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POLICY AND PRACTICE REVIEWS
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A Guide to International Climate Mitigation Policy and Finance Frameworks Relevant to the Protection and Restoration of Blue Carbon Ecosystems

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The protection, management and restoration of vegetated ecosystems on land and in the ocean ('natural climate solutions') can be a useful strategy for reducing net greenhouse gas emissions to help limit global warming. Their potential contribution to reducing net emissions has led to the development of policies and financial incentives for their protection and restoration. These have in turn created a set of expectations among some stakeholders, and interest in expanding these to encompass other ecosystems. However, there are specific rules about how abatement is calculated in international policy and climate finance, and the frameworks and terminology associated with them are often complex. This can be a barrier to stakeholders who want to leverage the potential of natural climate solutions, sometimes leading to incongruence between realised and anticipated benefits. In this article, we attempt to outline some of the key international policy and carbon market frameworks for coastal 'blue carbon' ecosystems, and the extent to which different ecosystems are accommodated. Currently, among the coastal ecosystems, only mangrove forests, seagrass meadows, and tidal marshes are typically considered in international policy and carbon market frameworks. The defining feature of these ecosystems is that the foundation species are plants that grow in sediment (soil). They are the only coastal ecosystems currently included in IPCC guidelines for national greenhouse gas inventories, and in compliance and voluntary carbon markets. There is interest in potentially including other marine ecosystems, such as kelp forests and unvegetated tidal flats, into carbon accounting frameworks, but there are unresolved questions about whether sequestration and storage of carbon by these ecosystems meets the rigorous standards required. Voluntary carbon markets have greater flexibility than mechanisms linked to national greenhouse gas inventories, and so might be early implementers of expanding methods to include other ecosystems. Incorporating coastal ecosystems into national greenhouse gas inventory is a useful action countries can take that will likely help generate incentives for protection and restoration of these important ecosystems.

Keywords: coastal wetlands, greenhouse gas inventory, restoration, carbon market, international climate policy

NATURAL CLIMATE SOLUTIONS

Effective protection, management, and restoration of vegetated ecosystems on land and in the ocean can help reduce net emissions of greenhouse gases (GHGs) to limit global warming (Howard et al., 2017; Fuss et al., 2018). These 'natural climate solutions' (NCS: Griscom et al., 2017) are part of an increasing emphasis on nature-based solutions (NbS) to multiple global problems (Seddon et al., 2020). Estimates of the potential global contribution of NCS are large, amounting to gigatons (Gt) per year and contributing substantially to the net emissions reduction required by 2030 to have a high probability of staying below 1.5°C of warming (Griscom et al., 2017). (See **Box 1** for a glossary with definitions of abbreviations and key terms used in this article.)

Harnessing natural ecosystems to achieve net emissions reductions can be achieved in two main ways. Firstly, emissions of naturally occurring GHG (carbon dioxide, methane, and nitrous oxide) occur when vegetated ecosystems are cleared or degraded, so protecting these ecosystems from such damage prevents those emissions. In the language of climate policy, this is referred to as avoided emissions (or avoided loss). In addition, restoring ecosystems — for example through revegetation — can lead to increased carbon sequestration (also called removal) because it can increase the mass of carbon stored in 'sinks' or 'reservoirs'. In vegetated ecosystems these sinks are aboveground (branches, stems) and belowground biomass (roots and rhizomes), and soil (Hiraishi et al 2014). Restoring ecosystems can also help avoid GHG emissions that occur in some land use activities (IPCC, 2013; Kroeger et al., 2017; IPCC, 2019a). Improving the management of ecosystems that are used more intensively by humans, for example by improving forestry and farming practices, is another way of reducing net emissions (Cook-Patton et al., 2021). In some cases, this might include modifying landscapes through afforestation. The reduction of net emissions, either through reducing GHG emissions or increasing sequestration, is referred to as abatement (**Box 1**).

The potential contribution of vegetated ecosystems to reducing net GHG emissions has led to the development of policies and financial incentives for their protection and restoration. These in turn have led to a set of expectations

BOX 1 | Glossary: list of key terms and abbreviations used in this article, in alphabetical order with definitions.

