Clarifying the role of coastal and marine systems in climate mitigation

Jennifer Howard[1†*], Ariana Sutton-Grier[2,3†], Dorothée Herr[4], Joan Kleypas[5], Emily Landis[6], Elizabeth Mcleod[7], Emily Pidgeon[1], and Stefanie Simpson[8]

The international scientific community is increasingly recognizing the role of natural systems in climate-change mitigation. While forests have historically been the primary focus of such efforts, coastal wetlands – particularly seagrasses, tidal marshes, and mangroves – are now considered important and effective long-term carbon sinks. However, some members of the coastal and marine policy and management community have been interested in expanding climate mitigation strategies to include other components within coastal and marine systems, such as coral reefs, phytoplankton, kelp forests, and marine fauna. We analyze the scientific evidence regarding whether these marine ecosystems and ecosystem components are viable long-term carbon sinks and whether they can be managed for climate mitigation. Our findings could assist decision makers and conservation practitioners in identifying which components of coastal and marine ecosystems should be prioritized in current climate mitigation strategies and policies.

Front Ecol Environ 2017; 15(1): 42–50, doi:10.1002/fee.1451

Within the context of climate-change mitigation, enhancing the capacity and role of natural carbon sinks has become an increasingly important scientific and political topic (note: for definitions of selected terms used throughout the main text see WebTable 1). Research on natural carbon sinks has focused primarily on oceans (Sabine *et al.* 2004) and terrestrial forests (Houghton *et al.* 1990), and most recently, on coastal systems (Mcleod *et al.* 2011). The ocean represents the largest active carbon sink on Earth, absorbing 20–35% of anthropogenic CO_2 emissions (Khatiwala *et al.* 2009). However, management strategies to enhance oceanic carbon sequestration and storage are currently impractical, and there is strong concern about the ecological impacts of such interventions (Russell *et al.* 2012; Committee on Geoengineering Climate 2015). Therefore, scientists and decision makers now focus on terrestrial and coastal ecosystems, which show high potential for climate mitigation and lend themselves to local and national management strategies. For example, the United Nations Framework Convention on Climate Change (UNFCCC) recognizes that terrestrial forests sequester large amounts of carbon in their biomass, and under the Convention, forests are the basis of climate mitigation strategies such as Reducing Emissions from Deforestation and Forest Degradation (REDD+). Similarly, coastal wetlands (mangroves, tidal marshes, and seagrasses) are increasingly acknowledged as important carbon sinks, based on their ability to sequester large amounts of carbon in their biomass and, more importantly, in their soil (Hiraishi *et al.* 2014). The carbon sequestered in coastal and marine vegetated ecosystems is known as "coastal wetland blue carbon". On a per area basis, coastal wetlands are more efficient carbon sinks than most terrestrial forests (Mcleod *et al.* 2011; Pan *et al.* 2011). Anthropogenic conversion and degradation of coastal wetlands can lead to major emissions, because much of the carbon stored in the soils is released back into the atmosphere and ocean (Pendleton *et al.* 2012; Kauffman *et al.* 2014), shifting the wetlands from net sinks to sources of carbon. The conservation, restoration, and sustainable use of these ecosystems are therefore essential to ensuring that the carbon sequestration

In a nutshell:

- Coastal wetlands sequester substantial amounts of carbon, mostly in soils
- Interest in the climate benefits of coastal wetlands has drawn attention to how other components of marine ecosystems might play a role in climate mitigation
- Coral reefs, kelp, and marine fauna, while important components of carbon cycling in the ocean, are not involved in long-term carbon sequestration
- Due to jurisdictional issues, practical management of coral, phytoplankton, kelp, and marine fauna within climate mitigation frameworks would be difficult
- Current climate mitigation efforts in the coastal and marine realm should focus primarily on coastal wetlands, as they represent long-term carbon sinks and potential carbon sources upon conversion, and can be managed for their carbon sequestration value

---

[1]*Conservation International, Arlington, VA* [*]*(jhoward@conservation.org);* [2]*University of Maryland, College Park, MD;* [3]*National Oceanographic and Atmospheric Administration (NOAA), Silver Spring, MD;* [4]*International Union for Conservation of Nature, Gland, Switzerland;* [5]*National Center for Atmospheric Research, Boulder, CO;* [6]*The Nature Conservancy, Arlington, VA;* [7]*The Nature Conservancy, Austin, TX;* [8]*Restore America's Estuaries, Arlington, VA;* [†]*these authors contributed equally to this work*

benefits are maintained, along with the many additional ecosystem services they provide (eg fisheries, coastal protection).

With the increasing recognition of the importance of coastal wetlands for climate mitigation, decision makers have expressed greater interest in the climate mitigation potential of other coastal and marine ecosystems and ecosystem components, particularly kelp, coral, phytoplankton, and marine fauna (WebFigure 1; Chung *et al*. 2013; Lutz and Martin 2014). While all of these components provide valuable services and have important conservation value, not all of them are suitable for consideration in climate-change policy frameworks. In this paper, we synthesize the state of the science and compare the long-term carbon sequestration ability of various coastal and marine systems to clarify which components should be prioritized in climate mitigation efforts.

Integrating natural carbon sinks into climate mitigation policy

All natural ecosystems cycle carbon as an important part of the energy transfer needed to support life. From a climate perspective, much of the carbon that naturally cycles through an ecosystem is part of the "baseline" condition, including fluxes into (eg carbon uptake via photosynthesis) and out of (eg carbon release via respiration) a system. However, the carbon pools and processes within each system that are pertinent to climate mitigation policies and national greenhouse-gas (GHG) inventories are those that (1) affect the levels of GHGs in the atmosphere enough to influence climate and (2) are responsive to human activities that can either increase (eg habitat degradation) or decrease (eg habitat restoration and conservation) GHG emissions. The following information is needed to ascertain whether an ecosystem or ecosystem component meets these requirements and to determine their potential emissions and removals for national GHG inventories:

(1) carbon sequestration rate;
(2) current carbon stocks, including the stability and permanence of those stocks (ie how will those stocks be affected if the system is degraded or destroyed?);
(3) geographic area;
(4) anthropogenic drivers of system loss leading to carbon emissions or removals; and
(5) emission rates from both degraded and intact states.

