preferences and motivations of multiple stakeholders and beneficiaries.

1. *Provide evidence to support or refute untested or underdeveloped ideas, including full scale trials and field tests supported by appropriate monitoring.*

A fundamental requirement of legislation, decision making and policy development is cross sectoral evidence tempered by an assessment of confidence. Yet, many proposed mitigation solutions, including genetic modification [148], assisted evolution, transplantation of species, biodiversity offsetting, and ecoengineering or other large-scale manipulations have not been interrogated or explicitly tested within a benthic context.

1. *Transition from highlighting important issues for science to address to formulating a partnership model of science-society that encompasses governance and socio-ecological challenges*.

The consequences of climate change for species, ecosystems and human society are disproportionately represented in the marine literature. Less attention has been devoted to delivering an integrated marine management plan that incorporates an appropriate framework for stakeholder identification and engagement [147].

1. *Investigate the linkages between benthic restoration and impacts on stakeholders, including those that consist of multiple steps between benthic change and the most desirable outcome.*

We often have limited understanding of how system changes impact key stakeholders. Yet, developing a qualitative and, where possible, quantitative understanding of the identity, composition and timing of pathways that lead to alternative outcomes is necessary to set and achieve sensible long-term restoration objectives.

In order to accomplish this research agenda, a consortium enterprise and a change of culture is needed to find meaningful solutions to the climate crisis, requiring interdisciplinary and international collaboration to seek measures that can be tested and applied. Practical applications need to be embraced and investigators need to work with institutions and agencies in order to identify research priorities and move solution orientated debate forward in a positive manner [149-150].

**7. Conclusions**

Adapting to climate change is contingent on being able to respond to the effects of climate-change impacts with meaningful countermeasures. Natural and nature-based solutions have been presented as a multifunctional, solution-oriented approach to increasing sustainability and have rapidly become the *de facto* means to alleviate or avoid the consequences of climate change. Marine benthic systems have been instrumental in many of the mitigation and adaptation plans already proposed, but our analysis suggests that significant further benefit can be derived from consideration of shelf and deep ocean environments. Progression in this area, however, will demand a shift in attention to the role of benthic species and habitats that are presently unrepresented, especially on the shelf, in the deep ocean and at higher latitudes. It also will require an emphasis on using technology and new ways of processing data to address questions at climatic and societal relevant scales. The importance of temporal and spatial scale, both in terms of the application of an intervention and in relation to any unforeseen negative outcomes cannot be emphasized enough. We conclude, however, that within this space many of the tools required are already present, theory and mechanistic understanding is well developed, and that there are the appropriate foundations to deliver a rich and fruitful research agenda capable of contributing to the development of a structured and holistic plan of enactment.

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**References**

1. Ripple WJ, Wolf C, Newsome TM, Galetti M, Alamgir M, Crist E, Mahmoud MI, Laurance WF. 2017 World scientists' warning to humanity: A second notice. Bioscience **67**, 1026-1028. (doi: 10.1093/biosci/bix125)
2. Stone R. 2018 Cuba's 100-year plan for climate change. Science **359**, 144-145. (doi: 10.1126/science.359.6372.144)
3. Anonymous. 2017 Natural language: the latest attempt to brand green practices is better than it sounds. Nature **541**, 133-134.
4. Anthony K, Bay LK, Costanza R, Firn J, Gunn J, Harrison P, Heyward A, Lundgren P, Mead D, Moore T. *et al*. (2017) New interventions are needed to save coral reefs. Nature Ecol. Evol. **1**, 1420-1422. (doi: 10.1038/s41559-017-0313-5)
5. Albert C, Spangenberg JH, Schröter B. 2017 Nature-based solutions: criteria. Nature **543**, 315-315. (doi: 10.1038/543315b)
6. Faivre N, Fritz M, Freitas T, de Boissezon B, Vandewoestijne S. 2017 Nature-Based Solutions in the EU: Innovating with nature to address social, economic and environmental challenges. Environ. Res. **159**, 509–518. (doi: 10.1016/j.envres.2017.08.032)
7. Nesshöver C, Assmuth T, Irvine KN, Rusch GM, Waylen KA, Delbaere B, Haase D, Jones-Walters, L, Keune H, Kovacs E. *et al.* 2017 The science, policy and practice of nature-based solutions: An interdisciplinary perspective. Sci. Total Environ. **579**, 1215–1227. (doi: 10.1016/j.scitotenv.2016.11.106)
8. Zwierzchowska I, Fagiewicz K, Poniży L, Lupa P, Mizgajski A. 2019 Introducing nature-based solutions into urban policy – facts and gaps. Case study of Poznań. Land Use Policy **85**, 161-175. (doi: 10.1016/j.landusepol.2019.03.025)
9. Luederitz C, Brink E, Gralla F, Hermelingmeier V, Meyer M, Niven L, Panzer L, Partelow S, Rau AL, Sasaki R *et al*. 2015. A review of urban ecosystem services: six key challenges for future research. Ecosystem Services **14**, 98-112. (doi: 10.1016/j.ecoser.2015.05.001)