Avoidance: actions that prevent the release of greenhouse gases into the atmosphere
Abatement: in climate policy, the act of reducing net emissions (it is also used to refer to the quantity of net emissions reduction)
Additionality: a principle that requires that a net reduction in emissions happens only because of specific finance (like sale of carbon credits), and would not happen without it
AFOLU: Agriculture, Forestry and Other Land Use, used in the context of IPCC guidelines which refer to GHG emissions from these sectors
Emissions factor: in carbon accounting a value representing the average mass of emissions or removals of a GHG (in CO_2-e: see **Box 2**) resulting from an activity
GHG: Greenhouse gas
IPCC: Intergovernmental Panel on Climate Change, an entity of the United Nations; it is not part of the UNFCCC, but was established by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) four years before the UNFCCC
Leakage: An increase in net GHG emissions outside a project or jurisdiction that occurs because of activities within it
LULUCF: Land use, land-use change, and forestry, referring to emissions and removals of greenhouse gases resulting from direct human interventions in these systems
Mitigation: in climate policy, an intervention to reduce the magnitude and effects of climate change
NDC: Nationally Determined Contributions, reports submitted to the UNFCCC that outline a country's commitments to reduce emissions and adapt to climate change
Net emissions: the sum of emissions minus sequestration
NbS: Nature-based solutions, actions that involve protecting, sustainably managing, or restoring ecosystems (natural or modified) to address societal challenges; NCS (see below) are NbS that are focussed primarily on climate change mitigation
NCS: Natural Climate Solutions, conservation, restoration, and/or improved land management actions that increase carbon storage or avoid GHG emissions in forests, wetlands, grasslands, or agricultural lands (Griscom et al., 2017)
Permanence: the risk that carbon stored or emissions avoided from a project activity will be released (back) into the atmosphere after a defined period
REDD+: Reducing emissions from deforestation and forest degradation, a framework created through the UNFCCC to guide activities that reduce emissions from deforestation and forest degradation, as well as the sustainable management of forests and the conservation and enhancement of forest carbon stocks in developing countries
Reservoir: a component of Earth's climate system where a GHG or carbon is stored.
Sequestration: removal of carbon dioxide from the atmosphere into long-term reservoirs (in blue carbon ecosystems, long-lived plant biomass or soil); usage typically implies a temporal aspect which distinguishes it from stock (see below)
Stock: the amount of carbon in a reservoir (see above)
UNFCCC: United Nations Framework Convention on Climate Change, an international environmental treaty to combat "dangerous human interference with the climate system", in part by stabilizing greenhouse gas concentrations in the atmosphere.

among some stakeholders. The expectations vary among the diverse suite of stakeholders, and can include inflated expectations of financial benefits (e.g. Pascual et al., 2014; Rakotomahazo et al., 2019), and aspirations to expand policy and finance frameworks to encompass ecosystems that are not currently included. However, there is specific guidance on how abatement should be calculated — including by countries when they report their GHG emissions to the United Nations Framework Convention on Climate Change (UNFCCC) and in the way net emissions reductions are accounted for in carbon markets. This guidance is based on information about GHG emissions and removals in different land uses and ecosystems. The rules and terminology used in accounting for carbon in international policy frameworks and carbon markets are often complex and many of the stakeholders who want to leverage the potential of natural climate solutions to achieve specific aims are unfamiliar with them, which can lead to incongruence between anticipated and realised benefits.

Here, we outline some of the key international policy and finance frameworks for coastal 'blue carbon' ecosystems, and the extent to which different ecosystems are accommodated (**Figure 1**). Blue carbon ecosystems are receiving increasing attention for their disproportionately high abatement potential relative to the area they cover, as well as the other benefits that they provide (such as protection from floods and damaging waves, and habitat for a wide variety of species, including fish that are caught for food or recreation: Menéndez et al., 2020; Friess et al., 2021). As a result, they are increasingly being incorporated into international policy frameworks and financial instruments (McLeod et al., 2011; Windham-Myers et al., 2018). There are growing expectations of potential financial benefits, and discussion about what ecosystems are included in existing frameworks, as well as how frameworks could be modified to encompass those ecosystems not currently included (e.g. Steven et al., 2019; Luisetti et al., 2020).