With this information, it is possible for climate mitigation policies to support interventions needed to reduce, protect, or enhance the potential of a natural systems to sequester and store carbon. Such interventions can potentially be included in existing climate-related policy frameworks or funding mechanisms (eg REDD+). Alternatively, there may be a need for new policies and regulations to be developed; typically, this is much more difficult and time consuming than applying existing policy. In either case, additional information will be required to inform the development or expansion of policy to include the carbon mitigation benefits found in marine ecosystems. For example, understanding community tenure rights, rights of use, and governance for an ecosystem or ecosystem component – as well as identifying which individuals, institutions, or governments are responsible for management, and who stands to gain from resulting climate benefits – are all critical for proper implementation of climate-related policies. Likewise, it is important to know who would be sanctioned for actions that result in carbon being released (eg deforestation of mangroves) and whether the ecosystem can be managed to secure existing carbon stocks.

Carbon sink capacity and implications for climate mitigation potential

Coastal wetlands (mangroves, tidal marshes, and seagrasses)

Mangroves are tropical forests found in coastal areas that are regularly flooded by tidal water and have a global coverage of 13.8–15.2 million ha (Spalding *et al*. 2010; Giri *et al*. 2011). Tidal marshes are coastal wetland ecosystems dominated by grass and shrub species that are regularly tidally flooded. Inventories of tidal marsh area have been difficult to obtain; models predict a global coverage of up to 40 million ha, although only 2.2 million ha have been verified (Mcleod *et al*. 2011; Duarte *et al*. 2013). Seagrasses are submerged aquatic flowering plants that are found in meadows along the shore of every continent except Antarctica (Green and Short 2003). The geographic extent of seagrass is not well resolved, but global estimates range from 17.7 to 60 million ha (Charpy-Roubaud and Sournia 1990; Duarte *et al*. 2005a, 2010; Mcleod *et al*. 2011). While new methods and technologies are allowing better mapping of the extent of coastal wetlands, each year extensive areas of these ecosystems are lost, sometimes before they can be accounted for.

Mangroves, tidal marshes, and seagrasses sequester and store large amounts of carbon through natural capture during photosynthesis or by trapping sediments and natural debris in their complex root systems. Within these ecosystems, CO_2 from the atmosphere is taken up via photosynthesis, most of which is returned almost immediately to the atmosphere through plant and microbe respiration or stored temporarily in plant foliage. The remainder is sequestered for a longer period of time in woody biomass and soil (Figure 1a). Between 50% and 90% of all coastal wetland carbon, depending on vegetation type, is found in the soil (Pendleton *et al*. 2012). In addition, tidal inundation keeps the soils wet or submerged, thereby inhibiting microbial action and slowing decomposition such that carbon accumulates in

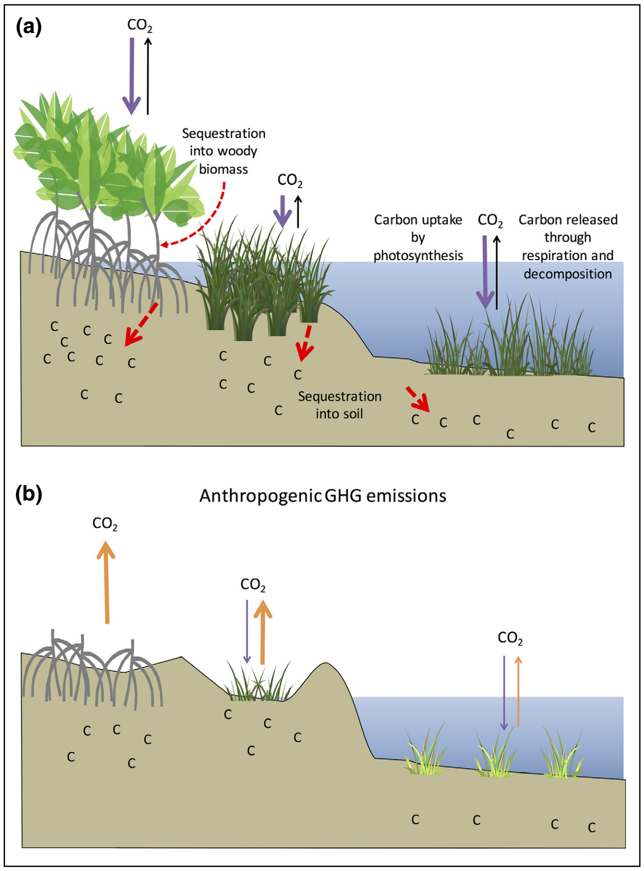

Figure 1. *(a) In intact coastal wetlands (from left to right: mangroves, tidal marshes, and seagrasses), carbon is taken up via photosynthesis (purple arrows) where it gets sequestered long term into woody biomass and soil (red dashed arrows) or respired (black arrows). (b) When soil is drained from degraded coastal wetlands, the carbon stored in the soils is consumed by microorganisms, which respire and release CO_2 as a metabolic waste product. This happens at an increased rate when the soils are drained (when oxygen is more available), which leads to greater CO_2 emissions. The degradation, drainage, and conversion of coastal blue carbon ecosystems from human activity (ie deforestation and drainage, impounded wetlands for agriculture, dredging) results in a reduction in CO_2 uptake due to the loss of vegetation (purple arrows) and the release of globally important GHG emissions (orange arrows). This is a unique trait of coastal blue carbon ecosystems compared to the other ecosystems discussed in the main text.*

soils and remains relatively stable. Coastal wetlands also accumulate carbon transported by river systems and tides, in the form of vegetation and sediment from adjacent ecosystems (Kennedy *et al.* 2010; Mcleod *et al.* 2011).