10. Davies C, Lafortezza R. 2019 Transitional path to the adoption of nature-based solutions. Land Use Policy **80**, 406–409. (doi: 10.1016/j.landusepol.2018.09.020)
11. Frantzeskaki N. 2019 Seven lessons for planning nature-based solutions in cities. Environ. Sci. Policy **93**, 101–111. (doi: 10.1016/j.envsci.2018.12.033)
12. van Oudenhoven APE, Aukesb E, Bontjec LE, Vikolainend V, van Bodegoma PM, Slinge JH. 2018 ‘Mind the Gap’ between ecosystem services classification and strategic decision making. Ecosystem Services **33**, 77–88. (doi: 10.1016/j.ecoser.2018.09.003)
13. Song YA, Kirkwood N, Maksimovic C, Zhen XD, O'Connor D, Jin YL, Hou DY. 2019 Nature based solutions for contaminated land remediation and brownfield redevelopment in cities: A review. Science Tot. Environ. **663**, 568-579. (doi: 10.1016/j.scitotenv.2019.01.347)
14. TakakuraT, Kitade S, Goto E. 2000 Cooling effect of greenery cover over a building. Energy and Buildings **31**, 1–6. (doi: 10.1016/S0378‐7788(98)00063‐2)
15. Hartig T, Kahn Jr. PH. 2016 Living in cities, naturally. Science **352**, 938-940. (doi: 10.1126/science.aaf3759)
16. Mabon L. 2019 Enhancing post-disaster resilience by ‘building back greener’: Evaluating the contribution of nature-based solutions to recovery planning in Futaba County, Fukushima Prefecture, Japan. Landscape and Urban Planning **187**, 105-118. (doi: 10.1016/j.landurbplan.2019.03.013)
17. Howard J, McLeod E, Thomas S, Eastwood E, Fox M, Wenzel L, Pidgeon E. 2017 The potential to integrate blue carbon into MPA design and management. Aquat. Conserv. **27**, 100-115. (doi: 10.1002/aqc.2809)
18. Temmerman S, Meire P, Bouma TJ, Herman PMJ, Ysebaert T, De Vriend HJ. 2013 Ecosystem-based coastal defence in the face of global change. Nature **504**, 79-83 (doi: doi:10.1038/nature12859)
19. Kabisch N, Frantzeskaki N, Pauleit S, Naumann S, Davis M, Artmann M, Haase D, Knapp S, Korn H Stadler J. 2016 Nature-based solutions to climate change mitigation and adaptation in urban areas: perspectives on indicators, knowledge gaps, barriers, and opportunities for action. Ecology and Society **21**, 39. (doi: 10.5751/ES-08373-210239)
20. Moosavi S. 2017 Ecological coastal protection: pathways to living shorelines. Procedia Engineering 196, 930 – 938. (doi: 10.1016/j.proeng.2017.08.027)
21. Möller I. 2019 Applying uncertain science to nature-based coastal protection: Lessons from shallow wetland-dominated shores. Front. Environ. Sci. **7**, 49. (doi: 10.3389/fenvs.2019.00049)
22. Leo KL, Gillies CL, Fitzsimons JA, Halee LZ, Beckf MW. 2019 Coastal habitat squeeze: A review of adaptation solutions for saltmarsh, mangrove and beach habitats. Ocean and Coastal Management 175, 180–190. (doi: 10.1016/j.ocecoaman.2019.03.019)
23. Saunders MI, Leon JX, Callaghan DP, Roelfsema CM, Hamylton S, Brown CJ, Baldock T, Golshani A, Phinn SR, Lovelock CE. *et al*. 2014 Interdependency of tropical marine ecosystems in response to climate change. Nature Climate Change **4**, 724-729. (doi: 10.1038/nclimate2274)
24. Soliveres S, van der Plas F, Manning P, Prati D, Gossner MM, Renner SC, Alt F, Arndt H, Baumgartner V, Binkenstein J. *et al.* 2016 Biodiversity at multiple trophic levels is needed for ecosystem multifunctionality. Nature **536**, 456–459. (doi: 10.1038/nature19092)
25. Buckner EV, Hernandez DL, Samhouri JF. 2018 Conserving connectivity: Human influence on subsidy transfer and relevant restoration efforts. Ambio 47, 493-503. (doi: 10.1007/s13280-017-0989-4)
26. Mitchell MGE, Bennett EM, Gonzalez A. 2013 Linking landscape connectivity and ecosystem service provision: current knowledge and research gaps. Ecosystems 16, 894-908. (doi: 10.1007/s10021-013-9647-2)
27. Howard J, Sutton-Grier A, Herr D, Kleypas J, Landis E, Mcleod E, Pidgeon E, Simpson S. 2017 Clarifying the role of coastal and marine systems in climate mitigation. Front. Ecol. Environ. 15, 42–50. (doi: 10.1002/fee.1451)
28. Barbier EB, Koch EW, Silliman BR, Hacker SD, Wolanski E, Primavera J, Granek EF, Polasky S, Aswani S, Cramer LA. *et al*. 2008 Coastal ecosystem-based management with nonlinear ecological functions and values. Science **319**, 321-323. (doi: 10.1126/science.1150349)
29. Warren M. 2019 Thousands of scientists back kids' climate strike. Nature **567**, 291-292 (doi: 10.1038/d41586-019-00861-z)
30. Overpeck JT, Conde C 2019 A call to climate action. Science **364**, 807. (doi: 10.1126/science.aay1525)
31. Bennett EM, Solan M, Biggs R, McPhearson T, Norstrom AV, Olsson P, Pereira L, Peterson GD, Raudsepp-Hearne C, Biermann F. *et al*. 2016 Bright spots: seeds of a good Anthropocene. Front. Ecol. Environ. **14**, 441–448. (doi: 10.1002/fee.1309)
32. Gruber N, Clement D, Carter BR, Feely RA, van Heuven S, Hoppema M, Ishii M, Key RM, Kozyr A, Lauvset SK. *et al*. 2019 The oceanic sink for anthropogenic CO2 from 1994 to 2007. Science **363**, 1193–1199. (doi: 10.1126/science.aau5153)
33. Zuercher R, Galloway AWE. 2019. Coastal marine ecosystem connectivity: pelagic ocean to kelp forest subsidies. Ecosphere **10**, e02602. (doi: 10.1002/ecs2.2602)
34. Visbeck M 2018 Ocean science research is key for a sustainable future. Nature Comms. **9**, 690. (doi: 10.1038/s41467-018-03158-3)
35. Rhein M, Rintoul SR. Observations: Ocean. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds.)]. (Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA), pp. 255–316.
