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Coastal Natural Climate Solutions:

An Assessment of Scientific Knowledge Surrounding Pathways for Carbon Dioxide Removal & Avoided Emissions in Nearshore Blue Carbon Ecosystems

Environmental Defense Fund
Natural Climate Solutions

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About this report

This is one of three reports produced by the Environmental Defense Fund (EDF) ocean science team as part of a two-year EDF project on natural climate solutions (NCS). With financial support from the Bezos Earth Fund, EDF seeks to build consensus around the scientific readiness, market suitability, socioeconomic dimensions and pathways to large-scale uptake of NCS within four major parts of the earth system – tropical forests, temperate forests, working (agricultural) lands and the oceans. The ultimate objective of EDF's work is to identify scalable interventions that could preserve or magnify NCS pathways and that are ready to implement – i.e., interventions that are likely to result in durable carbon sequestration via a NCS pathway, are likely to generate co-benefits and that present low risk of adverse social, economic or ecological adverse impacts. We also identify where further scientific and policy research is needed to result in NCS that meet these criteria.

Within the ocean system specifically, EDF is examining three sets of potential NCS interventions:

- Interventions in the open ocean, including carbon sequestration via the rebuilding of biomass in large marine mammals and epipelagic fishes, and the potential for avoided emissions by restricting or limiting new fishing in the mesopelagic ocean and/or benthic trawling,
- various interventions to conserve, restore and increase the productivity of macroalgal (seaweed) systems (natural beds and farms) to avoid GHG emissions and sequester more carbon (C) and
- interventions to conserve, restore and manage vegetated, coastal blue carbon ecosystems such as mangroves, marshes and seagrasses to avoid GHG emissions and increase C sequestration.

The present report attempts to describe the state of the science, including key uncertainties, surrounding the third set of pathways – those based on restoring and protecting coastal blue carbon ecosystems. EDF has prepared companion reports on the state of the science surrounding the open ocean and macroalgal pathways. Together, these ocean system reports served as inputs for a series of complex systems mapping workshops in which EDF engaged more than 60 outside experts to critically evaluate our initial findings; to identify co-benefits, risks, tradeoffs and equity concerns associated with the various pathways; and identify any promising additional pathways for carbon sequestration or avoided emissions. As such, the present report is just a starting point for discussion and exploration of the scientific and socioeconomic dimensions surrounding coastal blue carbon pathways, and does not necessarily reflect the consensus of EDF's nearshore blue carbon workshop participants. EDF is separately investigating the market readiness of pathways associated with forest and agricultural systems.

Executive Summary

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NCS are designed to avoid greenhouse gas (GHG) emissions or sequester carbon from the Earth's atmosphere by protecting, managing, restoring or enhancing ecosystems. There are now formal standards for carbon credits based on NCS in nearly every major terrestrial or coastal biome except the world's deserts. Yet there is wide divergence in the scientific and market readiness of these biomes to support high-quality, NCS-based carbon credits and reliable pathways for carbon dioxide removal (CDR) or negative emissions technologies more generally. In this report, we review some key scientific uncertainties and areas for further research surrounding the preservation and restoration of vegetated, coastal blue carbon ecosystems – mangroves, tidal marshes and seagrasses – as NCS pathways to capture and sequester carbon from the atmosphere or avoid new emissions.

As part of this analysis, we assessed the present suitability of each of these pathways to serve as a basis for the development of high-quality carbon credits[1] and, where appropriate, identified specific barriers to credit development such as challenges in monitoring, reporting and verification (MRV) or deficiencies in permanence or durability. In addition, we explore the added blue carbon potential in the ecological and socioeconomic linkages that can exist in certain geographic contexts among these ecosystem types, and between one or more these ecosystem types and coral reefs. This review does not address the potential for CDR from farmed or natural macroalgal systems (seaweeds) even though natural seaweed habitats are also coastal, as these systems are covered in a companion report.

General assessment

We found there were myriad urgent imperatives to conserve all coastal ecosystems, including coral reefs and natural macroalgal beds, regardless of carbon sequestration. Restoration of nearly all these ecosystem types would also yield many benefits, with the possible exception of seagrass restoration, which has at times proven to be ineffective. Because these systems store some carbon, it will be important to address the factors contributing to their loss and degradation, as this continues to result in the loss of carbon to the atmosphere. In addition, these systems generate valuable co-benefits, including support for recreation, support for livelihoods in both fisheries and tourism, coastal protection, biodiversity benefits and fisheries enhancement. In many instances, we found the focus on carbon sequestration as a primary objective, especially where the benefit is likely small or highly uncertain, may detract from efforts to generate excitement and support for preservation and restoration of these ecosystems. In these cases, we suggest a shift in framing to cast carbon sequestration as a co-benefit while focusing instead as a primary objective on enhancement of the other well-documented benefits these systems provide.

With several caveats we discuss below, we found that preservation of existing mangrove ecosystems was the coastal NCS pathway closest to full readiness to be a source of high-quality carbon credits, due to a

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[1] A proposed set of common criteria for evaluating carbon credit quality are described in a 2020 report released by the Carbon Credit Quality Initiative, a joint venture of EDF, WWF and the Oeko-Institut; available at edf.org/sites/default/files/documents/what_makes_a_high_quality_carbon_credit.pdf.

relatively advanced level of scientific understanding surrounding these systems' function and extent. We note that long-term persistence of these mangroves remains a subject of concern in the face of climate-induced shifts, and the balance of GHG emissions from these systems may well depend upon more complex management approaches. Restoration of mangroves was next, followed by preservation and then restoration of tidal marshes. We found that preservation and restoration of seagrass ecosystems were the pathways least ready for development, owing to both persistent uncertainties surrounding these ecosystems' overall trophic status (i.e., whether they are net sinks or sources of GHGs, with respect to the atmosphere) and evidence that restoration of seagrass ecosystems has at times been unsuccessful. We did not explicitly evaluate coral reefs as a basis for development of high-quality carbon credits since calcification – the formation of the carbonates in reef structure – serves a net source of CO_2 to the atmosphere.[2] However, we found there may be pathways, all of which require much further research, through which reefs can contribute indirectly to sequestration in adjacent and/or broader marine and coastal ecosystems.

Overarching uncertainties

The relative hierarchy above notwithstanding, we identified four nontrivial sources of uncertainty common to all these ecosystems that detract from their collective readiness to serve as a source of high-quality carbon credits:

First, increasing scientific evidence from all three vegetated coastal ecosystem types indicates there is substantial heterogeneity among individual ecosystems in whether they serve as carbon sources or sinks; the magnitude, type and source of carbon stored; fluxes of GHGs; import and export of carbon; and overall sequestration potential. Site-specific and ecosystem-scale measurements of relevant reservoirs (stocks) and fluxes (flows) of all greenhouse gasses will be necessary to build budgets of the accuracy and precision necessary to support high-quality carbon credits. For example, allometric models based on active remote sensing techniques can now estimate aboveground biomass in mangroves with astonishing precision, yet wide variation in the factors that control fluxes of GHGs in underlying soils, many of them not discernible from space or aircraft, make it largely impossible to accurately predict sequestration rate using a one-size-fits-all model. A full appreciation and consideration of the heterogeneity in the carbon cycle functions of these ecosystems is particularly important when considering impacts on equity and environmental justice, since the ecological and carbon richness of these systems is not evenly distributed around the world.

Second, we found evidence that fluxes of GHGs other than CO_2, including methane (CH_4) and nitrous oxide (N_2O), have not been adequately considered in the construction of GHG budgets for mangroves and tidal marshes. Multiple recent studies indicate that these fluxes may be substantial, weighing heavily in many cases against carbon sequestration estimated from fluxes of CO_2 alone. The factors that determine the strength of these CH_4 and N_2O fluxes are site-specific and include disturbance history, quantity and quality of allochthonous carbon inputs, including those from sources of terrestrial pollution, and inundation regime.

Third, there is substantial reason to question the permanence of carbon storage in these ecosystems given the projected, synergistic impacts of climate change and future land-use patterns. Owing to a lack of suitable predictive models, estimates of sequestration potential in these ecosystems – even those presented as cost-effective estimates – have typically neglected to account for the interaction of climate effects, such as sea level rise and the projected increase in frequency and severity of tropical storms, the alteration of rainfall patterns and related salinity regimes, and projected changes in land-use patterns, including a failure to account for the phenomenon of "coastal squeeze" (i.e., a failure to accommodate the upland migration of mangroves and tidal marshes in response to sea level rise).