Carbon in the plant biomass is stored for years to decades (Mcleod *et al.* 2011), whereas carbon in the soil can remain sequestered for millennia (Duarte *et al.* 2005b). Healthy coastal ecosystems continuously accrete carbon in the soil, which allows them to keep pace with sea-level rise; this means that they have a potentially limitless capacity to sequester carbon for long periods of time. Global estimates of carbon stocks in these systems range from 10.4–25.1 billion megagrams of carbon (Mg C; Table 1 and WebTable 2), but this is likely an underestimate, because although organic-rich soil profiles may extend several meters deep, most studies account for carbon only in the topmost meter of soil. The vast stocks of stable carbon, as well as the high rates of sequestration, demonstrate why coastal wetlands are well suited for climate mitigation policy efforts.

Coastal wetlands are relevant to climate mitigation in another respect; human activities can convert these large natural carbon sinks into major carbon sources (of GHG emissions). For example, when mangrove forests are drained for development, microbial action in the soil, previously inhibited by tidal inundation, oxidizes the carbon and emits it to the atmosphere as CO_2 (Figure 1b). Coastal wetland loss and drainage 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 (Table 1 and WebTable 2; Hiraishi *et al.* 2014). For mangroves and tidal marshes, this loss is largely due to human conversion and degradation related to coastal development, agriculture, and aquaculture. Loss of seagrass habitat is caused by several factors, but is mainly due to reduced water quality as a result of sediment and nutrient runoff from anthropogenic sources, and from direct impacts such as dredging and trawling (Pendleton *et al.* 2012). Managing coastal wetlands is not always straightforward, in part because it is typically subject to issues involving land tenure and jurisdictional boundaries; however, these ecosystems have secured a prominent position in terms of climate mitigation strategies, given their inherent capacity to sequester large volumes of carbon, given the large amounts of carbon already stored therein, and given that proper initiatives can help to ensure that their stored carbon is retained rather than released to the atmosphere.

Coral reefs

Coral reefs support numerous taxa and are formed by calcium carbonate ($CaCO_3$) deposits secreted over time, mainly by hard corals and calcareous algae. At present, shallow coral reefs cover an estimated 28.4 million ha globally (Spalding *et al.* 2001). Reefs not only provide coastal protection from storms and erosion, spawning and nursery grounds for economically important fish species, and jobs and income to local economies, but also represent hotspots of marine biodiversity.

Whether coral reef ecosystems are sources or sinks of atmospheric CO_2 depends on the balance between two sets of processes: photosynthesis/respiration and calcification/dissolution (Figure 2a). Symbiotic algae that live within coral polyps take up carbon through photosynthesis, but on most reefs this carbon is equal to or only slightly greater than the carbon released through coral, algal, and microbial respiration, resulting in low to no net

Table 1. Carbon storage potential of coastal and marine ecosystems

	Geographic extent	*Total carbon sequestered annually*	*Mean global estimate of carbon stock*	*Anthropogenic conversion rate*	*Potential emissions due to anthropogenic conversion*#
	Million hectares (ha)	*Million Mg C yr*$^{-1}$	*Total (million Mg C)*	*% yr*$^{-1}$	*Million Mg CO*$_2$
Mangroves	13.8–15.2	31.2–34.4	5617–6186	0.7–3.0	144.3–681.1
Tidal marshes	2.2–40	4.8–87.2	570–10,360	1.0–2.0	20.9–760.4
Seagrasses	17.7–60	41.4–82.8	4260–8520	0.4–2.6	62.5–813.0
Coral	28.4	NA	Unknown	0.4–0.57†	NA
Kelp	>2.35	NA	11.75	NA	NA
Phytoplankton	36,190*	0.5–2.4	507–23,885	NA	NA
Fauna	36,190*	NA	Unknown	NA	NA

Notes: *Based on global ocean area. †Only for the Great Barrier Reef. #Assuming all carbon is converted to CO_2 NA = not applicable. For a more detailed version of this Table, including references, please see WebTable 2.

carbon removal from the surrounding water column and atmosphere (Gattuso *et al.* 1998). Coral reef calcification occurs when $CaCO_3$ precipitates out of the water column onto the reef structure (Gattuso *et al.* 1999) and for every mole of $CaCO_3$ produced, about 0.6 moles of CO_2 is released to the atmosphere (Ware *et al.* 1992). As a counterbalance, coral reefs undergo dissolution when the surrounding water becomes undersaturated with $CaCO_3$ (as in the deep ocean and under future ocean acidification scenarios) – a process that involves capturing CO_2 out of the water column. Currently, coral calcification rates exceed dissolution rates, thereby allowing coral reef structures to grow. Thus, because the CO_2 released through calcification exceeds the CO_2 captured by dissolution (Figure 2a), coral reefs are generally considered as small sources of CO_2 to the atmosphere (Suzuki and Kawahata 2003; Borges *et al.* 2005). However, with increasing ocean acidification resulting from rising atmospheric CO_2 concentrations, the balance between calcification and dissolution may shift (Frankignoulle *et al.* 1994). Under future conditions of ocean acidification, many reefs are expected to enter a net dissolution phase (Eyre *et al.* 2014; Shaw *et al.* 2015) and may become CO_2 sinks but to the detriment of the overall health of reef ecosystems.