COASTAL 'BLUE CARBON' ECOSYSTEMS

All marine vegetation, as well as some other organisms (such as corals), convert inorganic carbon to organic carbon through photosynthesis. However, only mangrove forests, seagrass meadows and tidal marshes are typically considered 'blue carbon' ecosystems in current policy frameworks (Howard et al., 2017; Lovelock and Duarte, 2019).[1] The defining feature of these coastal ecosystems is that the foundation species are plants that grow in sediment[2] that is submerged at least part of the time by tidal water. Through photosynthesis these plants take up CO_2 [and, in the case of seagrass, bicarbonate (HCO_3^-)] and use it to create organic carbon substrates that are needed to maintain and grow new leaves, stems, roots and so on. Woody plant biomass can persist for many years, in some circumstances for centuries. Further, when a plant dies — or when part of a plant, say a leaf, is detached and falls to the sediment surface — a fraction of the organic carbon is incorporated into the sediment where it can persist for long periods, in some cases for millennia. Because the sediment of blue carbon ecosystems is typically inundated by water (through which oxygen moves more slowly than air), the rates of decomposition are very low, which facilitates accumulation of the organic matter. Indeed, in many of these ecosystems the carbon stock in the sediment is greater than that in the plant biomass (Alongi, 2014). In addition, unlike freshwater wetlands, the higher concentration of sulphate in seawater acts to reduce the anaerobic formation and release of methane (Bridgham et al., 2013), such that methane emissions from saline coastal wetlands tend to be lower than for other wetlands (Kroeger et al., 2017; although emissions can sometimes be high even in coastal wetlands — see Rosentreter et al., 2021).

The potential contribution of the three main blue carbon ecosystems (mangrove forests, seagrass meadows and tidal marshes) to global climate mitigation is a relatively modest proportion of the total abatement needed, perhaps a little more than ~1 Gt or so per year (Herr and Landis, 2016; Griscom et al., 2017) — to give this some context, global emissions were ~35 Gt in 2021 (Liu et al., 2022). However, actions to protect and restore blue carbon ecosystems could be an important contributor to abatement in some countries, such as those in which degradation of these ecosystems is a large contributor to emissions (Murdiyarso, 2019). In addition, these ecosystems offer a suite of other benefits, including reductions in the height of damaging storm waves, reducing inundation by storm surges, provision of habitat for species that are important for food and livelihoods, and more.

There is great interest in potentially including macroalgae and other marine ecosystems into blue carbon accounting frameworks (e.g. Krause-Jensen and Duarte, 2016; Sala et al., 2021), but there are unresolved questions about whether removal and sequestration of carbon by these ecosystems meets the rigorous standards required to incorporate potential abatement into policy and finance frameworks. Not all ecosystems create or store carbon in the same way, and not all do it equally effectively (Jobbagy and Jackson, 2000; McLeod et al., 2011). Here, we briefly outline the main international policy and climate finance (with focus on carbon markets) frameworks and how different ecosystems can be considered in the context of those frameworks.

INTERNATIONAL POLICY FRAMEWORKS

The main global entity through which countries cooperate to develop international policies that explicitly address the problem of increasing greenhouse gas concentrations is the United Nations Framework Convention on Climate Change (UNFCCC). Here, we briefly review a subset of the main

[1] Here we use the term tidal marsh to be consistent with Intergovernmental Panel on Climate Change terminology, but they are also often called salt marshes, or even tidal salt marshes: French (2019) Tidal salt marshes: sedimentology and geomorphology, in *Coastal Wetlands*, eds. G.M.E. Perillo, E. Wolanski, D.R. Cahoon & C.S. Hopkinson. Elsevier), 479-517.

[2] Here we use the term sediment because that is most familiar to many marine scientists but note that other authors also use the term soil, which corresponds to Intergovernmental Panel on Climate Change terminology.