Fourth, there is reason to believe that recent appraisals of the sequestration potential associated with restoration of all three types of vegetated systems, such as those contained in Griscom et al. (2017) and Roe et al. (2021), may represent substantial overestimates. Because roughly half of the world's coastal wetlands have been converted to agricultural use Pendleton et al. (2012) and Reise et al. (2021) conclude in a recent assessment of nature-based solutions that much of this land should not be included in estimates of the area available for restoration because restoring such systems could compromise food security or lead to emissions leakage.

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[2] The chemistry of carbonate formation is discussed in more detail in the included primer on carbon cycling (p. 12).

Other uncertainties

We also documented several other sources of uncertainty surrounding the various ecosystem types. These include:

- A lack of certainty surrounding the global extent of tidal marshes and, particularly, seagrasses, and their prospects for future extent, given upgradient migration necessary as sea level rises,
- an incomplete understanding of the quantity and fate of allochthonous carbon subsidies received by seagrasses, tidal marshes and mangroves from terrestrial sources or adjacent blue carbon ecosystems (e.g., coral reefs),
- a failure to consider the synergistic effects of climate change or potential ecological cascades on the permanence of carbon storage, particularly in tidal marshes, and
- in seagrasses, an incomplete understanding of the apparent heterogeneity in rates of air-sea gas exchange and the balance between carbonate production and dissolution, the net effect of which appears to make some seagrass ecosystems net sources of CO_2 with respect to the atmosphere while others are sources.

Research and development priorities

Following these uncertainties, we identified several significant research and development needs that could advance the readiness of these NCS pathways to support high-quality carbon credits and justify other investments to protect or accelerate them. These needs include (for multiple ecosystem types):

- Improvements in our fundamental understanding of the global extent of tidal marshes, particularly at high latitudes, and seagrasses.
- In mangroves and tidal marshes: Multiple, detailed, time-series field studies of total GHG emissions (including separate accounting for fluxes of CO_2, CH_4 and N_2O) and sequestration rates in a range of ecosystems sufficient to encompass the broad variation in different variables known to govern soil redox regimes and GHG production. These variables include changing hydroperiod, climate change impacts, seasonality, the system's history of disturbance and the quantity and quality of allochthonous C and nutrient inputs (such as those from terrestrial pollution sources).
- Development of additional, distributed, low-cost and robust (to environmental damage) technologies for measuring GHG fluxes. Such technologies and sensors would allow scientists, project developers and project auditors to make observations of GHG fluxes in multiple systems at the necessary level of precision to support carbon crediting projects, including in developing nations where funding may not be available for regular overflights by monitoring aircraft or capital infrastructure such as eddy flux covariance towers.
- Improved, spatially-explicit modeling approaches to predict GHG fluxes and net C sequestration in different mangrove and marsh ecosystems whose soil dynamics cannot be resolved solely using imagery taken from space or aircraft. These models should account for future ecosystem state due to the interactive effects of climate change and predicted land-use changes, including the phenomenon of coastal squeeze.
- Studies designed to better differentiate allochthonous and autochthonous sources of carbon, a scientific knowledge gap common to all coastal blue carbon ecosystems. The ability to distinguish among carbon sources is also critical in a carbon market context, since methodologies developed under Verra's voluntary carbon market standards require the deduction of allochthonous carbon from any claimed credit.[3]

For tidal marshes:

- Improved models to predict the carbon sequestration potential of tidal marshes, including associated peat soils, under future climate scenarios and different ecological regimes. These models must allow land managers to evaluate the potential impacts of trophic cascades and assumed land-use trends, in addition to climate-related variables such as sea level rise, warming and increased coastal storm frequency/severity. In addition, these models must account for climate-driven habitat succession between tidal marshes and mangroves.

For seagrass beds:

- Improved understanding of the sources and fate of carbonates in seagrass meadow sediments,

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[3] See, e.g., verra.org/wp-content/uploads/2018/03/VM0033-Methodology-for-Tidal-Wetland-and-Seagrass-Restoration-v2.0-30Sep21-1.pdf

including contributions to CO_2 production, both within seagrass beds and upstream of these ecosystems.

- Additional measurements of air-sea gas exchange above seagrass beds, leading to development of more robust predictive models.
- Improved understanding of the vulnerability of these systems to sea level rise.
- Continued investigation into the causes of restoration project failures in seagrass systems.

An additional need: new frameworks to account for intersystem linkages

Finally, we emerged with an important finding concerning current frameworks for identifying, quantifying and integrating the many ecological and biogeochemical linkages between different coastal blue carbon ecosystems, and between coastal systems and potential pathways for NCS in the open ocean. For the most part, these important linkages between blue carbon ecosystems have been appreciated only qualitatively, likely causing us to underestimate the collective potential that lies in their contribution to broader seascapes. This is particularly true of coral reefs: Although several studies have quantified the myriad co-benefits coral reefs provide as part of integrated ocean systems, we could find none that focused specifically on the contribution of reefs to carbon sequestration in adjacent blue carbon ecosystems of other types. Research of this sort is long overdue, but will first likely require a change in perspective that considers blue carbon ecosystems not in isolation, but as components of larger systems. The carbonate that forms coral reef structure is not a sink for atmospheric CO_2, but reef communities are complex – including a wide array of plants and other carbon fixers – and they may well indirectly assist many of the other closely associated blue carbon systems that do more directly sequester carbon. One very recent study suggests there may be value in integrating into these seascapes other types of nontraditional blue carbon habitats such as oyster reefs (Hurst et al., 2022); tidal forested wetlands also merit consideration.

Definitions:

Carbon market: A market in which units — allowances or credits — are traded between entities. When units are used for voluntary purposes or where carbon credits are certified solely by voluntary programs or standards, the market is often referred to as a “voluntary” carbon market. Where units are used to satisfy legal compliance obligations, this is often referred to as a “compliance” market.

Nature-based solutions (NBS): The full range of values humans derive from natural systems, defined by IUCN (2020) as “actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits”.

Natural climate solutions (NCS): A subset of NBS that directly addresses the GHG reduction benefits (i.e., increase carbon storage and/or avoid greenhouse gas emissions) that humans derive from natural systems via conservation, restoration, and/or improved management actions.

Carbon Dioxide Removal: process in which carbon dioxide gas (CO_2) is removed from the atmosphere and sequestered for long periods of time.

Monitoring, Reporting and Verification: A system or protocol for tracking specific methods and outcomes, transparently communicating specific information, and validating that the information is accurate and complete. Often abbreviated as MRV.

Carbon capture and storage: the process of trapping carbon dioxide produced by burning fossil fuels or any other chemical or biological process and storing it in such a way that it is unable to affect the atmosphere.

Blue Carbon: carbon sequestered mangrove forests, seagrass beds and tidal marshes (Mcleod et al., 2011). More recently, some have broadened the definition to include all carbon “captured by the world’s ocean and coastal ecosystems” (NOAA NOS, 2021).

Introduction: Natural Climate Solutions in Coastal Ecosystems

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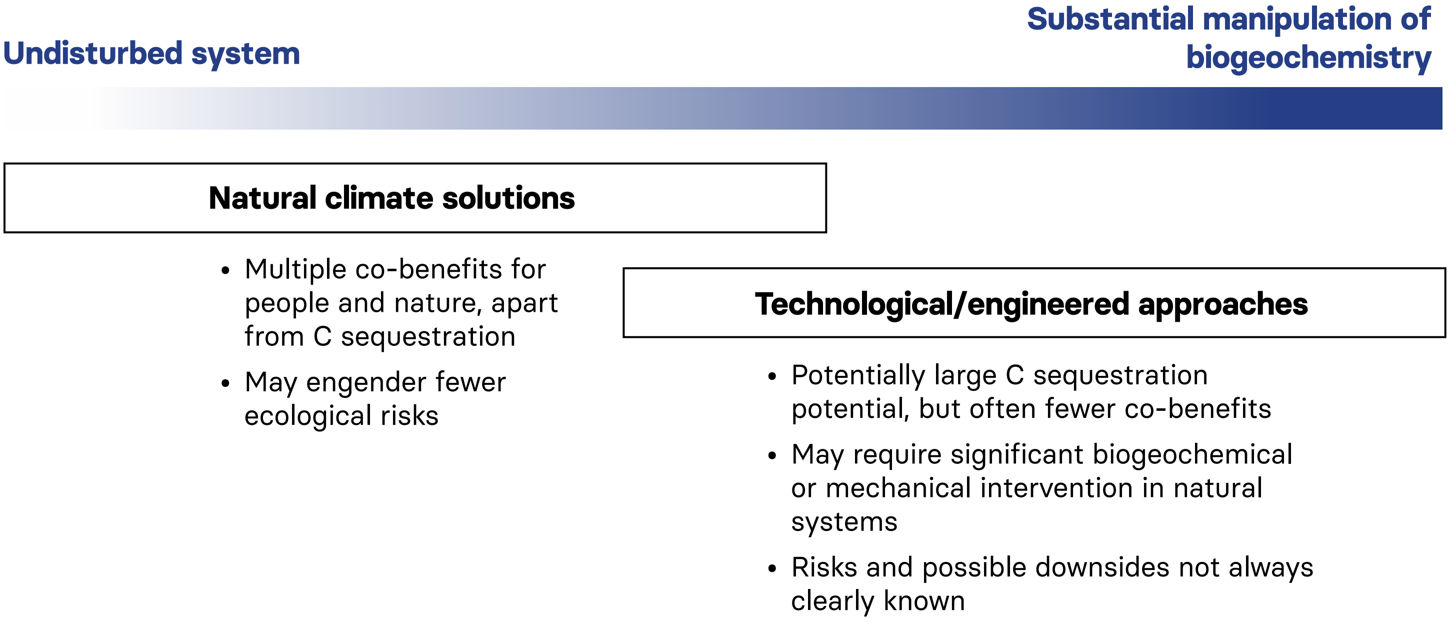
NCS as a subset of approaches for carbon dioxide removal