Despite their limited capacity to directly sequester carbon, at least over decadal to century timescales (Ware *et al.* 1992; Kleypas 1997), coral reefs provide important climate adaptation benefits (eg wave buffering from

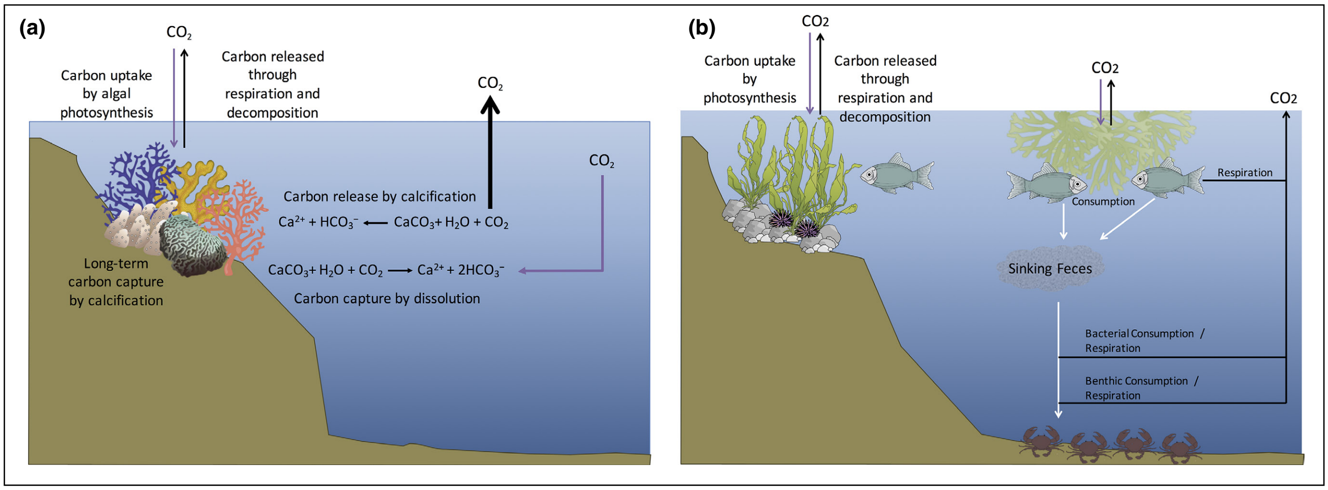

Figure 2. *(a) Coral reef systems can be either a CO_2 source or sink. They take up carbon through photosynthesis of their symbiotic algae and dissolution of the reef structure itself (purple arrows), and release carbon through respiration and calcification (black arrows). Currently, they are not sequestering carbon, because despite the carbon that is integrated into the reef structure, where it can remain for millennia, the net impact of calcification on the atmosphere is still an increase in CO_2. (b) Kelp take up carbon through photosynthesis (purple arrows) and release carbon through respiration (black arrows). The majority of kelp is consumed; in this way, some of the carbon in kelp moves into marine fauna biomass and excrement pools. Kelp do not sequester carbon long term due to their quick turnover rate and lack of a soil component. There is little evidence that any degraded kelp sinks to the bottom of the ocean, given that most, if not all, is consumed before reaching the seafloor.*

extreme storms) and support habitats with higher carbon sequestration potential (eg mangroves, seagrasses).

Kelp forests

Primarily occurring in nearshore temperate and polar regions, kelp forests contain dense stands of macroalgae and provide food and shelter for many marine species. Although the estimated areal extent of kelp habitat is approximately 2.35 million ha worldwide, only a fraction of this area has been verified (Graham *et al.* 2007). The carbon stored in kelp biomass ranges from 37–54 Mg C ha^{-1} (Muraoka 2004); given the estimated spatial extent of kelp forests, its projected global carbon stock is between 87–127 million Mg C (Table 1 and WebTable 2). Often free floating or attached to rocky substrates, kelp do not develop extensive rooting systems for trapping detritus and sediment such as vegetation in coastal wetlands and so do not have a soil carbon pool. Free floating, detached, or dead kelp is quickly consumed by marine fauna including avian species, and the fraction of kelp-based carbon that is ultimately sequestered through burial in ocean sediments is still poorly understood (Smale *et al.* 2013). The short life span of individual kelp plants (~1 year) and their lack of long-term carbon storage mean that they cannot act as effective long-term carbon sinks (Figure 2b; Spalding *et al.* 2003; Muraoka 2004) and are not considered as part of a viable climate mitigation strategy. Although harvesting kelp for human use (eg in cosmetics, paper, biofuel) could benefit climate mitigation by providing more sustainable alternatives to using products derived from petroleum or other natural resources (http://bit.ly/1gOLIhG), to date research on this topic is incomplete and is not being implemented at a globally relevant scale.

Phytoplankton

As single-celled organisms present in the oceans' water column, phytoplankton provide 70% of the oxygen we breathe and are a crucial source of food to marine fauna. Although the amount of phytoplankton in the world's oceans is uncertain, their total biomass is estimated to be between 0.5–2.4 billion Mg C (Table 1 and WebTable 2; Buitenhuis *et al.* 2013). Most phytoplankton are short lived or consumed by higher-trophic-level organisms, giving them a rapid turnover. Thus, carbon remains stored in their biomass only for hours to weeks, unlike carbon sequestered in mangrove wood, which can last for decades. However, a small yet important fraction of carbon in phytoplankton (0.1% or 0.5–2.4 million Mg C yr^{-1}) will sink and become sequestered long-term in seafloor sediments (Figure 3a; Falkowski 2012).