36. Peck LS, Barnes DKA, Cook AJ, Fleming AH, Clarke A. 2010 Negative feedback in the cold: ice retreat produces new carbon sinks in Antarctica. Global Change Biol. **16**, 2614–2623. (doi: 10.1111/j.1365-2486.2009.02071.x)
37. Macreadie PI, Nielsen DA, Kelleway JJ, Atwood TB, Seymour JR, Petrou K, Connolly RM, Thomson ACG, Trevathan-Tackett SM, Ralph PJ. 2017 Can we manage coastal ecosystems to sequester more blue carbon? Front. Ecol. Environ. **15**, 206–213. (doi:10.1002/fee.1484)
38. Bulleri F, Eriksson BK, Queiros A, Airoldi L, Arenas F, Arvanitidis C, Bouma TJ, Crowe TP, Davoult, D, Guizien K. *et al*. (2018) Harnessing positive species interactions as a tool against climate-driven loss of coastal biodiversity. PLoS Biol. **16**, e2006852. (doi: 10.1371/journal.pbio.2006852)
39. Morris RL, Konlechner TM, Ghisalberti M, Swearer SE. 2018 From grey to green: Efficacy of eco-engineering solutions for nature-based coastal defence. Glob Change Biol. **24**, 1827–1842. (doi: 10.1111/gcb.14063)
40. Narayan S, Beck MW, Reguero BG, Losada IJ, van Wesenbeeck B, Pontee N, Sanchirico JN, Ingram JC, Lange GM, Burks-Copes KA. 2016 The effectiveness, costs and coastal protection benefits of natural and nature-based defences. PLOS One **11(5)**, e0154735. (doi: 10.1371/journal.pone.0154735)
41. Snelgrove PVR. 1999 Getting to the bottom of marine diversity: sedimentary habitats. Bioscience **49**, 129-138. (doi: 10.2307/1313538)
42. Coleman N, Gason ASH, Poore GCB. 1997 High species richness in the shallow marine waters of south east Australia. Mar. Ecol. Prog. Ser. **154**, 17-26. (doi: 10.3354/meps154017)
43. Grassle JF, Maciolek NJ. 1992. Deep-sea species richness: regional and local diversity estimates from quantitative bottom samples. Am. Nat. 139, 313-341. (doi: 10.1086/285329)
44. Snelgrove PVR, Soetaert K, Solan M, Thrush S, Wei C-L, Danovaro R, Fulweiler RW, Kitazato H, Ingole B, Norkko A *et al*. Global carbon cycling on a heterogeneous seafloor. Trends Ecol. Evol. **33**, 96-105. (doi: 10.1016/j.tree.2017.11.004)
45. Bonaglia S, Bruchert V, Callac N, Vicenzi A, Fru EC, Nascimento FJA. 2017 Methane fluxes from coastal sediments are enhanced by macrofaunal. Sci. Rep. **7**, 13145. (doi: 10.1038/s41598-017-13263-w)
46. Wenzhofer F, Adler M, Kohls O, Hensen C, Strotmann B, Boehme S, Schulz HD. 2001 Calcite dissolution driven by benthic mineralization in the deep-sea: In situ measurements of Ca2+, pH, pCO2 and O2. Geochim. Cosmochim. Acta **65**, 2677-2690. (doi: 10.1016/S0016-7037(01)00620-2)
47. Covich AP, Austen MC, Barlocher F, Chauvet E, Cardinale BJ, Biles CL, Inchausti P, Dangles O, Solan M, Gessner MO *et al*. 2004 The role of biodiversity in the functioning of freshwater and marine benthic ecosystems. Bioscience **54**, 767–775. (doi: 10.1641/0006-3568(2004)054[0767:TROBIT]2.0.CO;2)
48. Thurber AR, Sweetman AK, Narayanaswamy BE, Jones DOB, Ingels J, Hansman RL. 2014 Ecosystem function and services provided by the deep sea. Biogeosciences **11**, 3941-3963. (doi: 10.5194/bg-11-3941-2014)
49. Ouellette D, Desrosiers G, Gagne JP, Gilbert F, Poggiale JC, Blier PU, Stora G. 2004 Effects of temperature on in vitro sediment reworking processes by a gallery biodiffusor, the polychaete *Neanthes virens*. Mar. Ecol. Prog. Ser. **266**, 185–193. (doi:10.3354/meps266185)
50. Laverock B, Kitidis V, Tait K, Gilbert JA, Osborn AM, Widdicombe S. 2013 Bioturbation determines the response of benthic ammonia-oxidizing microorganisms to ocean acidification. Phil Trans R Soc B **368**, 20120441. (doi: 10.1098/rstb.2012.0441)
51. Devereux R, Lehrter JC, Cicchetti G, Beddick DL, Yates DF, Jarvis BM, Aukamp J, Hoglund MD. 2019 Spatially variable bioturbation and physical mixing drive the sedimentary biogeochemical seascape in the Louisiana continental shelf hypoxic zone. Biogeochemistry **143**, 151-169. (doi: 10.1007/s10533-019-00539-8)
52. Leorri E, Martin RE, Horton BP 2009 Field experiments on bioturbation in salt marshes (Bombay Hook National Wildlife Refuge, Smyrna, DE, USA): implications for sea-level studies. J. Quatern. Sci. **24**, 139-149. (doi: 10.1002/jqs.1183)
53. Bulling MT, Hicks, N, Murray L, Paterson DM, Raffaelli D, White PCL, Solan M. 2010 Marine biodiversity-ecosystem functions under uncertain environmental futures. Phil. Trans. R. Soc. B. **365**, 2107-2116. (doi: 10.1098/rstb.2010.0022)
54. Godbold JA, Solan M. 2013 Long-term effects of warming and ocean acidification are modified by seasonal variation in species responses and environmental conditions. Phil Trans R Soc B **368**, 20130186. (doi: 10.1098/rstb.2013.0186)