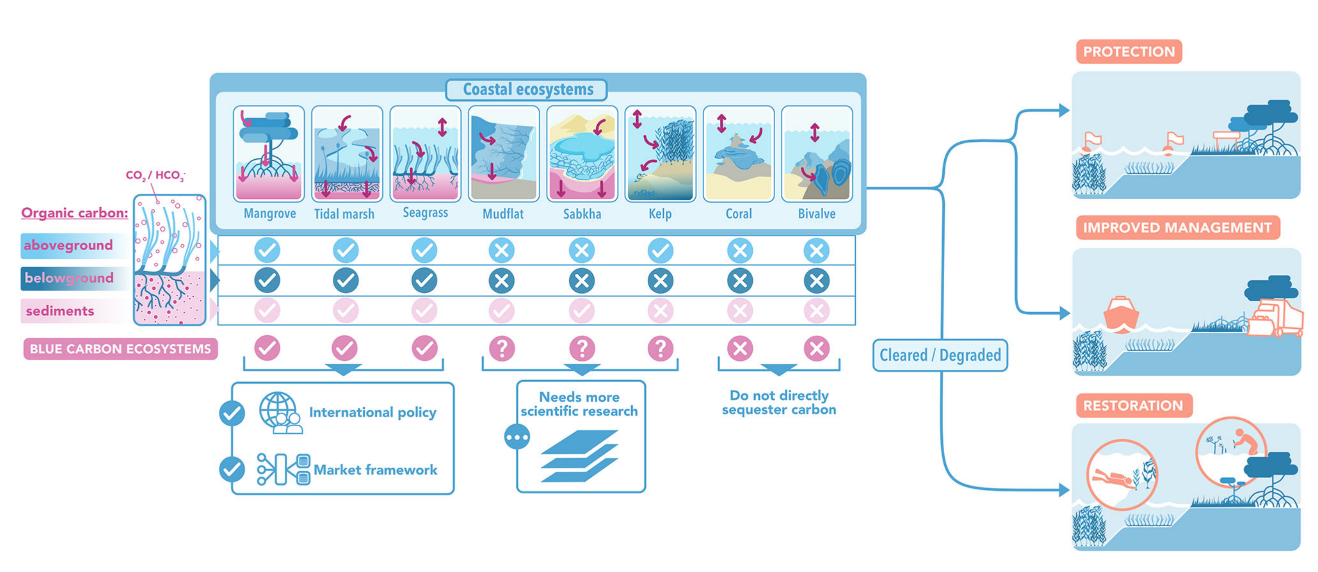

FIGURE 1 | Schematic representation of key concepts related to protection, improved management, and restoration of blue carbon ecosystems.

UNFCCC mechanisms relevant to protection and restoration of coastal blue carbon ecosystems (for a more detailed review see Herr et al., 2019b).

As a framework convention, the UNFCCC establishes the mechanisms to achieve its objectives through a suite of legal instruments agreed to at the annual Conference of Parties — the (now expired) Kyoto Protocol and the Paris Agreement are well-known examples.[3] These decisions are diverse, and include aspects such as the magnitude of ambition (originally focussing on mitigation but increasingly also encompassing adaptation), different strategies to achieve that ambition, and ways of generating the finance to enable them (Kuyper et al., 2018).

Multiple processes and mechanisms have been implemented in the years since the establishment of the UNFCCC (Bodansky and Rajamani, 2018). Blue carbon ecosystems are relevant to a number of the current ones, including several that are still being negotiated (Dobush et al., 2021; Herr and Hamilton, 2021). We don't attempt to review all of them, but Nationally Determined Contributions (NDC) and REDD+ (Reducing emissions from deforestation and forest degradation), are worth noting because they have received attention in the context of blue carbon. NDC are plans that are submitted to the UNFCCC Secretariat by each of the Parties to the Paris Agreement. In the context of the UNFCCC, a Party is essentially a country, which is assigned into one of three groups according to the level of commitments that they are able to make.[4] NDC are an obligation on Parties to the Paris Agreement, which describe voluntary commitments that are consistent with the principle enshrined in the original convention text that countries have 'common but differentiated responsibilities'. As such, each country sets its own emissions reduction targets, and outlines plans to achieve them (as well as adapt to climate change) in their NDC. Blue carbon ecosystems can contribute towards mitigation and adaptation efforts, and there are a wide variety of actions that could be built into these national plans (Herr and Landis, 2016; Lecerf et al., 2021). Among these is the opportunity to incorporate coastal wetlands in national greenhouse gas inventories (outlined below), which in turn creates a set of incentives for increased protection and restoration of blue carbon ecosystems.