Natural Climate Solutions aim to avoid greenhouse gas (GHG) emissions or sequester carbon from the Earth's atmosphere by protecting, managing or restoring ecosystems (Griscom et al., 2017). These natural solutions lie along a broad spectrum of carbon dioxide removal (CDR) pathways that includes, at the other extreme, engineered solutions such as the various forms of carbon capture and storage (CCS) and artificial fertilization of the oceans with iron or other nutrients (Fig. 1). While there is a strong argument that no climate solution requiring human intervention can truly be considered "natural" (e.g., Osaka et al., 2021), some CDR pathways require substantially more modification of ecosystems through human engineering than others; as is the case for nearly all strategies aimed at capturing and storing carbon dioxide via technological approaches, the timescale over which the approach sequesters carbon will depend heavily on the location and methods employed (Siegel et al., 2021).



Undisturbed system

Substantial manipulation of biogeochemistry

Natural climate solutions

- Multiple co-benefits for people and nature, apart from C sequestration
- May engender fewer ecological risks

Technological/engineered approaches

- Potentially large C sequestration potential, but often fewer co-benefits
- May require significant biogeochemical or mechanical intervention in natural systems
- Risks and possible downsides not always clearly known

FIGURE 1.
Conceptual schematic showing the space occupied by natural climate solutions (NCS) and engineered/technological CDR approaches, respectively, along a continuum of intervention in the target system.

In contrast, NCS typically offer multiple co-benefits for people and nature, in addition to their function as mechanisms for carbon sequestration or emissions avoidance. Through the preservation or enhancement of biogeochemical processes, these NCS can make ecosystems more resilient in the face of climate change, provide food for growing populations, provide ecosystem services such as coastal storm protection and water filtration, and support human livelihoods in industries as diverse as outdoor recreation, agriculture and marine operations (Leavitt et al., 2021).

Interest in NCS, which can form the basis for carbon credits or offsets, or support other non-credit-based vehicles for decarbonization, has traditionally focused on pathways in terrestrial biomes, including agroforestry practices (Anderson and Zerriffi 2012), management of temperate forests (Ontl et al., 2020), revegetation or avoided conversion of tropical forests (Griscom et al., 2020), and modification of agricultural practices to preserve or increase stocks of carbon in terrestrial cropland soils (Bossio et al., 2020; Oldfield et al., 2021). The characterization and quantification of NCS pathways in vegetated, coastal blue carbon ecosystems such as tidal marshes, mangrove swamps and seagrass beds, is a comparatively younger area of research, while interest in the NCS potential of open-ocean ecosystems has emerged even more recently. Indeed, the term "blue carbon" itself originated in just 2009 (Nellemann et al., 2009), referring specifically to the carbon sequestered mangrove forests, seagrass beds and tidal marshes (Mcleod et al., 2011). More recently, some have broadened the definition to include all carbon "captured by the world's ocean and coastal ecosystems" (NOAA NOS, 2021).[4]

Coastal blue carbon ecosystems

Coastal blue carbon ecosystems, which occupy somewhere between 709,000 – 856,000 km^2 (0.15% of Earth's surface, or 0.2% of ocean surface area),[5] support high areal rates of primary productivity compared with other biomes but face significant threats from coastal human development (Duarte 2017). The rapid loss of coastal blue carbon systems, on the scale of ten times faster than the loss of tropical forests (Duarte et al., 2013), represents an incredible loss of carbon sequestration capacity and opportunity to reap the benefits of myriad ecosystem services. By one measure, the combined, present-day rate of carbon burial in seagrasses, mangroves and tidal marshes sediments represents roughly 50% of the overall rate of carbon burial in marine sediments (Duarte et al., 2005). Importantly, blue carbon systems often exist as habitat mosaics, with significant exchanges of carbon and nutrients among them. Biodiversity in some of these systems is high, creating complex food webs and correspondingly complex biogeochemical processes.

Rapid growth in our knowledge of the complex biogeochemical cycles that define these ecosystems (Lovelock and Duarte 2019), their charismatic appeal to human sensibilities and the many ecosystem services they provide has stimulated interest in new market-based mechanisms to finance their restoration and conservation (Stuchtey et al., 2020; Vanderklift et al., 2019), and both Verra and Gold Standard now have protocols for the development of credits based on marshes, mangroves and seagrasses. Globally, coastal blue carbon habitats are estimated to store 10 – 24 Pg C and sequester 30.0 – 70.1 Tg C yr^{-1} (Lovelock and Reef 2020), though, as we discuss at length later in the report, this figure does not account for fluxes of CH_4 or N_2O, which could offset the effects of carbon sequestration with respect to radiative forcing in the atmosphere. Macreadie et al. (2021) estimate that conservation of coastal blue carbon ecosystems could avoid approximately 83 Tg C in new emissions per year, with restoration having the potential to sequester an additional 229 Tg C yr^{-1}. Importantly, these ecosystems are not equally distributed throughout the world, with mangroves dominating over other coastal ecosystem types in the tropics, and some nations having far more blue carbon coastline than others (Macreadie et al., 2021).

The future of these systems to continue as sinks largely depends on the combined effects of habitat loss, loading of anthropogenic nutrients, natural landward migration, restoration, ocean acidification and sea level rise, among other factors, particularly for mangroves and marshes. Coastal space is a precious global commodity for development, biodiversity and

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[4] Emerging NCS pathways in open ocean ecosystems are described in a separate, companion report prepared by the EDF ocean science team.

[5] Based on extent estimates of Slobodian and Badoz (2019) for mangroves, UNEP-WCMC (2016) for seagrasses, J. Li et al. (2020) for coral reefs (upper and lower bounds of probable extent) and Mcowen et al. (2017) for emergent marshes, and the ocean surface area of Eakins and Sharman (2007). The calculation we present here agrees generally with that of Duarte et al. (2013), though the Duarte et al. estimate of 0.2% global extent also included some macroalgae. In all instances, the estimate for seagrasses is particularly uncertain due to the ineffectiveness of remote sensing approaches in delineating seagrass habitat.

natural carbon storage. The United Nations estimates approximately 40% of the world's population lives within 100 km of a coastline and is increasing in step with urbanization.[6] Globally, over 60% of coastal wetlands have been lost since 1900, and 25% – 50% in the past 50 years (Duarte et al., 2013).

Recent studies suggest that under certain conditions, sea level rise could result in substantial net gains in blue carbon. Under this scenario, gains would occur through a landward-expanding footprint of blue carbon systems as long as sediment supply is not restricted and sufficient accommodation space is created (Macreadie et al., 2019; Schuerch et al., 2018). But landward expansion could stress or eliminate parts of systems already pushed near their biotic depth or light limits (Mueller et al., 2016). Additionally, increased storm frequency or intensity, marine heatwaves, eutrophication, pollution and freshwater availability can all contribute to changes in productivity, biodiversity, carbon sequestration and remineralization of stored carbon, and the emission of GHGs to the atmosphere (Macreadie et al., 2019). A fundamental assumption underlying all projections involving the possible expansion of blue carbon habitat is that human actions and infrastructure will accommodate this movement; this includes restraint in new construction of buildings or other infrastructure (dikes, seawalls, etc.) on coastlines that could otherwise be occupied by mangroves or tidal marshes, and sensitivity to dredging or damming of rivers that would limit critical sediment supply (Rogers et al., 2019). For example, with no additional accommodations that would allow wetland expansion in response to sea level rise, global coastal wetland extent is likely to shrink by up to 30% by 2100.