55. Halpern BS, Walbridge S, Selkoe KA, Kappel CV, Micheli F, D'Agrosa C, Bruno JF, Casey KS, Ebert C, Fox HE. *et al*. 2008 A global map of human impact on marine ecosystems. Science **319**, 948-952. (doi: 10.1126/science.1149345)
56. Solan M, Cardinale BJ, Downing AL, Engelhardt KAM, Ruesink JL, Srivastava DS 2004 Extinction and ecosystem function in the marine benthos. Science **306**, 1177-1180. (doi: 10.1126/science.1103960)
57. Godbold JA, Hale R, Wood CL, Solan M 2017 Vulnerability of macronutrients to the concurrent effects of enhanced temperature and atmospheric pCO2 in representative shelf sea sediment habitats. Biogeochemistry **135**, 89-102. (doi: 10.1007/s10533-017-0340-y)
58. Nicholls RJ, Brown S, Goodwin P, Wahl T, Lowe J, Solan M, Godbold JA, Haigh ID, Lincke D, Hinkel J. *et al.* 2018 Stabilization of global temperature at 1.5°C and 2.0°C: implications for coastal areas. Phil. Trans. R. Soc. A **376**, 20160448. (doi: 10.1098/rsta.2016.0448)
59. Sweetman AK, Thurber AR, Smith CR, Levin LA, Mora C, Wei CL, Gooday AJ, Jones DOB, Rex M, Yasuhara M. *et al.* 2017. Major impacts of climate change on deep-sea benthic ecosystems. Elem Sci. Anth. **5**,4. (doi: 10.1525/elementa.203)
60. Bastakoti RC, Gupta J, Babel MS, van Dijk MP 2014 Climate risks and adaptation strategies in the Lower Mekong River basin. Regional Environ. Change **14**, 207-219. (doi: 10.1007/s10113-013-0485-8)
61. Pinsky M, Mantua N. (2014). Emerging adaptation approaches for climate-ready fisheries management. Oceanography **27**, 146–159. (doi: 10.5670/oceanog.2014.93)
62. Vignola R, Harvey CA, Bautista-Solis P, Avelino J, Rapidel B, Donatti C, Martinez R. 2015 Ecosystem-based adaptation for smallholder farmers: Definitions, opportunities and constraints. Agriculture Ecosystems Environ. **211**, 126-132. (doi: 10.1016/j.agee.2015.05.013)
63. Skern-Mauritzen M, Ottersen G, Handegard NO, Huse G, Dingsor GE, Stenseth NC, Kjesbu, OS. 2016 Ecosystem processes are rarely included in tactical fisheries management. Fish and Fisheries **17**, 165-175. (doi: 10.1111/faf.12111)
64. Carlson, CA Giovannoni, SJ 2019 Marine environmental epigenetics. Annu. Rev. Mar. Sci. **11**, 335-368. (doi: 10.1146/annurev-marine-010318-095114)
65. Hobday AJ, Hartog JR, Spillman CM, Alves O. (2011). Seasonal forecasting of tuna habitat for dynamic spatial management. Canadian J. Fisheries Aquat. Sci. **68**, 898–911. (doi: 10.1139/F2011-031)
66. Hermansen O, Heen K. 2012 Norwegian Salmonid farming and global warming: socioeconomic impacts. Aquaculture Economics Management **16**, 202-221. (doi: 10.1080/13657305.2012.704617)
67. Machado L, Magnusson M, Paul NA, Kinley R, de Nys R, Tomkins N. 2016 Dose-response effects of *Asparagopsis taxiformis* and *Oedogonium* sp. on in vitro fermentation and methane production. J. Appl. Phycol. **28**, 1443–1452. (doi: 10.1007/s10811-015-0639-9)
68. Miller DD, Ota Y, Sumaila UR, Cisneros-Montemayor AM, Cheung WWL. 2018 Adaptation strategies to climate change in marine systems. Glob. Change Biol. **24**, e1-e14. (doi: 10.1111/gcb.13829)
69. Chung IK, Oak JH, Lee JA, Shin JA, Kim JG, Park KS. 2013 Installing kelp forests/seaweed beds for mitigation and adaptation against global warming: Korean Project Overview. ICES J. Mar. Sci. **70**, 1038–1044. (doi:10.1093/icesjms/fss206)
70. Burrows MT, Schoeman DS, Buckley LB, Moore P, Poloczanska ES, Brander KM, Brown C, Bruno JF, Duarte CM, Halpern BS. *et al*. 2011 The pace of shifting climate in marine and terrestrial ecosystems. Science **334**, 652-655. (doi: 10.1126/science.1210288)
71. Li BF et al. 2019 Quasi-real-time and high-resolution spatiotemporal distribution of ocean anthropogenic CO2. Geophys. Res. Lett. **46**, 4836-4843. (doi: 10.1029/2018GL081639)
72. Kroeker KJ, Kordas RL, Crim R, Hendriks IE, Ramajo L, Singh GS, Duarte CM, Gattuso JP. 2013 Impacts of ocean acidification on marine organisms: quantifying sensitivities and interaction with warming. Glob. Change Biol. **19,** 1884-1896. (doi: 10.1111/gcb.12179)
73. Vinagre C, Dias M, Cereja R, Abreu-Afonso F, Flores AAV, Mendonca V. 2019 Upper thermal limits and warming safety margins of coastal marine species - Indicator baseline for future reference. Ecological Indicators **102**, 644-649. (doi: 10.1016/j.ecolind.2019.03.030)
74. Mos M, Dworjanyn SA, Mamo LT, Kelaher BP 2019 Building global change resilience: Concrete has the potential to ameliorate the negative effects of climate-driven ocean change on a newly-settled calcifying invertebrate. The Science of the Total Environment **646**, 1349–1358. (doi: 10.1016/j.scitotenv.2018.07.379)