REDD+ is a mechanism created and modified through the UNFCCC process that focuses on using forest management to reduce emissions (from forest clearing or degradation) and increase removal of atmospheric CO_2 into sinks (primarily trees). It is characterised by payments that are contingent on achieving specific results — thus embedding financial incentives into the approach (Angelsen and McNeill, 2012). Seagrass meadows and tidal marshes are not forests, but some mangroves are considered forests, depending on a country's definition of what a forest is. Notwithstanding that some definitions do not resonate well in particular cultural circumstances (Putz, 2010), the UNFCCC has a general operational definition of a forest: "…a minimum area of land of 0.05-1.0 hectares with tree crown cover (or equivalent stocking level) of more than 10-30 per cent with trees having the potential to reach a minimum height of 2-5 metres at maturity *in situ*" (Schoene et al., 2007). However, within this broad definition, countries can elect to further refine their definition of a forest. If mangroves happen to fit the national definition of a forest, then they can be included in REDD+, although so far there have been relatively few mangrove projects. Countries that participate in REDD+ should establish a Forest Reference Emission Level (FREL), which sets the baseline mass of net emissions (in tCO_2-e: see **Box 2**) against which to evaluate changes; these are typically calculated from national estimates over multiple years (Romijn et al., 2013).

[3] If you are confused about the difference between a protocol, an agreement and other instruments, you aren't alone, see: https://treaties.un.org/Pages/overview.aspx?path=overview/definition/page1_en.xml.
[4] https://unfccc.int/parties-observers

BOX 2 | tCO_2-e

Different greenhouse gases — carbon dioxide, methane, nitrous oxide, and so on — absorb different proportions of infrared radiation, and so their contribution to atmospheric warming isn't proportional to their concentration in the atmosphere (Lashof and Ahuja, 1990). In addition, the different gases persist in the atmosphere for different lengths of time. Because of this, in an effort to allow for a common standard to account for emissions, each is assigned a 'global warming potential' (Smith and Wigley, 2000), based on the amount of warming expected over a specified duration (usually 100 years), relative to carbon dioxide (IPCC, 1990). This is used to calculate 'carbon dioxide equivalent', CO_2-e: in carbon accounting this is expressed as a unit of mass, so tCO_2-e is a measure of the mass of CO_2 that would generate an equivalent amount of warming. Relative to carbon dioxide the warming potential of methane and nitrous oxide are 25 and 298 times greater.

UNFCCC mechanisms also guide international cooperation, facilitating countries to assist each other in meeting their commitments. One way in which they can do so is through formally recognised internationally transferred mitigation outcomes (ITMOs), in which one country assists another (say, through providing financial assistance), and in return receives the right to claim some of the net emissions reductions. ITMOs are also quantified in units of tCO_2-e. Their use can be complicated and has been somewhat contentious (Allen et al., 2021). One contentious aspect is the possibility that some emission reductions could be counted by more than one country, which would inflate estimates of net emissions reduction globally (called 'double counting', for example if a project in one country is funded through ODA from another and both want to count the emission reductions achieved from the project to offset their emissions). To avoid this, rules agreed to through the UNFCCC stipulate that, if the country in which the project occurs wishes to sell their emissions reductions they cannot count them towards their own target but the buyer (the donor country) can.

The UNFCCC also provides a framework for a variety of mechanisms to generate finance to implement actions that are intended to reduce net emissions, especially in developing countries. These include establishing formal entities to receive donations and disburse the funds (such as the Green Climate Fund), and establishing agreed rules for transfer of funds between countries (Romano et al., 2018). These have been implemented in various ways since the UNFCCC was formed, and international climate finance is now substantially influenced by the mechanisms introduced in the Paris Agreement (and subsequently outlined in detail in the rules drafted afterwards, the so-called 'Paris Rulebook'). In particular, the way that international carbon markets are used to generate finance to support international cooperation is outlined in several parts of Article 6 of the Paris Agreement (Schneider, 2019). These rules are especially relevant to protection and restoration of blue carbon ecosystems, which tend to occur disproportionately in developing countries (Herr et al., 2018). We review how carbon markets work later in this article.