Report overview

In this report, we first present a brief primer on the storage and cycling of carbon in coastal blue carbon ecosystems and then examine individually each of the different ecosystem types. We identify key scientific uncertainties surrounding each ecosystem and recommend some areas for further research and development; a brief discussion on coral reefs argues for the integration of these non-traditional blue carbon systems into broader seascape frameworks with adjacent ecosystem types. Finally, we conclude with some findings concerning carbon markets.

An important caveat: no substitute for reduced emissions

While this report focuses on carbon sequestration, it is important to note that no strategy for removal of existing CO_2 from the Earth's atmosphere is a substitute for avoided or reduced emissions, even when removal is accomplished through some form of NCS or via a hybrid approach such as bioenergy with carbon capture or storage (BECCS). For two primary reasons, there is no way to fully reverse the warming effect of new GHG emissions when one fully evaluates their impact over the decadal to centennial timescales most immediately relevant for climate change. First, certain impacts of new GHG emissions are committed nearly as soon as the contribution of these emissions to warming is realized; for example, the effect of new emissions on heating and acidification of the ocean interior and, due to the presence of multiple positive feedbacks, new melting of polar ice leading to global sea level rise, cannot be fully reversed by removal of an equivalent quantity of CO_2 in the future (Golledge et al., 2015; Gruber 2011; Levermann et al., 2013). Second, experiments in global climate models show that CO_2 removal from the atmosphere will become less and less effective over time as much of the anthropogenic carbon that has already been "pushed" into the ocean and land carbon reservoirs over the past 150 years move back into the atmosphere through a massive process of chemical re-equilibration between the main components of the surface Earth system (Canadell et al., 2021). For example, for a 100 Pg C removal of CO_2 from the atmosphere today, only about a quarter of the removed CO_2 will appear to remain out of the atmosphere after 80 – 100 years (Keller et al., 2018).[7] Thus, while solutions that remove carbon from the atmosphere can assist us in our critical effort to limit global warming, a method or policy intervention that reduces or avoids new emissions should take priority if there is a choice between the two.

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[6] un.org/esa/sustdev/natlinfo/indicators/methodology_sheets/oceans_seas_coasts/pop_coastal_areas.pdf

[7] The authors of the 2021 Intergovernmental Panel on Climate Change (IPCC) summarize this quite simply: "An emission of CO_2 into the atmosphere is more effective at raising atmospheric CO_2 than an equivalent CO_2 removal is at lowering it." (Canadell et al., 2021)

A very brief primer on carbon cycling in vegetated, coastal blue carbon ecosystems

Tidal marsh, mangrove and seagrass ecosystems store carbon in both living biomass and in underlying substrate.[8] The distribution of stored carbon among these two compartments varies across both ecosystem types and across individual ecosystems of the same type. The soils or sediments can contain both organic and inorganic (i.e., consisting of carbonates such as $CaCO_3$) carbon, with some fraction of each originating within the ecosystem itself (termed "autochthonous" carbon) and some fraction originating from outside the ecosystem (termed "allochthonous" carbon). In seagrass systems, the living biomass of some symbiotic plant species (i.e., species other than seagrasses themselves) may contain substantial quantities of inorganic as well as organic carbon (Gullström et al., 2018). Additional carbon, either fixed within or transformed by these systems, may become part of either or both of the ocean's massive organic and inorganic dissolved carbon reservoirs; a small refractory fraction may persist for centuries to millennia. The carbon in these various pools or reservoirs may be more or less labile (i.e., amenable to degradation or remineralization by any number of abiotic and biological processes). The lability of the carbon in a given reservoir – along with the rates of C input or fixation from photosynthesis, lateral transport, calcification, etc. – helps determine the residence time of the carbon within the reservoir, which is in turn a primary determinant of the timescale of sequestration.

A variety of physical and biogeochemical processes serve as fluxes that move carbon between these storage reservoirs. These include processes by which carbon is fixed or remineralized within the systems themselves (photosynthesis, biogenic calcification, respiration, other microbially-mediated reduction-oxidation reactions in soils/sediments that produce or consume greenhouse gasses, etc.) and physical processes that transport carbon into, within, or out of the systems, both laterally and vertically. These latter processes include tidal inundation, advection, wet and dry atmospheric deposition, and inputs via rivers, submarine groundwater discharge and overland stormwater flow of natural or anthropogenic organic matter, sediments, and/or other dissolved or suspended constituents. The presence and size of these various reservoirs – and magnitude and direction of fluxes that connect them – determine how much carbon is processed and stored by each particular blue carbon ecosystem, and whether and to what extent a given system serves as a net source or sink of carbon with respect to the atmosphere.

Full understanding of the carbon budgets of coastal blue carbon ecosystems requires an accounting of biogenic carbonates. The formation of carbonates, whether by corals, other invertebrates, algae or planktonic species, represents a net source of CO_2 to the atmosphere that can outweigh (in a carbon budget sense) any C fixed and sequestered via photosynthesis. In seawater at equilibrium with the current concentration of CO_2 in the atmosphere, approximately 0.6 units of CO_2 are produced for every unit of $CaCO_3$ precipitated (Frankignoulle et al., 1995). Thus, whether carbonates are precipitated from seawater within the ecosystem or this calcification happens elsewhere – for example, many seagrass beds receive massive inputs of carbonates from adjacent systems, including reefs – the CO_2 that is produced must be accounted for so as not to overestimate net sequestration. A corollary is that the formation of $CaCO_3$ – such as that contained in the large reservoirs of coral reefs or carbonate-rich sediments that form the foundation for seagrass beds – serves as a net source of CO_2 to the atmosphere, and thus one should not generally look to the present-day formation of reef structure as a climate mitigation pathway.

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[8] In the case of seagrasses, salt marshes and coral reefs, this substrate is referred to as sediment. In the case of mangroves, the substrate is normally considered soil; however, there is some technical debate on this point among soil scientists (e.g., Ferreira et al., 2007).

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Mangroves

Extent, current storage and sequestration potential

Scientists have leveraged recent advances in passive remote sensing, LIDAR imaging and allometry (Liu et al., 2021; Simard et al., 2019; Thomas et al., 2018) to estimate the global extent and carbon stores in the aboveground biomass of mangroves with a precision exceeding that of marshes and seagrasses (Macreadie et al., 2021). Mangroves are estimated to cover between 137,600 km^2 (Bunting et al., 2018) and 150,000 km^2 (Slobodian and Badoz, 2019) of the Earth's surface, with total aboveground C storage ranging from 1.2 Pg C (Hamilton and Friess, 2018) to 3.9 Pg C (Simard et al., 2019). However, the majority of C stored by mangrove ecosystems is held in underlying soils, making estimates of total mangrove C storage largely dependent on the depth to which one integrates below the land surface. When only the top 1 m of soil is included, total storage has been estimated at between 6.4 Pg C (Sanderman et al., 2018) and 7.3 Pg C (Goldstein et al., 2020). When integrating to 2 m depth, mangrove systems may store as much as 12.6 Pg C globally in combined aboveground and belowground biomass and underlying soils (Sanderman et al., 2018).

Estimating rates of C sequestration by mangroves, or their future sequestration potential, is less straightforward than estimating the systems' current geographic extent or present storage. There is general scientific consensus that most mangrove systems are net sinks of CO_2. However, a growing body of research indicates there is substantial heterogeneity in rates of CH_4 and N_2O production by mangrove soils, suggesting we must make changes to the way GHG budgets are calculated for specific systems and for mangroves globally. This heterogeneity may well depend upon management approaches and climate-driven effects. Recent estimates of present-day global C sequestration rates by mangroves range from 24 Tg C yr^{-1} (Alongi 2014) to 33 Tg C yr^{-1} (Lovelock and Reef, 2020). There is substantial variation in estimates of the emissions that would be avoided by preventing further conversion and degradation of existing mangrove forests, as well as the potential additional sequestration that could be achieved through restoration of mangrove systems. Estimates of the former range from a maximum, unconstrained by potential costs, of 0.130 Pg CO_2e yr^{-1} (Griscom et al., 2017), to two lower, cost-effective potentials calculated using different methods of 0.065 Pg CO_2e yr^{-1} (Roe et al., 2021) and 0.117 Pg CO_2e yr^{-1} (Griscom et al., 2017).