75. Brown CJ, Harborne AR, Paris CB, Mumby PJ 2016 Uniting paradigms of connectivity in marine ecology. Ecology **97**, 2447-2457. (doi: 10.1002/ecy.1463)
76. Solan M, Ward ER, White EL, Hibberd EE, Cassidy C, Schuster JM, Hale R, Godbold JA. 2019 Worldwide measurements of bioturbation intensity, ventilation rate, and the mixing depth of marine sediments. Sci. Data **6**, 58. (doi: 10.1038/s41597-019-0069-7)
77. Woodson CB, Micheli F, Boch C, Al-Najjar M, Espinoza A, Hernandez A, Vazquez-Vera L, Saenz-Arroyo A, Monismith SG, Torre J. 2018 Harnessing marine microclimates for climate change adaptation and marine conservation. Conserv. Lett. **12**, e12609. (doi: 10.1111/conl.12609)
78. Powell EJ, Tyrrell MC, Milliken A, Tirpak JM, Staudinger MD. 2019 A review of coastal management approaches to support the integration of ecological and human community planning for climate change. J. Coastal Conserv. **23**, 1–18. (doi: 10.1007/2Fs11852-018-0632-y)
79. Duarte CM, Krause-Jensen D. 2018 Intervention options to accelerate ecosystem recovery From coastal eutrophication. Front. Mar. Sci. **5**, 470. (doi: 10.3389/fmars.2018.00470)
80. Krause-Jensen D, Duarte CM. 2016 Substantial role of macroalgae in marine carbon sequestration. Nature Geoscience **9**, 737–742. (doi: 10.1038/NGEO2790)
81. Geraldi NR, Ortega A, Serrano O, Macreadie PI, Loyelock CE, Krause-Jensen D, Kennedy H, Lavery PS, Pace ML, Kaal J. 2019 Fingerprinting blue carbon: Rationale and tools to determine the source of organic carbon in marine depositional environments. Front. Mar. Sci. **6**, 263. (doi: 10.3389/fmars.2019.00263)
82. Petersen JK, Hasler B, Timmermann K, Nielsen P, Torring DB, Larsen MM, Holmer M. 2018 Mussels as a tool for mitigation of nutrients in the marine environment. Mar. Poll. Bull. **82**, 137-143. (doi: 10.1016/j.marpolbul.2014.03.006)
83. Timmermann K, Maar M, Bolding K, Larsen J, Windolf J, Nielsen P, Petersen JK. 2019 Mussel production as a nutrient mitigation tool for improving marine water quality. Mar. Ecol. Prog. Ser. **11**, 191–204. (doi: 10.3354/aei00306)
84. Gren I-M, Säll S, Aklilu AZ, Tirkaso W. 2018 Does mussel farming promote cost savings and equity in reaching nutrient targets for the Baltic Sea? Water **10**,1682. (doi: 10.3390/w10111682)
85. Bergstrom P, Carlsson MS, Lindegarth M, Petersen JK, Lindegarth S, Holmer M. 2017 Testing the potential for improving quality of sediments impacted by mussel farms using bioturbating polychaete worms. Aquaculture Research **48**, 161-176. (doi: 10.1111/are.12870)
86. Fodrie FJ, Rodriguez AB, Gittman RK, Grabowski JH, Lindquist NL, Peterson CH, Piehler MF, Ridge JT. 2017 Oyster reefs as carbon sources and sinks. Proc. R. Soc. B **284**, 20170891. (doi: 10.1098/rspb.2017.0891)
87. Chowdhury MSN, Walles B, Sharifuzzaman SM, Hossain MS, Ysebaert T, Smaal AC. 2019 Oyster breakwater reefs promote adjacent mudflat stability and salt marsh growth in a monsoon dominated subtropical coast. Sci. Rep. **9**, 8549. (doi: 10.1038/s41598-019-44925-6)
88. Reguero BG, Beck MW, Bresch DN, Calil J, Meliane I. 2018 Comparing the cost effectiveness of nature-based and coastal adaptation: A case study from the Gulf Coast of the United States. PLOS One **13**, e0192132. (doi: 10.1371/journal.pone.0192132)
89. DePiper GS, Lipton DW, Lipcius RN. 2017 Valuing ecosystem services: Oysters, denitrification, and nutrient trading programs. Marine Resource Economics **32**, 1-20. (doi: 10.1086/688976)
90. Onorevole KM, Thompson SP, Piehler MF. 2018 Living shorelines enhance nitrogen removal capacity over time. Ecol. Engineering **120**, 238-248. (doi: 10.1016/j.ecoleng.2018.05.017)
91. Pearson TH, Rosenberg R. 1978 Macrobenthic succession in relation to organic enrichment and pollution of the marine environment. Oceanogr. Mar. Biol. Ann. Rev. **16**, 229-311.
92. Rhoads DC, McCall PL, Yingst JY. 1978 Disturbance and production on estuarine seafloor. Am. Nat. **66**, 577-586.
93. Rumohr H, Bonsdorff E, Pearson TH. 1996 Zoobenthic succession in Baltic sedimentary habitats. Archives of Fisheries and Marine Research **44**, 179 – 214.
94. Boogert NJ, Paterson DM, Laland KN. 2006 The implications of niche construction and ecosystem engineering for conservation biology. Bioscience **56**, 570-578. (doi: 10.1641/0006-3568(2006)56[570:TIONCA]2.0.CO;2)
95. Byers JE, Cuddington K, Jones CG, Talley TS, Hastings A, Lambrinos JG, Crooks JA, Wilson WG. 2006 Using ecosystem engineers to restore ecological systems. Trends. Ecol. Evol. **21**, 493-500. (doi: 10.1016/j.tree.2006.06.002)
96. Pearson TH. 2001 Functional group ecology in soft-sediment marine benthos: The role of bioturbation. Oceanogr. Mar. Biol. Ann. Rev. **39**, 233-267.