The size of the world's phytoplankton carbon pool is considered to be relatively stable (with seasonal variations), but changing ocean temperatures and circulation patterns may lead to shifts in phytoplankton species extent and community composition, which may alter carbon fluxes (Lam *et al.* 2011; Committee on Geoengineering Climate 2015). Despite representing a globally relevant carbon sink, phytoplankton are not well suited for climate mitigation policies because their sequestration capacity cannot be manipulated without geoengineering (about which the scientific community has articulated major concerns; Committee on Geoengineering Climate 2015), issues of jurisdiction on the high seas remain a challenge, and

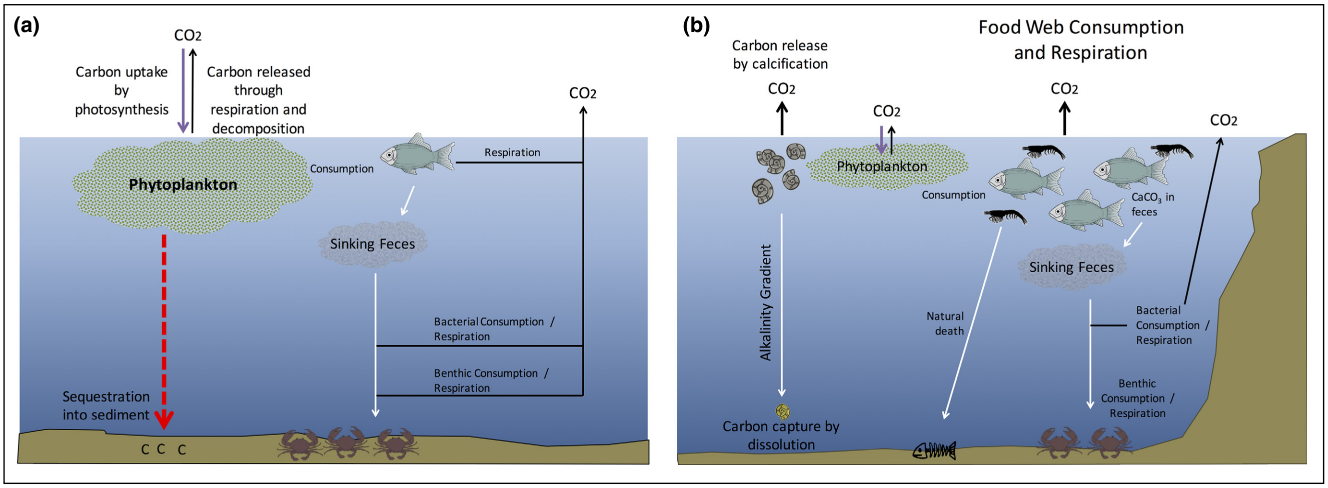

Figure 3. *(a) Phytoplankton take up carbon through photosynthesis (purple arrow) and release carbon through respiration (black arrow). The majority of phytoplankton are consumed by higher-trophic-level organisms where some of the carbon gets integrated into marine fauna biomass and excrement pools. A small yet key percentage of phytoplankton sinks to the bottom of the ocean where it is sequestered long term in the sediment (red dashed arrow). (b) Marine fauna. Fish and krill do not take up or sequester carbon themselves; instead they accumulate carbon that was taken up by phytoplankton (purple arrow). The formation of* $CaCO_3$ *to create the shells of calcifiers at the surface and its dissolution as it sinks drives a surface to deepwater alkalinity gradient, which further reduces the capacity of the ocean's surface to absorb* CO_2*. None of these organisms are considered to sequester carbon.*

substantial scientific uncertainties prohibit accurate carbon accounting of sequestration by phytoplankton at this time (for further discussion, see the penultimate section below).

Marine fauna

By accumulating carbon in their biomass and releasing carbon through respiration and defecation, marine fauna – specifically calcifiers (eg shellfish, zooplankton, and pteropods), krill, and teleost fish – play a role in carbon cycling (Figure 3b). These organisms are found in all major marine waterbodies and populations vary by region and depth, though the largest known krill population is located off Antarctica (Atkinson *et al.* 2008).

Calcifiers

The shells of planktonic calcifiers can act as ballast to increase the transport of organic carbon to the deep sea, and thereby sequester it for long periods of time. However, the formation of $CaCO_3$ at the surface and its dissolution as it sinks drives a surface to deepwater alkalinity gradient, which reduces the capacity of the surface ocean to absorb CO_2 (Mathez 2013). In addition, calcifiers build their shells using the same calcification process as corals, resulting in the same net production of CO_2. Therefore, based on current scientific understanding, we believe that calcifiers have a limited impact on climate mitigation through carbon sequestration.

Krill

Although estimated to have a mean carbon pool of 35 million Mg C (Atkinson *et al.* 2009; Laffoley *et al.* 2014), krill do not remove carbon from the atmosphere themselves, and most of the carbon assimilated into the krill's biomass via consumption is in turn consumed by higher-trophic-level predators. Krill feces are estimated to contribute 0.037–56.94 Mg C yr^{-1} ha^{-1} to the deepwater carbon flux baseline; however, the majority of the carbon in feces is consumed and either respired or excreted by bacteria and benthic organisms (Pakhomov *et al.* 2002; Denman *et al.* 2007), and so plays a negligible role in climate mitigation through carbon sequestration.

Teleost fish

Rather than removing atmospheric carbon directly, teleost (ray-finned) fish accumulate carbon in their biomass by consuming phytoplankton or other marine organisms. This carbon is later released through respiration and defecation (in the form of $CaCO_3$). Fish feces also have a high Mg content, which increases the $CaCO_3$ dissolution near the ocean surface. This balance between calcification (source of CO_2) and dissolution (sink of CO_2) neutralizes much of the CO_2 released due to the calcification process (Woosley *et al.* 2012; Barrett *et al.* 2014). Another aspect of carbon excretion through fish feces is that it increases the rate at which carbon sinks to the ocean floor. However, most fish feces are rapidly consumed and the carbon in them is respired or excreted by bacteria during its descent. This restricts the amount of carbon in feces ultimately reaching the deep ocean (Denman *et al.* 2007) and thereby limits the contributions of fish to long-term ocean carbon sequestration. It is also not clear if there is any additional sequestration value resulting from fish consumption and subsequent excretion. For example, the carbon sequestered by phytoplankton – whether as a component of dead phytoplankton, fish biomass, or fish feces – would eventually sink to the seafloor regardless of its path. While increases in fish populations, and hence fish biomass, will result in a temporary increase in the fish biomass carbon pool, it would not affect the long-term sequestration of carbon in the deep ocean above the natural baseline (Figure 3b).