Estimates of potential additional C sequestration via restoration range from a maximum potential of 0.596 Pg CO_2e yr^{-1} (Griscom et al., 2017) to lower, cost-effective estimates of 0.179 Pg CO_2e yr^{-1} (Griscom et al., 2017) and 0.0057 Pg CO_2e yr^{-1} (Roe et al., 2021). Notably, neither of the studies containing these various emissions estimates explicitly accounted for the effects of climate change when estimating the potential restoration area, or the durability of storage, required to achieve the final values. The failure to account for these climate effects, which include direct impacts from warming temperatures, sea level rise and the associated phenomenon of coastal squeeze, and the predicted increase in frequency of tropical cyclones, is discussed below as a substantial source of uncertainty surrounding nearly all coastal blue carbon ecosystems.

Deforestation and conversion of mangrove habitats to other land uses are the largest sources of mangrove loss. For example, a recent estimate by Adame et al. (2021) suggests that under current land-use trajectories, 2,391 Tg CO_2-eq will be emitted due to mangrove deforestation between 2020 – 2100; when accounting as well for lost potential sequestration, that number jumps to 3,392 Tg CO_2-eq by 2100. An additional source of uncertainty is contained in such calculations: Many past studies have treated CO_2 emissions as if they occurred only in the year of loss, but it can take years to decades for mangrove carbon to be fully remineralized (Adame et al., 2021).

Key uncertainties

Our literature review identified two primary sources of uncertainty surrounding the preservation and restoration of mangroves as a natural climate solution:

- Inadequate quantitative understanding of the effects on these systems of climate change, including coastal squeeze arising from interactions between coastal land-use patterns and climate effects such as sea level rise, and
- an incomplete understanding of the production in mangrove ecosystem soils of greenhouse gasses such as CH_4 and N_2O, substantial production of which could challenge traditional assertions, based on calculations that consider only fluxes of CO_2, that the systems are substantial net sinks of C with respect to the atmosphere.

A growing body of research indicates that these underlying sources of uncertainty can manifest very differently in different mangrove ecosystems depending on their particular geography, biogeochemistry and land-use and disturbance history. Most importantly, these differences suggest the blue carbon community must begin earnestly accounting for two emergent features of these systems before harnessing their carbon processing capacity as a source of NCS:

- Substantial heterogeneity across geographies and from one system to the next in both current and potential rates of sequestration under various climate and land-use scenarios, and
- substantial uncertainty, heterogeneously distributed, in the degree of permanence of the carbon stored within them.

In addition to these two primary sources of uncertainty, we identified several others pertaining to carbon accounting.

Climate-related effects, including coastal squeeze

The most sizable potential gains or losses in blue carbon stocks may depend on how shoreward mangrove migration patterns are managed for sea level rise (Lovelock and Reef 2020). Although mangroves provide support for biodiversity, flood and storm protection, and food provisioning via fisheries, in addition to their potential carbon sequestration capacity, they are severely threatened by loss of area and degradation (Inoue 2019; Menéndez et al., 2020). One of the main threats to mangroves arises from an inability of mangrove sediment surface elevations to keep pace with accelerated sea level rise (Gilman et al., 2008). On the other hand, rising global temperatures may increase primary production and expand these systems' potential range both landward and toward the Earth's poles, including encroaching on the fringes of marsh habitat (Alongi 2014). By 2100, this range expansion could yield 0.8 – 1.5 Pg C in new net C storage globally, if expansion is adequately accommodated for in coastal land-use planning decisions (Lovelock and Reef 2020); however, this figure does not account for respiration, which has been estimated at around ~ 91% of net primary production in mangroves (Alongi 2014).

Further complicating global projections, mangrove habitat can be destroyed or impaired by tropical storms (Lagomasino et al., 2021; Taillie et al., 2020), leading to new C emissions and a reduction in C storage potential. Changes in climate modes, such as intensification of El Niño events, may have similar site-specific consequences (Lovelock and Reef 2020). However, in one estimation, tropical storms have damaged only 0.1% of global mangrove cover since the 1950s (Lovelock and Reef 2020), whereas deforestation and development claimed at least 20% – 35% of global mangroves in the last 50 years (Polidoro et al., 2010). Both the frequency and intensity of tropical storms are predicted to increase as the Earth continues to warm, suggesting that the impact of these events on mangroves may increase; further study is warranted. Finally, there is a concern that the prevalence of mangrove diseases in these dense, monospecific stands may increase as stress on some stands expands under climate forcing, even in important protected areas such as Cuba's Jardines de la Reina National Park (D. Rader, *personal communication*).

Production and significance of GHGs other than CO_2

While there is general scientific consensus that mangrove ecosystems are net sinks for CO_2 (Zeng et al., 2021), scientists have increasingly recognized the importance of microbially mediated biogeochemical processes in mangrove soils in generating fluxes of other potent greenhouse gasses – CH_4 and N_2O – at magnitudes that may substantially reduce net rates of sequestration in these systems (Rosentreter, Al-Haj, et al., 2021). The production rates of these gasses can be highly heterogeneous in both space and time, with flux magnitudes depending on a range of factors whose relative importance in shaping the soil redox environment we are just now beginning to understand. In some earlier studies, for example, production of CH_4 was assumed to be negligible (Middelburg et al., 1996), though this may reflect methodological limitations at the time the work was conducted. The variables that can influence GHG fluxes and net C sequestration in mangrove soils include a variety of climate change effects (Macreadie et al., 2019), seasonality, inundation regime (Rosentreter et al., 2018), the particular system's history of disturbance and the quantity and quality of any allochthonous C or nutrient inputs (from, e.g., sources of terrestrial pollution such as wastewater effluent or agricultural runoff; Alongi 2014; Kristensen 2007). In the extreme case, deforested mangroves converted to aquaculture ponds, whether abandoned or in operation, are net GHG sources (Cameron et al., 2019); there is increasing evidence that a wide range of aquatic ecosystems are net sources of CH_4, in particular (Rosentreter, Borges, et al., 2021).

Other uncertainties surrounding carbon accounting and allochthonous carbon inputs

Much as we currently lack a full understanding of the role of GHGs other than CO_2 in shaping carbon cycles in mangroves, we still do not fully understand the respective roles of allochthonous and autochthonous carbon sources in these systems. Besides long-term deposition, a substantial share of leaf biomass is consumed or lost to leaching, providing an important energy source for aquatic organisms (Alongi et al., 1998). Conversely, organic and inorganic carbon can also be transported into mangrove ecosystems from surrounding areas. As with seagrasses, allochthonous carbon sources can play important roles in mangroves by drawing down atmospheric CO_2, shaping the redox environment in soils and maintaining relative elevation in the face of sea level rise (Saderne et al., 2019).

Measures of organic carbon burial alone underestimate total mangrove CO_2 removal. As most blue carbon systems are sites of net carbonate dissolution (Saderne et al., 2019), the bicarbonate produced in mangroves may contribute considerably to local CO_2 drawdown via the impact of this bicarbonate production on alkalinity. In the Red Sea, sediments in mangroves are carbonate-rich (~ 80% by dry weight). Seasonal flooding of mangrove stands introduces eroding carbonates from adjacent reefs, which dissolve in acidic microenvironments (Middleburg et al., 1996) surrounding the roots of mangroves. Post-dissolution, the change in total alkalinity facilitates absorption by surface waters of atmospheric CO_2 (Saderne et al., 2019). Due to the variation in carbonate supply across mangrove sites (Saderne et al., 2019), we believe explicit inclusion of carbonate dissolution and a full accounting of all allochthonous and autochthonous fluxes must be a part of ecosystem-specific carbon budgets in these systems, as with the need for improved quantification of non-CO_2 GHG fluxes.

Areas for further research and development

While we found the science and market development surrounding mangroves were the most developed of the three coastal blue carbon ecosystems, we identified several areas for further research and development. These include both scientific questions and mechanisms to address uncertainties in market protocols and crediting schemes, including technologies for monitoring, reporting and verification (MRV):

- Multiple, detailed, time-series field studies of total GHG emissions (including separate accounting for fluxes of CO_2, CH_4 and N_2O) and sequestration rates in a range of mangrove ecosystems sufficient to encompass the broad variation in different variables known to govern soil redox regimes and GHG production. These variables include climate change impacts, seasonality, inundation and salinity regime, the system's history of disturbance and the quantity and quality of allochthonous C inputs (such as those from terrestrial pollution sources).[9]

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[9] We note that at least one such effort, the NASA Carbon Monitoring System (CMS) BLUEFLUX project, is already underway. The study will combine a series of field measurements in south Florida with existing remote sensing products and eddy covariance gas flux data to produce "daily-gridded CO_2 and CH_4 flux product for the Caribbean region for the time period 2000 – present day." See carbon.nasa.gov/cgi-bin/inv_pgp.pl?pgid=4317.