97. Volkenborn N, Hedtkamp SIC, van Beusekom JEE, Reise K. 2007 Effects of bioturbation and bioirrigation by lugworms (*Arenicola marina*) on physical and chemical sediment properties and implications for intertidal habitat succession. Estuar. Coast. Shelf Sci. **74**, 331-343. (doi: 10.1016/j.ecss.2007.05.001)
98. Cameron C, Hutley LB, Friess DA, Munksgaard NC. 2019 Hydroperiod, soil moisture and bioturbation are critical drivers of greenhouse gas fluxes and vary as a function of landuse change in mangroves of Sulawesi, Indonesia. Sci. Tot. Environ. **654**, 365-377. (doi: 10.1016/j.scitotenv.2018.11.092)
99. Halpern BS, Silliman BR, Olden JD, Bruno JP, Bertness MD. 2007 Incorporating positive interactions in aquatic restoration and conservation. Front. Ecol. Environ. **5**, 153-160. (doi: 10.1890/1540-9295(2007)5[153:IPIIAR]2.0.CO;2)
100. Suykerbuyk W, Bouma TJ, van der Heide T, Faust C, Govers LL, Giesen WBJT, de Jong DJ, van Katwijk MM. 2012 Suppressing antagonistic bioengineering feedbacks doubles restoration success. Ecol. Appl. **22**, 1224-1231. (doi: 10.1890/11-1625.1)
101. Quintana CO, Shimabukuro M, Pereira CO, Alves BGR, Moraes PC, Valdemarsen T, Kristensen E, Sumida PYG. 2015 Carbon mineralization pathways and bioturbation in coastal Brazilian sediments. Sci. Rep. **5**, 16122. (doi: 10.1038/srep16122)
102. Wang JQ, Zhang XD, Jiang LF, Bertness MD, Fang CM, Chen JK, Hara T, Li B. 2015 Bioturbation of burrowing crabs promotes sediment turnover and carbon and nitrogen movements in an estuarine Salt Marsh. Ecosystems **13**, 586-599. (doi: 10.1007/s10021-010-9342-5)
103. Vardaro MF, Ruhl HA, Smith Jr KL. 2009 Climate variation, carbon flux, and bioturbation in the abyssal North Pacific. Limnol. Oceanogr. **54**, 2081-2089. (doi: 10.4319/lo.2009.54.6.2081)
104. Shen H, Thrush SF, Wan XH, Li H, Qiao Y, Jiang G, Sun RJ, Wang LB, He PM. 2016 Optimization of hard clams, polychaetes, physical disturbance and denitrifying bacteria of removing nutrients in marine sediment. Mar. Poll. Bull. **110**, 86-92. (10.1016/j.marpolbul.2016.06.081)
105. Martin JH, et al. 1994 Testing the iron hypothesis in ecosystems of the equatorial Pacific Ocean. Nature **371**, 123-129. (doi: 10.1038/371123a0)
106. Yoon J-E, Yoo KC, Macdonald AM, Yoon HI, Park KT, Yang EJ, Kim HC, Lee JI, Lee MK, Jung, J. *et al*. 2018 Ocean iron fertilization experiments – past, present, and future looking to a future Korean Iron Fertilization Experiment in the Southern Ocean (KIFES) project. Biogeosciences **15**, 5847–5889. (doi: 10.5194/bg-15-5847-2018)
107. Lenton TM, Vaughan NE. 2009 The radiative forcing potential of different climate geoengineering options. Atmos. Chem. Phys**. 9**, 5539-5561. (doi: 10.5194/acp-9-5539-2009)
108. Lawrence MG. 2002 Side effects of oceanic iron fertilisation. Science **297**, 1993. (doi: 10.1126/science.297.5589.1993b)
109. Wolff GA, Billett DSM, Bett BJ, Holtvoeth J, FitzGeorge-Balfour T, Fisher EH, Cross I, Shannon R, Salter I, Boorman B. *et al*. 2011 The effects of natural Iron fertilisation on deep-sea ecology: The Crozet Plateau, Southern Indian Ocean. PLoS ONE **6**, e20697. (doi: 10.1371/journal.pone.0020697)
110. Keller DP, Feng EY, Oschlies A. 2014 Potential climate engineering effectiveness and side effects during a high carbon dioxide-emission scenario. Nature Comm. **5**, 3304. (doi: 10.1038/ncomms4304)
111. van der Molen J, Ruardii P, Greenwood N. 2016 Potential environmental impact of tidal energy extraction in the Pentland Firth at large spatial scales: results of a biogeochemical model. Biogeosciences **13**, 2593-2609. (doi: 10.5194/bg-13-2593-2016)
112. Barrio Frojan CRS, Cooper KM, Bolam SG 2016 Towards an integrated approach to marine benthic monitoring. Mar Poll Bull. **104**, 20-28. (doi: 10.1016/j.marpolbul.2016.01.054)
113. Thompson CEL, Silburn B, Williams ME, Hull T, Sivyer D, Amoudry LO, Widdicombe S, Ingels J, Carnovale G, McNeill CL. *et al.* 2017 An approach for the identification of exemplar sites for scaling up targeted field observations of benthic biogeochemistry in heterogeneous environments. Biogeochemistry **135**, 1-34. (doi: 10.1007/s10533-017-0366-1)
114. Roberts CM, O'Leary BC, McCauley DJ, Cury PM, Duarte CM, Lubchenco J, Pauly D, Saenz-Arroyo A, Sumaila UR, Wilson RW. *et al.* 2017 Marine reserves can mitigate and promote adaptation to climate change. Proc. Nat. Acad. Sci. USA. **114**, 6167-6175 (doi: 10.1073/pnas.1701262114)
115. Micheli F, Saenz-Arroyo A, Greenley A, Vazquez L, Montes JAE, Rossetto M, De Leo GA. 2012 Evidence that marine reserves enhance resilience to climatic impacts. PLoS ONE **7**, e40832. (doi: 10.1371/journal.pone.0040832)
116. Unsworth RKF, Collier CJ, Henderson GM, McKenzie LJ. 2012 Tropical seagrass meadows modify seawater carbon chemistry: Implications for coral reefs impacted by ocean acidification. Environ Res Lett **7**, 024026. (doi: 10.1088/1748-9326/7/2/024026)
117. Jones SE, Jago CF. 1993 In situ assessment of modification of sediment properties by burrowing invertebrates. Mar. Biol. **115**, 133-142. (doi: 10.1007/BF00349395)