In summary, calcifiers, krill, and teleost fish are important components of the carbon cycle in oceans but do not contribute to long-term carbon sequestration. Calcification in fecal production and shell formation is a source of CO_2 and because fish and krill fail to remove carbon directly from the atmosphere, they do not substantially alter the baseline of carbon ultimately sequestered in the oceans. Management and policy actions that lead to changes in fish and krill populations would therefore have negligible value in long-term climate mitigation. In addition, most populations of marine fauna reside in the open ocean or cross international boundaries and their members actively or passively disperse, occasionally over vast distances, thus presenting jurisdictional challenges regarding management responsibilities and sanctions. For all these reasons, calcifiers, krill, and teleost fish have limited potential to contribute to climate mitigation efforts.

Informed climate mitigation policy

To achieve emissions reduction targets and inform climate mitigation policies, we argue that a comprehensive strategy is necessary, one that recognizes the role of – and implements effective, science-driven management practices in – natural ecosystems, including coastal wetlands. Although reducing fossil-fuel-based GHG emissions is a direct means to this end, avoided emissions can be gained by protecting habitats, some of which may also offer sequestration-related services. However, much of the relevant ecosystem-specific scientific data regarding carbon storage, sequestration rates, and anthropogenic emissions is neither easily accessible to decision makers nor comparable across studies and habitats, thereby complicating informed policy discussions. To address this issue, we briefly summarize the carbon sequestration value and potential emissions from conversion of the marine ecosystems and ecosystem components mentioned above (Table 1 and WebTable 2) and the criteria required for their consideration in climate mitigation efforts (WebTable 3).

Our understanding of the carbon sequestration capacity of corals, kelp, and marine fauna suggests that they do not represent consequential, verifiable, long-term carbon sinks with respect to the atmosphere. Corals are currently a carbon source, and marine fauna do not sequester carbon directly but are simply a component of the carbon cycle. Kelp ecosystems take up carbon in the short term, but without a meaningful soil component, they do not maintain long-term sinks. The carbon sequestered by phytoplankton in deep-ocean sediments is globally important, due to the abundance of phytoplankton, but is inherently difficult and impractical to manage given its pan-oceanic distribution. In addition, the only current management strategy to increase phytoplankton productivity above the baseline involves artificially increasing nutrients (iron, nitrogen, phosphorus) in large expanses of the ocean; however, strong concerns have been expressed regarding the impacts of such geoengineering projects on ocean ecosystems (Russell *et al.* 2012). Similarly, open-ocean ecosystems are predominantly outside national jurisdictional boundaries, hindering inclusion of these marine ecosystems in climate mitigation-related policies (eg Nationally Determined Contributions under the Paris Agreement). Policy challenges include lack of clarity regarding who would (1) determine and implement management strategies, (2) conduct assessments to support national GHG inventories, or (3) receive financial gains (such as carbon credits) resulting from climate mitigation activities.

The scientific evidence supporting the role of mangroves, tidal marshes, and seagrasses as long-term carbon sinks is well-established. Recognizing the potential of these coastal wetlands to shift from carbon sinks to carbon sources through anthropogenic degradation further supports the need for their conservation and restoration. Coastal wetlands should be integrated into national GHG inventories and climate mitigation strategies, and indeed this has been recommended by the Intergovernmental Panel on Climate Change (IPCC) (Hiraishi *et al.* 2014). To follow the IPCC guidance, countries should conduct national carbon assessments for their coastal wetlands to determine existing carbon stocks and estimates of emissions from converted ecosystems, as well as threats and rates of loss to inform management efforts. These initial steps provide the background knowledge needed to inform national policy, including GHG inventories, but also the development (or revision) of national strategies to manage coastal wetland carbon sinks and sources.

Coastal wetlands are included in existing frameworks under the UNFCCC (eg Nationally Appropriate Mitigation Actions [NAMAs]; REDD+; Land Use, Land-Use Change and Forestry [LULUCF] sectors), and related climate financing mechanisms. Based on the governance challenges associated with open-ocean geographies and/or the current science demonstrating that they are inconsequential stores of carbon, four components – corals, kelp, phytoplankton, and marine fauna – are ineligible to be included in current UNFCCC mitigation finance mechanisms and should not be prioritized at this time in climate mitigation efforts. Instead, conservation practitioners should consider other international policy and funding opportunities (eg biodiversity conservation and climate adaptation) to support the protection and restoration of these important components of coastal and marine ecosystems.

Conclusions

Coastal blue carbon ecosystems (mangroves, tidal marshes, and seagrasses) represent important climate mitigation opportunities. These ecosystems have high rates of carbon sequestration, act as long-term carbon sinks, and are contained within clear national jurisdictions; in addition, management strategies exist to integrate them into GHG accounting. By contrast, other marine ecosystems and ecosystem components (ie corals, kelp, and marine fauna) do not act as substantial and/or long-term carbon sinks. Phytoplankton are a long-term carbon sink but their consideration in climate mitigations policies is limited due to challenges associated with ownership, management, and a lack of practical accounting methods. Despite limitations, these marine systems play a vital role in maintaining the baseline of the carbon cycle of the ocean and provide many other services including coastal protection, habitat, food security, and tourism income. Efforts to protect and manage these marine ecosystems are therefore essential to maintaining these benefits. However, we recommend that the efforts of national governments to implement climate mitigation strategies and reduce emissions should focus on coastal blue carbon ecosystems that represent critical and manageable carbon sinks.