- Development of additional, distributed, low-cost and robust (to environmental damage) technologies for measuring GHG fluxes. Such technologies and sensors would allow scientists, project developers and project auditors to make observations of GHG fluxes in multiple systems at the necessary level of precision to support carbon crediting projects, including in developing nations where funding may not be available for regular overflights by monitoring aircraft or capital infrastructure such as eddy flux covariance towers (Zeng et al., 2021).
- Improved, spatially explicit modeling approaches to predict GHG fluxes and net C sequestration in different mangrove ecosystems whose soil dynamics cannot be resolved solely using imagery taken from space or aircraft. The development of carbon crediting projects requires we know not just how much carbon a mangrove ecosystem contains in its above- and belowground biomass, but the magnitude of various GHG fluxes from underlying soils at present and in the future. These models should account for future ecosystem state due to the interactive effects of climate change and predicted land-use changes, including the phenomenon of coastal squeeze.
- Improved predictions of the effects of increased tropical storm intensity and frequency on the destruction and degradation of mangrove ecosystems, including the timescales over which any previously sequestered C could be released to the atmosphere.
- Studies designed to better understand and quantify ecological and biogeochemical linkages between different coastal blue carbon ecosystems and between coastal systems and potential pathways for NCS in the open ocean, perhaps using a seascape framework (Muller-Karger et al., 2014).
- Studies designed to better differentiate allochthonous and autochthonous sources of C, a knowledge gap common to all coastal blue carbon ecosystems (Saderne et al., 2019). The ability to distinguish among C sources is particularly critical since methodologies developed under Verra’s voluntary C market standards require deduction of allochthonous C from any claimed credit.

Tidal Marshes

UNSPLASH | JP VALERY

Extent, current storage and sequestration potential

Our understanding of the global extent, current C storage and C sequestration potential of tidal marshes is generally less than that of mangroves but substantially greater than that of seagrasses. Accessible marshes may be readily sampled and monitored with current technology. However, these systems' total global areal extent remains poorly mapped – at least compared with mangroves – because even many of the best current remote sensing methods have difficulty distinguishing marsh habitat from surrounding land-use types (Macreadie et al., 2021). Estimates of extent have ranged over two orders of magnitude, from 22,000 km^2 (Chmura et al., 2003) to 400,000 km^2 (Duarte et al., 2005), with two recent studies placing the extent at 54,950 km^2 and 90,800 km^2, respectively (Mcowen et al., 2017; Murray et al., 2022); the former is a conservative estimate that does not include marshes that may exist in high-latitude regions. Estimates of total C storage by tidal marshes range from 0.9 – 1.5 Pg C (Macreadie et al., 2021) to as much as 6.5 Pg C (Duarte et al., 2013). Goldstein et al. (2020) estimated that marshes store 5.6 Pg C in combined aboveground, belowground and soil organic C, measuring globally to a depth of 1 m.

There is moderate scientific consensus that marsh ecosystems serve as a net sink for C, burying approximately 15 Tg C yr^{-1} in soils (Lovelock and Reef, 2020). But, as with the estimates of sequestration by mangroves reviewed in the previous section of this report, this estimate does not account for N_2O or CH_4 emissions, which could offset much of the claimed sequestration (Rosentreter, Al-Haj, et al., 2021). Methane emissions vary across marsh types but can be substantial (Bloom et al., 2010; Mitsch et al., 2013). As with mangroves, there is substantial variation in estimates of the emissions that would be avoided by preventing further conversion and degradation of existing marshes, as well as the potential additional sequestration that could be achieved through restoration of marshes. Estimates of the former range from a maximum, unconstrained by potential costs, of 0.042 Pg CO_2e yr^{-1} (Griscom et al., 2017), to a lower, "cost-effective potential" of 0.038 Pg CO_2e yr^{-1} (Griscom et al., 2017). Estimates of potential additional C sequestration via restoration of marshes range from a maximum potential of 0.036 Pg CO_2e yr^{-1} (Griscom et al., 2017) to a lower, cost-effective estimate of 0.022 Pg CO_2e yr^{-1} (Griscom et al., 2017). These estimates do not explicitly take into account climate effects such as habitat migration, increased inundation from more frequent or severe tropical storms or the effects of altered precipitation patterns on salinity regimes.

Under certain circumstances, the restoration of tidally restricted marshes may come with an additional climate benefit. The restoration of natural water and salinity levels in marshes that have been previously disconnected from their natural tidal inputs can in many cases rapidly reduce the combined CH_4 and CO_2 emissions from such systems (Fargione et al., 2018; Kroeger et al., 2017). However, more data are needed to fully understand the global scale of potential reductions in CH_4 emissions associated with marsh restoration activities (Kroeger et al., 2017; X. Li and Mitsch 2016).

Key uncertainties

Need for integrated modeling of ecological impacts, land-use, and climate effects

The accurate prediction of C sequestration by marsh ecosystems requires integrated consideration of ecological impacts, expected future land-use patterns and climate-related changes, including sea level rise. Marsh habitats are relatively easily directly converted for uses including coastal development and agriculture, except where precluded by law and policy (Pendleton et al., 2012). Indirectly, human-caused changes in ecosystem structure and nutrient inputs can dramatically change ecosystem function, diversity, sequestration, storage, and erosion of carbon. Upgradient migration can be abruptly curtailed by structures built at the wetland/upland boundary – a prevalent practice in even well-managed wetland systems. Emerging work suggests that successful management and restoration strategies must identify multiple stressors, acquire baselines and pay particular attention to biological changes, as opposed to only focusing on acute disturbances (Coverdale et al., 2014). Coverdale et al. (2014) use the example of an ecological cascade involving burrowing crabs to illustrate the potential importance of ecology in driving carbon sequestration. Released from predation, the proliferating crabs in just three decades mobilized 150 – 250 years of accumulated peat in New England salt marshes, turning many of them from net carbon sinks to carbon sources when the peat was then remineralized.

Competing feedbacks associated with climate and sea level rise

Sea level rise, among other climate effects, is a critical control on sequestration by tidal marshes. Yet carbon cycle feedbacks involving climate and sea level rise can be both positive and negative: Some of these dynamics may drive increased sequestration in tidal marshes while others may act to depress sequestration potential. For example, poleward migration of mangroves may reduce the fraction of coast covered by tidal marsh habitat (Cavanaugh et al., 2014; Saintilan et al., 2014), but there is some hope – in addition to historical evidence – that sea level rise could have a compensating positive effect in some instances on carbon sequestration by marshes.

Tidal marshes in areas that have experienced rapid relative sea level rise over the late Holocene (4200 ya – present) have on average 1.7 - 3.7 times more carbon in the top 20 cm of underlying sediment than marshes in regions that have experienced comparative stability in sea level (Rogers et al., 2019). The authors attributed this disparity to the lower quantity of "accommodation space" available to migrating marshes in areas without rapid sea level rise. Broadly, they assessed that additional carbon accretion in coastal marshes could increase as a function of both lateral and vertical accommodation space. Additional possible feedback may be associated with the effect of increased inundation on soil redox chemistry.

Extensive historical marsh management – including ditching and draining for mosquito control as well as coastal development – has introduced further serious concerns about the future of these systems. In some cases, upgradient movement of salt into interior marsh systems both through surface channels and groundwater movement creates important but inadequately characterized risks.

Production and significance of GHGs other than CO_2; fate of allochthonous inputs

Perhaps even more so than in mangroves, there is significant uncertainty in tidal marshes surrounding the production of GHGs other than CO_2 (Macreadie et al., 2019; Rosentreter, Al-Haj et al., 2021). Coastal wetlands that receive substantial groundwater-based or other watershed-derived nitrate may be especially vulnerable to N_2O emissions, depending on hydroperiod, and require much additional research (Moseman-Valtierra et al., 2011). Restoration of normal inundation regimes in tidally restricted wetlands can reduce CH_4 fluxes, but the specific factors that determine the extent of these reductions are not completely understood (Kroeger et al., 2017; X. Li and Mitsch 2016). Similarly, there is uncertainty surrounding how much allochthonous carbon ends up in tidal marshes, and how long it remains there (Saintilan et al., 2013). These uncertainties contribute to the heterogeneity in both how these systems process carbon and how much they ultimately sequester.