118. Pansch C, Scotti M, Barboza FR, Al-Janabi B, Brakel J, Briski E, Bucholz B, Franz M, Ito M, Paiva F. *et al*. 2018 Heat waves and their significance for a temperate benthic community: A near-natural experimental approach. Glob. Change Biol. **24**, 4357-4367. (doi: 10.1111/gcb.14282)
119. Milbrandt EC, Thompson M, Coen LD, Grizzle RE, Ward K. 2015 A multiple habitat restoration strategy in a semi-enclosed Florida embayment, combining hydrologic restoration, mangrove propagule plantings and oyster substrate additions. Ecol. Engineer. **83**, 394-404. (doi: 10.1016/j.ecoleng.2015.06.043)
120. Kellogg ML, Smyth AR, Luckenbach MW, Carmichael RH, Brown BL, Cornwell JC, Piehler, MF, Owens MS, Dalrymple DJ, Higgins CB. *et al*. 2014 Use of oysters to mitigate eutrophication in coastal waters. Estuar. Coast. Shelf Sci. **151**, 156–168. (doi: 10.1016/j.ecss.2014.09.025)
121. Petersen JK, Hasler B, Timmermann K, Nielsen P, Torring DB, Larsen MM, Holmer M. 2014 Mussels as a tool for mitigation of nutrients of nutrients in the marine environment. Mar. Poll. Bull. **82**, 137–143. (doi: 10.1016/j.marpolbul.2014.03.006)
122. Zadinelo IV, dos Santos LD, Cagol L, de Muniz GIB, Ellendersen LDN, Alves HJ, Bombardelli RA. 2018 Adsorption of aquaculture pollutants using a sustainable biopolymer. Environ. Sci. Poll. Res. **25**, 4361-4370. (doi: 10.1007/s11356-017-0794-4)
123. Rizal A, Dhahiyat Y, Zahidah, Andriani Y, Handaka, AA, Sahidin A. 2018 The economic and social benefits of an aquaponic system for the integrated production of fish and water plants. IOP Conf. Series: Earth and Environmental Science **137**, 012098. (doi: 10.1088/1755-1315/137/1/012098)
124. Jones KR, Klein CJ, Halpern BS, Venter O, Grantham H, Kuempel CD, Shumway N, Friedlander AM, Possingham HP, Watson, JEM. 2018 The location and protection status of Earth's diminishing marine wilderness. Current Biology **28**, 2506-2512. (doi: 10.1016/j.cub.2018.06.010).
125. Walsworth TE, Schindler DE, Colton MA, Webster MS, Palumbi SR, Mumby PJ, Essington TE, Pinsky ML. 2019 Management for network diversity speeds evolutionary adaptation to climate change. Nature Climate Change. (doi: 10.1038/s41558-019-0518-5)
126. Queiros AM, Huebert KB, Keyl F, Fernandes JA, Stolte W, Maar M, Kay S, Jones MC, Hamon, KG, Hendriksen, G. 2018 Solutions for ecosystem-level protection of ocean systems under climate change. Glob. Change Biol. **22**, 3927–3936. (doi: 10.1111/gcb.13423)
127. Brown CJ, Saunders MI, Possingham HP, Richardson AJ. 2013 Managing for interactions between local and global stressors of ecosystems. PLoS One **8**, e65765. (doi: 10.1371/journal.pone.0065765)
128. Godbold JA, Bulling MT, Solan M. 2011 Habitat structure mediates biodiversity effects on ecosystem properties. Proc. R. Soc. B **278**, 2510-2518. (doi: 10.1098/rspb.2010.2414)
129. Gilby B, Olds, AD, Connolly RM, Henderson CJ, Schlacher TA. 2017 Spatial restoration ecology: placing restoration in a landscape context. Bioscience **68**, 1007-1019. (doi: 10.1093/biosci/biy126)
130. Wohlgemuth D, Solan M, Godbold JA. 2017 Species contributions to ecosystem process and function can be population dependent and modified by biotic and abiotic setting. Proc. R. Soc. B **284**, 20162805. (doi: 10.1098/rspb.2016.2805)
131. Lipcius RN, Eggleston DB, Schreiber SJ, Seitz RD, Shen J, Sisson M, Stockhausen WT, Wang HV. 2008 Importance of metapopulation connectivity to restocking and restoration of marine species. Rev. Fisheries Sci. **16**, 101-110. (doi: 10.1080/10641260701812574)
132. Goni R, Hilborn R, Diaz D, Mallol S, Adlerstein S. 2018 Net contribution of spillover from a marine reserve to fishery catches. Mar. Ecol. Prog. Ser. **400**, 233-243. (doi: 10.3354/meps08419)
133. Hilário A, Metaxas A, Gaudron SM, Howell KL, Mercier A, Mestre NT, Ross RE, Thurnherr AM, Young C. 2015 Estimating dispersal distance in the deep sea: challenges and applications to marine reserves. Front. Mar. Sci. **2**, 6. (doi: 10.3389/fmars.2015.00006)
134. Hock K, Wolff NH, Ortiz JC, Condie SA, Anthony KRN, Blackwell PG, Mumby, PJ. 2017 Connectivity and systemic resilience of the Great Barrier Reef. PLoS Biol **15**, e2003355. (doi: 10.1371/journal.pbio.2003355)
135. Elsasser B, Farinas-Franco JM, Wilson CD, Kregting L, Roberts D. 2013 Identifying optimal sites for natural recovery and restoration of impacted biogenic habitats in a special area of conservation using hydrodynamic and habitat suitability modelling. J. Sea Res. **77**, 11-21. (doi: 10.1016/j.seares.2012.12.006)
136. Mumby PJ, Sanchirico JN, Broad K, Beck MW, Tyedmers P, Morikawa M, Okey TA, Crowder LB, Fulton EA, Kelso, D. *et al.* 2017 Avoiding a crisis of motivation for ocean management under global environmental change. Global Change Biol. **23**, 4483-4496. (doi: 10.1111/gcb.13698)
137. Holt AR, Godbold JA, White PCL, Slater A-M, Pereira EG, Solan M. 2011 Mismatches between legislative frameworks and benefits restrict the implementation of the Ecosystem Approach in coastal environments. Mar. Ecol. Prog. Ser. **434**, 213–228. (doi: 10.3354/meps09260)
138. Webb TJ, Vanden Berghe E, O'Dor R 2010 Biodiversity's big wet secret: The global distribution of marine biological records reveals chronic under-exploration of the deep pelagic ocean. PLOS One **5**, e10223 (doi: 1 0.1371/journal.pone.0010223)