Acknowledgements

We thank P Megonigal and J Fourqurean for helpful discussions and comments. ASG was supported by NOAA grant NA14NES4320003 (Cooperative Institute for Climate and Satellites – CICS) at the University of Maryland/ESSIC. EM was supported by The Nature Conservancy and the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMUB), as part of the International Climate Initiative (IKI); the BMUB supports this initiative on the basis of a decision adopted by the German Bundestag. DH was supported by IUCN and the Prince Albert II de Monaco Foundation as part of their Blue Carbon grant.

References

Atkinson A, Siegel V, Pakhomov EA, *et al*. 2008. Oceanic circumpolar habitats of Antarctic krill. *Mar Ecol-Prog Ser* **362**: 1–23.

Atkinson A, Siegel V, Pakhomov EA, *et al*. 2009. A re-appraisal of the total biomass and annual production of Antarctic krill. *Deep-Sea Res* **56**: 727–40.

Barrett PM, Resing JA, Buck NJ, *et al*. 2014. Calcium carbonate dissolution in the upper 1000 m of the eastern North Atlantic. *Global Biogeochem Cy* **28**: 386–97.

Borges AV, Delille B, and Frankignoulle M. 2005. Budgeting sinks and sources of CO_2 in the coastal ocean: diversity of ecosystems counts. *Geophys Res Lett* **32**: L14601.

Buitenhuis E, Vogt M, Moriarty R, *et al*. 2013. MAREDAT: towards a world atlas of MARine Ecosystem DATa. *Earth System Sci Data* **5**: 227–39.

Charpy-Roubaud C and Sournia A. 1990. The comparative estimation of phytoplanktonic, microphytobenthic and macrophytobenthic primary production in the oceans. *Mar Microb Food Webs* **4**: 31–57.

Chung IK, Oak JH, Lee JA, *et al*. 2013. Installing kelp forests/seaweed beds for mitigation and adaptation against global warming: Korean Project Overview. *ICES J Mar Sci* **70**: 1038–44.

Committee on Geoengineering Climate. 2015. Technical evaluation and discussion of impacts. Climate intervention: carbon dioxide removal and reliable sequestration. Report no 9780309305297. Washington, DC: National Academies Press.

Denman KL, Brasseur G, Chidthaisong A, *et al*. 2007. Couplings between changes in the climate system and biogeochemistry. In: Solomon S, Qin D, Manning M, *et al*. (Eds). Climate change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK, and New York, NY: Cambridge University Press.

Duarte CM, Borum J, Short FT, and Walker DI. 2005a. Seagrass ecosystems: their global status and prospects. In: Polunin NVC (Ed). Aquatic ecosystems: trends and global prospects. Cambridge, UK: Cambridge University Press.

Duarte CM, Losada IJ, Hendriks IE, *et al*. 2013. The role of coastal plant communities for climate change mitigation and adaptation. *Nature Climate Change* **3**: 961–68.

Duarte CM, Marbà N, Gacia E, *et al*. 2010. Seagrass community metabolism: assessing the carbon sink capacity of seagrass meadows. *Global Biogeochem Cy* **24**: GB4032.

Duarte CM, Middelburg JJ, and Caraco NF. 2005b. Major role of marine vegetation on the oceanic carbon cycle. *Biogeosciences* **2**: 1–8.

Eyre BD, Andersson AJ, and Cyronak T. 2014. Benthic coral reef calcium carbonate dissolution in an acidifying ocean. *Nature Climate Change* **4**: 969–76.

Falkowski P. 2012. Ocean science: the power of plankton. *Nature* **483**: S17–S20.

Frankignoulle M, Canon C, and Gattuso JP. 1994. Marine calcification as a source of carbon dioxide: positive feedback of increasing atmospheric CO_2. *Limnol Oceanogr* **39**: 458–62.

Gattuso JP, Allemand D, and Frankignoulle M. 1999. Photosynthesis and calcification at cellular, organismal and community levels in coral reefs: a review on interactions and control by carbonate chemistry. *Am Zool* **39**: 160–83.

Gattuso JP, Frankignoulle M, and Wollast R. 1998. Carbon and carbonate metabolism in coastal aquatic ecosystems. *Ann Rev Ecol Syst* **29**: 405–34.

Giri C, Ochieng E, Tieszen LL, *et al*. 2011. Status and distribution of mangrove forests of the world using Earth observation satellite data. *Global Ecol Biogeogr* **20**: 154–59.

Graham MH, Kinlan BP, Druehl LD, *et al*. 2007. Deep-water kelp refugia as potential hotspots of tropical marine diversity and productivity. *P Natl Acad Sci USA* **104**: 16576–80.

Green EP and Short FT (Eds). 2003. World atlas of seagrasses. Berkeley, CA: University of California Press.

Hiraishi T, Krug T, Tanabe K, *et al*. (Eds). 2014. Supplement to the 2006 IPCC guidelines for national greenhouse gas inventories: wetlands. Geneva, Switzerland: IPCC.

Houghton JT, Jenkins GJ, and Ephraums JJ (Eds). 1990. Climate change: the IPCC scientific assessment. Report prepared for Intergovernmental Panel on Climate Change by Working Group I. Cambridge, UK; New York, NY; and Melbourne, Australia: Cambridge University Press.

Kauffman JB, Heider C, Norfolk J, and Payton F. 2014. Carbon stocks of intact mangroves and carbon emissions arising from their conversion in the Dominican Republic. *Ecol Appl* **24**: 518–27.

Kennedy H, Beggins J, Duarte CM, *et al*. 2010. Seagrass sediments as a global carbon sink: isotopic constraints. *Global Biogeochem Cy* **24**: GB4026.

Khatiwala S, Primeau F, and Hall T. 2009. Reconstruction of the history of anthropogenic CO_2 concentrations in the ocean. *Nature* **462**: 346–49.

Kleypas J. 1997. Modeled estimates of global reef habitat and carbonate production since the last glacial maximum. *Paleoceanography* **12**: 533–45.