Areas for further research and development

The research agenda we identified for tidal marshes overlaps substantially with that for mangroves. We find that additional research is needed in the following areas:

- Better global mapping of the extent of tidal marshes, particularly at high latitudes.
- Multiple, detailed, time-series field studies of total GHG emissions (including separate accounting for fluxes of CO_2, CH_4 and N_2O) and sequestration rates in a range of tidal marsh ecosystems sufficient to encompass the broad variation in different variables known to govern soil redox regimes and GHG production.
- Improved models to predict the extent and C sequestration potential of tidal marshes under future climate scenarios and different ecological regimes. These models must allow land managers to evaluate the potential impacts of trophic cascades and assumed land-use trends, in addition to climate-related variables such as sea level rise, warming and increased coastal storm frequency/severity. In addition, these models must account for climate-driven habitat succession between tidal marshes and mangroves.
- Better knowledge of the relative contributions of allochthonous and autochthonous carbon sources to marsh organic carbon pools, and the labilities of the carbon derived from these two sources.

Seagrasses

UNSPLASH | BENJAMIN JONES

Extent, current storage and sequestration potential

The extent and current carbon storage of seagrasses are the least constrained of the three major types of vegetated blue carbon ecosystems, and though there is little argument about their ecological importance, there is substantial uncertainty surrounding their carbon sequestration potential. Due largely to the limited usefulness of passive remote sensing methods in discerning habitat beneath the ocean surface, nearly all estimates of the areal extent of seagrasses involve some amount of interpolation and projection. These estimates range from 150,000 to 600,000 km^2 (Duarte, 2017; Duarte and Chiscano 1999), with one recent study identifying 345,000 km^2 of ocean where environmental conditions (temperature, turbidity, nutrient regime, etc.) were suitable for seagrass habitat, overlapping in many cases with verified point observations of occurrence (United Nations Environment Programme World Conservation Monitoring Centre [UNEP-WCMC] and Short, 2021). Nearly 90% of identified seagrass beds are found in the tropics (Saderne et al., 2019).

Seagrass sediments are believed to store a substantial amount of organic carbon, rivaling that stored in mangroves on a per-area basis (Fourqurean et al., 2012). Seagrass sediments store substantial quantities of inorganic carbon (i.e., carbonates) derived from allochthonous sources such as adjacent coral reefs (Mazarrasa et al., 2015; Saderne et al., 2019), but some seagrass systems may also support substantial autochthonous production of carbonates, making it difficult to discriminate between sources. Estimates of total global organic C storage in seagrasses range from 4.2 to 8.4 Pg C (Fourqurean et al., 2012); Goldstein et al. (2020) estimate that seagrasses store 5 Pg C in combined aboveground biomass, belowground biomass and sediment organic carbon when integrated to a depth of 1 m.

Key uncertainties

Global extent; the fundamental debate over storage and trophic status, largely due to the role of carbonates

As we describe above, there is fundamental uncertainty surrounding these systems' present and future potential global extent. Further, while the rate of carbon burial in seagrass beds has been estimated at 27.4 Tg C yr^{-1} (Fourqurean et al., 2012), multiple uncertainties – and differences in the approach to carbon accounting, particularly with regard to defining ecosystem boundaries – make it difficult to determine whether these systems serve as net sources or sinks of carbon with respect to the atmosphere and how much carbon they sequester.

First, it can be difficult to discriminate among the autochthonous and allochthonous sources of organic and inorganic carbon in seagrass sediments, and the source fraction of each can vary widely from one system to the next (Macreadie et al., 2019). The substantial amount of inorganic carbon present in seagrass ecosystems, much of it derived from sources outside of the seagrass bed itself (Saderne et al., 2019), has led to a debate over carbon accounting: If the aim is to make a claim concerning net sequestration of CO_2 from the atmosphere, when should one account for the CO_2 produced when these carbonates were initially precipitated from seawater? One the one hand, if one does not count this CO_2 against the carbon buried within a given seagrass ecosystem, one might conclude that this burial ultimately represents a net sink for CO_2. However, if the initial emissions associated with precipitation are accounted for as part of the carbon budget of the seagrass system, it is likely the system will emerge as a net source of CO_2. This choice of accounting method can have serious implications for carbon markets, and thus there is considerable debate about whether carbon derived from coral reefs or terrestrial sources that is buried in seagrass beds can be counted as an avoided emission. For example, the voluntary market framework VM0033 requires this carbon (all allochthonous organic carbon) to be accounted for and excluded from project credits (Kelleway et al., 2020).

Air-sea gas exchange

Second, observational challenges surrounding measurement of air-water CO_2 exchange above seagrass beds can preclude robust estimates of overall global C fluxes and air-sea flux measurements indicate that the overall trophic status of seagrass beds can vary widely from one system to the next (Van Dam, Polsenaere, et al., 2021). Loss of seagrass extent in the future will likely cause emissions, ranging from 0.1 – 0.6 Pg C (Lovelock and Reef, 2020). Saderne et al. (2019) found that about 90% of the $CaCO_3$ buried in seagrass meadows was derived from allochthonous sources, but that CO_2 emissions from the autochthonous production of carbonates could offset 30 percent of the system's overall net CO_2 sequestration. Recent evidence suggests that calcification occurring directly within some seagrass beds may drive even greater rates of CO_2 production, making some systems strong net sources of CO_2 to the atmosphere (Van Dam, Zeller, et al., 2021).

Ineffective restoration necessitates better understanding of factors driving losses

Regardless of source, the carbon buried in seagrass sediments is very vulnerable to remineralization – and restoration of these ecosystems has often proven unsuccessful (Macreadie et al., 2021). Thus, avoided conversion and degradation most likely represents a more viable NCS pathway than restoration in this case (Kelleway et al., 2020). Griscom et al. (2017) estimated that avoided conversion and degradation of seagrasses could net 0.119 – 0.132 Pg $CO_2e\ yr^{-1}$ in avoided emissions, (Griscom et al., 2017), while the cost-effective restoration potential was near zero. In addition to the potential lack of permanence associated with ineffective restoration of these ecosystems, Oreska et al. (2020) found that the restoration of seagrass meadows could enhance CH_4 and N_2O emissions, reducing any total possible sequestration benefit from restoration by about 6%.

We find that seagrass conservation approaches should consider direct disturbance or removal, along with alterations of hydrodynamic cycles by dams, climate-induced changes in rainfall patterns, and nutrient, sediment, and biodiversity dynamics – both current and projected. Adverse environmental conditions that cause seagrass mass mortality ultimately reduce biodiversity and ecosystem services while increasing remineralization (Salinas et al., 2020). Future work should also seek a betting understanding of the impacts of grazers and bioturbation (Lovelock and Reef 2020). For example, overfishing can result in loss of predators that are needed to regulate the population of grazers. In some regions, such as the Red Sea, seagrasses play limited roles in carbon sequestration, but support high levels of biodiversity which indirectly contributes to carbon fluxes and ecological services in neighboring systems (Gajdzik et al., 2021).

Areas for further research and development

The NCS pathways centered on seagrasses are the least well constrained of the three major types of vegetated coastal ecosystem. We identified several areas for further research and development:

- Better fundamental understanding of the global extent of seagrasses and their likely future extent; this is likely to involve some combination of active remote sensing and field surveys.
- Improved understanding of the sources and fate of carbonates in seagrass meadow sediments, including contributions to CO_2 production both within seagrass beds and upstream of these ecosystems.
- Additional measurements of air-sea gas exchange above seagrass beds, leading to development of more robust predictive models.
- Continued investigation into the causes of restoration project failures in seagrass systems.

Coral Reefs & Blue Carbon

UNSPLASH | MAREK OKON

Reefs as components of integrated seascapes: A new perspective within the blue carbon discourse

Coral reefs have not been traditionally considered a source of NCS because the production of calcium carbonate (i.e., the biologically catalyzed precipitation of inorganic carbon from seawater) is a net source of CO_2 to the atmosphere (Macreadie et al., 2019). Yet a more expansive view of the role of reefs in the carbon cycle – as components of broader seascapes in which carbon is exchanged between and processed by multiple, interdependent coastal and marine ecosystems – reveals several possible ways, nearly all of them as yet unquantified, that these systems may help the ocean sequester carbon. Reefs not only support a wide array of organisms – including many primary producers – but also provide both a physical foundation and ecological scaffold for organisms and biogeochemical processes that may contribute to carbon sequestration in surrounding waters or in adjacent mangrove or seagrass ecosystems, and support biodiversity and many other co-benefits that manifest well beyond their physical boundaries (Guannel et al., 2016; Mumby 2006). As such, the preservation of coral reefs warrants the same attention as a conservation strategy as that given to vegetated coastal habitats in the context of NCS.