Other international agreements also deal with natural climate solutions in a way that is relevant for protection and restoration of blue carbon ecosystems, each with a different and complementary focus. For example, the Convention on Biological Diversity focuses on conservation of biological diversity (including ecosystems), the Sendai Framework for Disaster Risk Reduction focuses on preventing and reducing disaster risk (including through harnessing the benefits provided by natural ecosystems), the Convention on Wetlands of International Importance especially as Waterfowl Habitat[5] focuses on conservation of wetlands, and the UNESCO World Heritage Convention is focussed on protection and preservation of particular sites considered to be of outstanding value to humanity. Actions implemented under these agreements can also contribute to reducing net emissions. The extent to which these agreements complement each other, and UNFCCC agreements, is an important area but none have a specific focus on climate mitigation. The Sustainable Development Goals, a set of broad goals and associated targets established by the United Nations General Assembly, does have specific targets related to climate change, but one of which is to implement the UNFCCC. Since none are specifically focussed on climate mitigation, we don't discuss them further.

NATIONAL GREENHOUSE GAS INVENTORY

One of the main tools the UNFCCC uses to assess how successful (or not) countries are at reducing net greenhouse gas emissions is the national GHG inventory (Troxler et al., 2019). These are designed to account for GHG emissions by sources and removals by sinks from all sectors of a country's economy. These inventories are submitted more frequently and in greater detail by certain countries (essentially, developed countries: Perugini et al., 2021). From 2024 all Parties to the Paris Agreement will need to submit a Biennial Transparency Report (which should include a report on that country's GHG inventory report, among other things) every two years. Developed countries will still need to submit national GHG inventories each year.

The UNFCCC has adopted detailed methods and standardised reporting procedures for GHG inventories that have been produced by the Intergovernmental Panel on Climate Change (IPCC). GHG inventories include emissions and removals of three naturally occurring GHG that are particularly relevant to blue carbon ecosystems — carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) — as well as four types of synthetically-produced fluorinated gases.

In preparing GHG inventories for submission to the UNFCCC, countries are required to calculate emissions sources and sinks from multiple sectors (UNFCCC, 2009; UNFCCC, 2016). Coastal wetlands are included in a sector called land-use change and forestry (LULUCF), which since 2006 has been combined with agriculture to create a single consolidated

[5]more typically known as the Ramsar Convention after the city in Iran where it was originally signed.

sector: Agriculture, Forestry, and Other Land Use (AFOLU: **Box 3**)[6]. AFOLU activities contribute towards a significant net source of global GHG emissions – approximately 23% of CO_2-e (5.2 ± 2.6 Gt CO_2 yr^{-1}) from 2007-2016 (IPCC, 2019b). Countries don't need to report on everything that IPCC gives guidance on though. Land can be both a source and a sink of GHG, making estimates of emissions and removals in the AFOLU sector complex.

The IPCC guidelines contain detailed instructions for calculating GHG emissions and removals from a suite of managed and natural ecosystems, including (since 2013) coastal wetlands (mangroves, tidal marshes, and seagrasses: the three blue carbon ecosystems). Current guidelines provide methods to calculate GHG emissions and removals for these ecosystems under four activities (**Figure 2**):

- Forest management practices in mangroves.
- Extraction activities (which includes excavation, dredging, construction of ponds for aquaculture or salt production).
- Drainage activities (in which the soil is intact but water levels on the landscape are reduced, usually to facilitate agricultural production).
- Rewetting, revegetation, or creation (rehabilitation and restoration of ecosystems).

For each of these activities, GHG emissions and removals can be estimated with different 'tiers' of certainty (Troxler et al., 2019). At the coarsest resolution are 'Tier 1' assessments, which accommodate estimates generated from global datasets (called 'default values') to calculate GHG emissions and removals for a country. These default values are estimated from available scientific literature at the time and are assumed to be generally representative. At the next level of resolution, 'Tier 2' assessments use national data should it be available, while 'Tier 3' assessments are the highest resolution and involve site-specific data at finer spatial resolutions or nationally implemented models (e.g. Richards and Evans, 2004). Countries can apply different tiers to different activities depending on data availability.

The IPCC provides guidance for obtaining data, as well as default values for Tier 1 assessments. However, they recommend that Tier 2 or Tier 3 assessments are done where possible, because the default values may not accurately reflect emissions and removals for the country being assessed. Estimating net GHG emissions can involve estimating the difference in carbon stocks based on emissions factors for specific activities (which are supplied by the IPCC), estimating the difference in carbon stocks measured at two points in time, or measuring or modelling the GHG flux between the soil and vegetation and the atmosphere or water (Troxler et al., 2019).