Laffoley D, Baxter JM, Thevenon F, and Oliver J (Eds). 2014. The significance and management of natural carbon stores in the open ocean. Gland, Switzerland: IUCN.

Lam PJ, Doney SC, and Bishop JK. 2011. The dynamic ocean biological pump: insights from a global compilation of particulate organic carbon, $CaCO_3$, and opal concentration profiles from the mesopelagic. *Global Biogeochem Cy* **25**: GB3009.

Lutz SJ and Martin AH. 2014. Fish carbon: exploring marine vertebrate carbon services. Arendal, Norway: GRID-Arendal.

Mathez EA. 2013. Climate change: the science of global warming and our energy future. New York, NY: Columbia University Press.

Mcleod E, Chmura GL, Bouillon S, *et al*. 2011. A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO_2. *Front Ecol Environ* **9**: 552–60.

Muraoka D. 2004. Seaweed resources as a source of carbon fixation. *Bull Fish Res Ag Japan* **1**: 59–64.

Pakhomov EA, Froneman PW, and Perssinotto R. 2002. Salp/krill interactions in the Southern Ocean: spatial segregation and implications for the carbon flux. *Deep-Sea Res Pt II* **49**: 1881–907.

Pan Y, Birdsey RA, Fang J, *et al*. 2011. A large and persistent carbon sink in the world's forests. *Science* **333**: 988–93.

Pendleton L, Donato DC, Murray BC, *et al*. 2012. Estimating global "blue carbon" emissions from conversion and degradation of vegetated coastal ecosystems. *PLoS ONE* **7**: e43542.

Russell LM, Rasch PJ, Mace GM, *et al*. 2012. Ecosystem impacts of geoengineering: a review for developing a science plan. *Ambio* **41**: 350–69.

Sabine CL, Feely RA, Gruber N, *et al*. 2004. The oceanic sink for anthropogenic CO_2. *Science* **305**: 367–71.

Shaw EC, Phinn SR, Tilbrook B, and Steven A. 2015. Natural in situ relationships suggest coral reef calcium carbonate production will decline with ocean acidification. *Limnol Oceanogr* **60**: 777–88.

Smale DA, Burrows MT, Moore P, *et al*. 2013. Threats and knowledge gaps for ecosystem services provided by kelp forests: a Northeast Atlantic perspective. *Ecol Evol* **3**: 4016–38.

Spalding H, Foster MS, and Heine JN. 2003. Composition, distribution, and abundance of deep-water (> 30 m) macroalgae in central California. *J Phycol* **39**: 273–84.

Spalding M, Kainuma M, and Collins L. 2010. World atlas of mangroves. London, UK, and Washington, DC: Earthscan.

Spalding M, Ravilious C, and Green E. 2001. World atlas of coral reefs. Prepared at the UNEP World Conservation Monitoring Centre. Berkeley, CA: University of California-Berkeley.

Suzuki A and Kawahata H. 2003. Carbon budget of coral reef systems: an overview of observations in fringing reefs, barrier reefs and atolls in the Indo-Pacific regions. *Tellus B* **55**: 428–44.

Ware JR, Smith SV, and Reaka-Kudla ML. 1992. Coral reefs: sources or sinks of atmospheric CO_2? *Coral Reefs* **11**: 127–30.

Waycott M, Duarte CM, Carruthers TJB, *et al*. 2009. Accelerating loss of seagrasses across the globe threatens coastal ecosystems. *P Natl Acad Sci USA* **106**: 12377–81.

Woosley RJ, Millero FJ, and Grosell M. 2012. The solubility of fish-produced high magnesium calcite in seawater. *J Geophys Res* **117**: C04018.

Supporting Information

Additional, web-only material may be found in the online version of this article at http://onlinelibrary.wiley.com/doi/10.1002/fee.1451/suppinfo

University at Buffalo
The State University of New York

Faculty Position in Freshwater Molecular Ecology (open rank)
University at Buffalo

The Department of Biological Sciences at the University at Buffalo is seeking outstanding applicants for a tenured/tenure track faculty position (open rank) in freshwater molecular ecology. A competitive startup package will be provided to the successful candidate.

The University at Buffalo (UB) is the largest and most comprehensive campus in the State University of New York (SUNY) system. The Department of Biological Sciences is a comprehensive center for innovative, interdisciplinary life sciences research. The faculty position is offered as part of the newly established Institute on Research and Education in Energy, Environment and Water (RENEW) at UB in its Freshwater Coastal Ecosystems & the Blue Economy focus area. The goal of this focus area is to advance research in water and environmental sustainability. As such, the successful candidate will work in an interdisciplinary group of highly collaborative faculty whose research impacts all areas of freshwater science, including engineering, economics, and environmental policy management. Further details on RENEW and the focus area can be found at https://www.buffalo.edu/renew.html.

The successful candidate will be expected to maintain an externally funded research program and to participate in graduate and undergraduate teaching. Successful candidates are envisioned to articulate "T-shaped" research programs that combine deep disciplinary studies with interdisciplinary work to advance the research and teaching missions of the University at Buffalo, the RENEW Institute and the Department of Biological Sciences.

Applicants should have a Ph.D. (or other doctorate degree), at least two years of postdoctoral experience, a scholarly publication record and fluency in both spoken and written English. Candidates at the senior level should have an exceptional record of research funding and display leadership in their field.

To apply, electronically submit a curriculum vitae, description of current and future research interests (3 pages maximum), and copies of published or in press publications (no more than five) from recent work to: https://www.ubjobs.buffalo.edu/applicants/Central?quickFind=59630. Applications will be reviewed upon completion, but for full consideration should be received by February 15, 2017. Please consult our website (http://www.biology.buffalo.edu) for information about UB, our department and our community.

UB is an AA/EOE and welcomes all to apply including veterans and individuals with disabilities.

© The Ecological Society of America