The global areal extent of coral reefs is estimated to be between 154,000 – 301,110 km^2 (J. Li et al., 2020). The inorganic carbon in coral reefs is stored primarily in coral framework and underlying/adjacent permeable sediments (Perry 2011; associated animals and plants, such as calcareous algae, may also store some inorganic carbon); the latter may account for up to 95% of reef system surface area (Atkinson 2011; Gattuso et al., 1998). However, the total magnitude of these reservoirs is difficult to estimate due to the global heterogeneity of reef morphologies and challenges in system boundary definition ($CaCO_3$ beds can extend for hundreds of meters beneath some reefs, and ancient reef frameworks can reach far out to sea, making it difficult to define where a reef ends and limestone bedrock begins).

Among the most important linkages between reefs and other blue carbon ecosystems are the carbonate subsidies they provide to mangroves, seagrasses and tidal marshes. Transport of reef-derived carbonate into neighboring mangroves and seagrasses can increase total alkalinity in these systems upon dissolution and thus promote higher rates of sediment C burial (Saderne et al., 2019). Reciprocally, such vegetated ecosystems provide important nurseries and feeding grounds for many reef-associated organisms (Mumby 2006; Mumby et al., 2004). While many of these interconnections have been described qualitatively in high-profile studies (Mumby et al., 2004), and with some of them even quantified (e.g., biodiversity), the possible carbon sequestration benefits of these linkages remain largely unexplored.

Coral reefs and climate change

Research on impacts of climate change in warm, shallow water ecosystems has focused predominantly on the biocalcification of corals. The geological record indicates a shift from coral- to foraminifera-dominated reef states in response to warming, implying that the systems may be more adaptable to ocean climate change than previously believed (Kawahata et al., 2019; Titelboim et al., 2021). Mounting research suggests that foraminifera contribute to carbonate production and, in some low-lying South Pacific islands, may be the main source of beach sand and support island shoreline stability (Titelboim et al., 2021). Laboratory studies suggest that while more resilient than some hermatypic corals, calcification of even highly tolerant benthic foraminifera will be negatively affected by the extent of warming projected for 2100 (Fujita et al., 2014; Kawahata et al., 2019; Titelboim et al., 2021). Climate-induced reef degradation could also indirectly inhibit carbon sequestration by other blue carbon ecosystems: Macreadie et al. (2019) note that erosion of coral reefs as a result of sea level rise could allow wave heights to increase in adjacent lagoons, leading to loss in sediment carbon stores from seagrass meadows and mangroves.

There is some debate whether undegraded reefs are truly resilient or just have not yet been degraded by bleaching or other adverse impacts. Gajdzik et al. (2021) argue the latter – that tropical reefs are simply "waiting in line" for degradation, presenting examples from the Seychelles and Red Sea where reefs lauded as protected were subsequently bleached and degraded. Moreover, there remains significant uncertainty surrounding the strategy and efficacy of "managed resilience" (Steneck et al., 2019) for coral reefs. The basic idea being tested is whether conservation interventions such as the banning of fishing and removal of pollutants and other disturbances leaves tropical and subtropical coral reefs in a more resilient state (Bates et al., 2019). At the time of writing this report, this debate does not appear to have a clear winner. It is on balance fair to say that managed resilience has been demonstrated in certain contexts, but not in others. Both camps, which collectively represent the majority of the researchers on the subject (R. Boenish, *personal communication*) importantly agree that coral reef resilience and the long-term presence of the ecosystem services reefs provide can be most furthered through the cessation of burning fossil fuels. Any benefits stemming from managed resilience will come as a distant second to directly combating climate change (Hughes et al., 2018).

Areas for further research and development

Although several studies have quantified the myriad co-benefits coral reefs provide as part of broader, integrated seascapes, we could find none that focused specifically on the contribution of reefs to carbon sequestration in adjacent blue carbon ecosystems of other types. Research of this sort is long overdue but will first likely require a change in perspective that considers blue carbon ecosystems not in isolation, but as components of larger systems. Coral reefs themselves will never be long-term sinks for atmospheric carbon dioxide, but they may indirectly assist many of the other blue carbon systems that do sequester carbon.

Carbon crediting schemes

Both Verra and Gold Standard have established protocols for the generation of voluntary carbon credits based on blue carbon ecosystems, and there are two clean development mechanism (CDM) compliance protocols for blue carbon ecosystem restoration under the United Nations Framework Convention on Climate Change. In addition, Eco-Markets Australia has also created at least two methodologies for the development of "Reef Credits" based on reductions in anthropogenic sediment and nutrient loads, both of which negatively impact coral reefs.[10] To date, only a small handful of projects have been registered under these various protocols.

The current versions of the Verra protocols require a "permanence" of 100 years, while Gold Standard's protocol assumes that any sequestration from a project developed under its protocol will be permanent in a geochemical sense (i.e., not be emitted back to the atmosphere over a climatically relevant timescale). By definition, CDM protocols are designed to support the development of shorter-term emissions credits – termed tCERs or lCERs, depending on the claimed term – which must be renewed upon expiration. Given the significant concerns that emerged during our review concerning the durability of carbon sequestered by coastal blue carbon ecosystems in the face of projected changes in both climate and land-use patterns, we question whether a 100-year time horizon could be reliably supported by many of these ecosystems. Recent interest in ton-year accounting approaches (Chay et al., 2022) and new models that suggest even temporary C storage in natural systems could yield large potential climate mitigation benefits (Matthews et al., 2022) may offer a way forward for development of credits in light of these uncertainties. Indeed, Verra is considering the incorporation of such mechanisms in a current public consultation.[11]

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[10] eco-markets.org.au/methodologies/ and www.greenbiz.com/article/hsbc-invests-worlds-first-reef-credit-system.

[11] verra.org/wp-content/uploads/2016/05/VCS-Program-Public-Consultation-2022.02.07.pdf.

Conclusions

The world's coastal blue carbon ecosystems support multiple, interdependent pathways for investment in carbon sequestration and other ecosystem services on the coastlines of every continent except Antarctica. Many of these systems store carbon at areal rates far exceeding those of other global ecosystem types, and the proximity of these systems to human population centers provides a direct means to connect millions of people to the co-benefits that can be realized through preservation or restoration. Yet the promise of these ecosystems as NCS is currently limited by both scientific uncertainties and logistical and practical barriers. Among the uncertainties common to NCS pathways based on all three types of coastal blue carbon ecosystem – seagrasses, marshes and mangroves – we identified three overarching concerns:

- The failure of existing biogeochemical models to account for substantial heterogeneity among individual ecosystems in trophic status; magnitude, type and source of carbon stored; fluxes of GHGs; import and export of carbon; and overall sequestration potential,
- a lack of full understanding and appreciation of fluxes of GHGs other than CO_2, including CH_4 and N_2O, and
- an incomplete understanding by scientists, project developers and others of the risks to permanence of carbon storage in these ecosystems from the synergistic effects of climate change and future land-use patterns, including sea level rise, the projected increase in frequency and severity of tropical storms, and coastal squeeze.

We also identified additional uncertainties and areas for further research pertaining to each of the three ecosystem types. In particular, we found there is a critical need for new frameworks that consider individual blue carbon systems as components of broader, interconnected seascapes, rather than isolated ecosystems. Only through full evaluation and appreciation of the ecological, biogeochemical and socioeconomic linkages between adjacent blue carbon systems, and the terrestrial and open ocean systems that lie beyond their boundaries, can we hope to accurately assess the magnitude of the carbon sequestration service and other co-benefits these systems provide. This is especially true in the case of coral reefs, which do not necessarily sequester carbon from the atmosphere in reef carbonates but may contribute to C sequestration and other ecosystem services in adjacent mangrove forests or seagrass beds by providing them with biogeochemical subsidies and supporting critical habitat for species that play a pivotal role in the function of those other systems.

We propose a three-phase approach to realize the full potential of blue carbon ecosystems as NCS, including identification of the pathways which are unlikely to serve as sources of reliable carbon sequestration or avoided emissions over the relevant timescales, yet may still provide other benefits in substantial quantities. First, we propose an effort to prioritize future research and development efforts surrounding blue carbon ecosystems, with the goal of identifying which uncertainties, including those we identify in this report, could most likely be addressed in the nearest term, and with the greatest overall catalytic effect. Second, we would identify policy or market interventions to scale blue carbon NCS using existing carbon crediting frameworks or governance schemes. Finally, we would broaden the scope of our effort by identifying opportunities for sustaining and restoring high performing ecosystems using new, innovative mechanisms that do not fit within existing models. These would likely include frameworks based on a seascape model, along with a critical reevaluation of the focus on carbon sequestration as a primary objective when developing NCS pathways in blue carbon systems.

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