Since the IPCC issued guidance for including wetlands into national GHG inventory (Hiraishi et al 2014 ; IPCC, 2019a), scientists have continued to refine the estimates of removals and emissions and to publish new data. This has enabled higher resolution estimates (e.g. Murdiyarso et al., 2015; Kauffman et al., 2017; Vinh et al., 2019) and improved models (e.g. Atwood et al., 2017; Rovai et al., 2018; Adame et al., 2021). The data and models underpinning national GHG inventories are continually improving, there are still some data gaps that need to be addressed, especially regarding flux of GHGs in blue carbon ecosystems, spatial patterns in emissions and removals within and among ecosystems, and the contribution of seagrasses.

So far, few countries have included coastal wetlands in their national GHG inventory, although capacity building and other activities to enable widespread reporting has been increasing (Green et al., 2021). If a country includes mangroves in the FREL through REDD+, they should report them using the same methods under forests, not wetlands, in their national GHG inventory (Green et al., 2021).

CLIMATE FINANCE AND CARBON MARKETS

Climate finance can occur in multiple forms. It can include grants, or loans, or even investment into private companies, such as through purchasing shares (Romano et al., 2018). It can also occur in forms intended to generate profit for the investors (such as bonds), or by risk transfer mechanisms like insurance. Some, such as results-based payments under REDD+ (which mostly occurs in the form of Official Development Assistance grants from developed countries: European Commission Directorate-General for Climate Action, 2018) require rigorous processes for measuring net abatement following a similar process as GHG inventories (Michel et al., 2016). One of the most widely used mechanisms for generating climate finance is carbon markets, developed in part due to a recognition that grants and donations alone were unlikely to generate sufficient finance, but also in response to a worldview which favoured an economic ideology based on letting the private sector attempt to resolve problems (Newell and Paterson, 2010).

[6] The other sectors are Energy, Industrial Processes and Product Use, Waste and Other.

BOX 3 | Classification and delineation of coastal wetlands as land cover categories

Coastal wetlands are defined within the AFOLU sector as areas that "consist of organic and mineral soils that are covered or saturated, for all or part of the year, by tidal freshwater, brackish or saline water and are vegetated by vascular plants" (Hiraishi et al 2014). This includes blue carbon ecosystems – mangroves, tidal marshes, and seagrasses. Each country must have a clear definition of the ecosystems that are represented by coastal wetlands so that the land cover category can be appropriately assigned within the AFOLU inventory consistently over time. These definitions might be different between countries depending on the type of coastal wetlands and their national extent.

Estimating CO_2 emissions and removals using the IPCC guidance requires information on the extent of area encompassed by each ecosystem. The boundaries of blue carbon ecosystems can extend landward beyond the extent of frequent tidal inundation, such as with supratidal salt marshes, and seaward to any depth at which seagrass could occur. The boundaries and extent can be challenging to quantify in these ecosystems — for example, seagrasses are difficult to map because they are underwater, and it can be difficult to delineate boundaries between high intertidal marshes and terrestrial vegetation.