139. Raffaelli D, Solan M, Webb TJ. 2005 Do marine ecologists do it differently? Mar. Ecol. Prog. Ser. **304**, 283-289.
140. Diaz S, Demissew S, Carabias J, Joly C, Lonsdale M, Ash N, Larigauderie A, Adhikari JR, Arico S, Baldi, A. *et al.* 2015 The IPBES Conceptual Framework - connecting nature and people. Current Opinion Environ. Sustainability **14**, 1-16. (doi: 10.1016/j.cosust.2014.11.002)
141. Kim CK, Toft JE, Papenfus M, Verutes G, Guerry AD, Ruckelshaus MH, Arkema KK, Guannel G, Wood SA, Bernhardt, JR. *et al.* 2012 Catching the right wave: evaluating wave energy resources and potential compatibility with existing marine and coastal uses. PLOS One **7**, e47598. (doi: 10.1371/journal.pone.0047598)
142. Charles A. 2012. People, oceans and scale: governance, livelihoods and climate change adaptation in marine social–ecological systems. Current Opinion in Environmental Sustainability **4**, 351-357. (doi: 10.1016/j.cosust.2012.05.011)
143. Purkis SJ 2018 Remote sensing tropical coral reefs: The view from above. Ann. Rev. Mar. Sci. **10**, 149-168. (doi: 10.1146/annurev-marine-121916-063249)
144. Wynn RB, Huvenne VAI, Le Bas TP, Murton BJ, Connelly DP, Bett BJ, Ruhl HA, Morris KJ, Peakall J, Parsons DR. *et al.* 2014 Autonomous Underwater Vehicles (AUVs): Their past, present and future contributions to the advancement of marine geoscience. Mar. Geol. **352**, 451-468. (doi: 10.1016/j.margeo.2014.03.012)
145. Foo SA, Asner GP. 2019. Scaling up coral reef restoration using remote sensing technology. Front. Mar. Sci. **6**, 79. (doi: 10.3389/fmars.2019.00079)
146. Goodell W, Stamoulis KA, Friedlander AM. 2018 Coupling remote sensing with in situ surveys to determine reef fish habitat associations for the design of marine protected areas. Mar. Ecol. Prog. Ser. **588**, 121-134. (doi: 10.3354/meps12388)
147. Newton A, Elliott M. 2016 A typology of stakehodlers and guidelines for engagement in transdisciplinary, participatory processes. Front. Mar. Sci. 3, 230 (doi: 10.3389/fmars.2016.00230)
148. Rudd MA, Moore AFP, Rochberg D, Bianchi-Fossati L, Brown MA, D'Onofrio D, Furman CA, Garcia J, Jordan B, Kline J. *et al*. 2018 Climate research priorities for policy-makers, practitioners, and scientists in Georgia, USA. Environ. Management **62**, 190–209. (doi: 10.1007/s00267-018-1051-4)
149. Breed MF, Harrison PA, Blyth C, Byrne M, Gaget V, Gellie NJC, Groom SVC, Hodgson R, Mills JG, Prowse TAA. *et al.* 2019 The potential of genomics for restoring ecosystems and biodiversity. Nature Reviews Genetics (doi: 10.1038/s41576-019-0152-0)
150. Ling SD, Hobday AJ. 2019 National research planning accelerates relevance and immediacy of climate-adaptation science. Mar. Fresh. Res. **70**, 62–70. (doi: 10.1071/MF17330)
151. Hedley JD, Roelfsema C, Brando V, Giardino C, Kutser T, Phinn S, Mumby PJ, Barrilero O, Laporte J, Koetz B 2018. Coral reef applications of Sentinel-2: Coverage, characteristics, bathymetry and benthic mapping with comparison to Landsat 8. Remote Sensing of Environment **216**, 598-614. (doi: 10.1016/j.rse.2018.07.014)
152. Perry RI, Boutillier JA, Foreman MG 2000 Environmental influences on the availability of smooth pink shrimp, *Pandalus jordani*, to commercial fishing gear off Vancouver Island, Canada. Fisheries Oceanography **9**, 50-61. (doi: 10.1046/j.1365-2419.2000.00121.x)
153. Perry R, Ommer RE. 2003 Scale issues in marine ecosystems and human interactions. Fisheries Oceanography **12**, 513-522. (doi: 10.1046/j.1365-2419.2003.00254.x)

**Figure legends**

**Figure 1.** The predictable and sequential changes in community structure and sedimentary conditions typically expressed following a stochastic perturbation or directional forcing. The successional sequence (right to left) follows the same pathway with distance from, or time since, perturbation and is reversible, transitioning from a highly diverse and active invertebrate community (left) to a microbial dominated sediment devoid of macrofauna (right) as perturbation intensifies. This sequence forms a credible means to assess the status, restoration capacity and management options available to manipulate the functional performance of soft sediment benthic ecosystems as part of a mitigation programme. Sediment colour reflects redox status (light shades oxidized, darker shades reduced and black anoxic). Redrawn from refs. [91-93].

**Figure 2.** A) The relationship between the spatial and temporal characteristics of: marine physical characteristics (solid black lines), the requirements for various marine remote sensing objectives (colour shaded), specific benthic communities (grey shaded) and some exemplar remote sensing techniques (red dashed lines), highlighting the potential overlaps in space and time and the range of information that can be leveraged from remotely sensed data. B) Indicative spatial and temporal scales of climate change impacts on marine attributes (dark blue), coastal hazards (red) and changing benthic habitats and species compositions (green), with relevant socio-economic scales overlain (grey shaded). Figure redrawn from refs. [151-153]