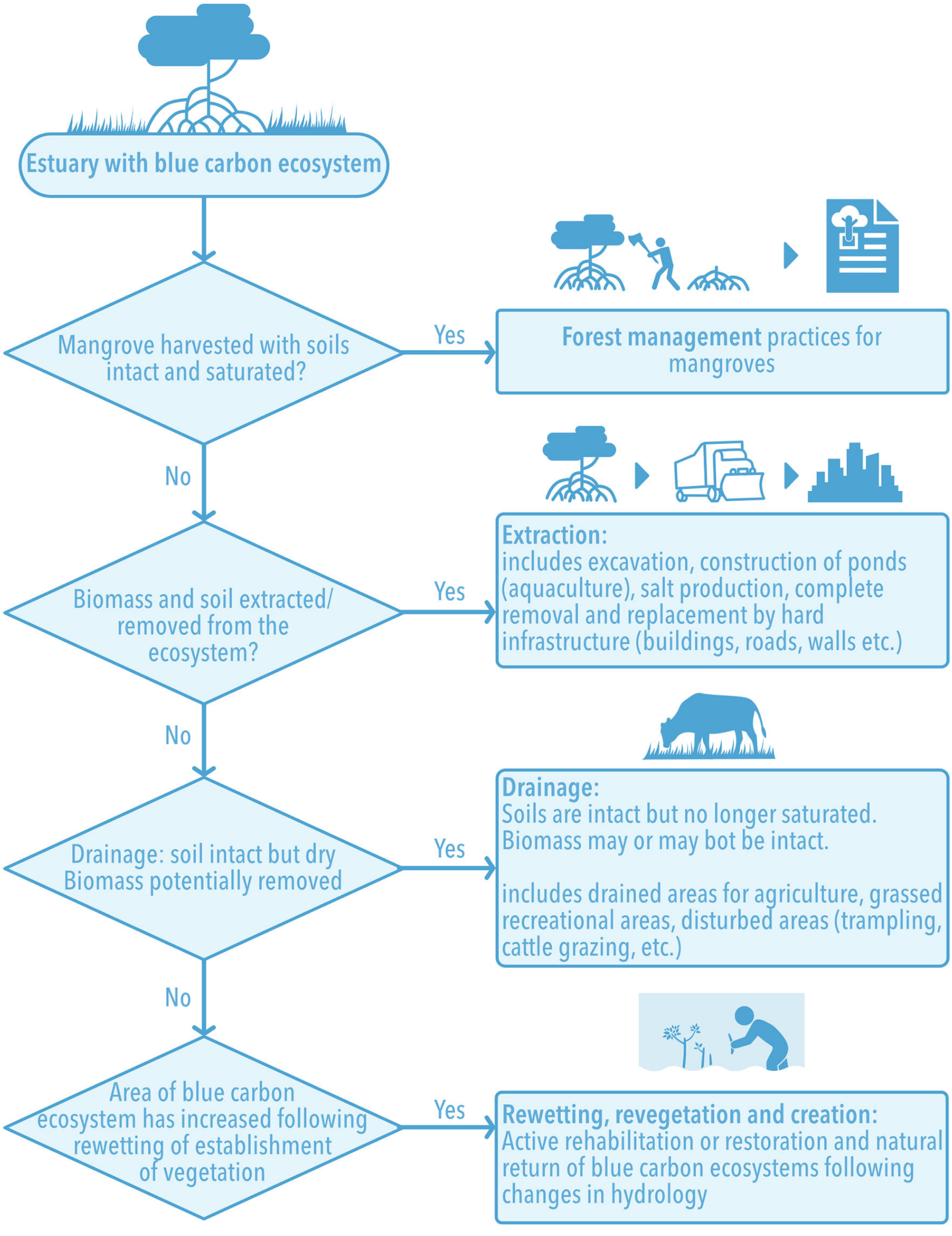

FIGURE 2 | Decision tree to assign reported changes in blue carbon ecosystems to the emissions and removals categories provided by the Hiraishi et al 2014 Wetlands Supplement. Adapted from (Hiraishi et al 2014).

Carbon markets are mechanisms which are designed to allow emitters (say, a company) to account for emissions that they cannot reduce by paying for emissions reductions (or 'offsets') elsewhere. Specifically, they are frameworks to trade (i.e. buy and sell) those emissions reductions, and can be broadly categorised into compliance and voluntary markets (Vanderklift et al., 2019; Streck, 2020). The units traded have different names in different schemes, but they are typically referred to under the general term 'carbon credit'; each credit represents one tonne of carbon dioxide equivalent (tCO_2-e: see **Box 2**).

Each credit therefore reflects a unit of mass that represents a net emissions reduction that has been achieved by either reducing emissions (say, by replacing fossil fuel with renewable energy or by not clearing a patch of mangrove forest) or by removing CO_2 from the atmosphere and sequestering the carbon in biomass or soil (say, by restoring a degraded mangrove forest). Each credit has a unique serial number, which is listed on one or more public registries. Once the owner of the credit wishes to claim it for emissions reductions, the credit is 'retired' (also sometimes called 'surrendered') and a note to that effect is made against the serial number. It is then taken off the market so that it can no longer be sold or given away, preventing the possibility that a single credit might be claimed more than once.

Compliance markets are used in some jurisdictions to enforce the requirements of legislation or regulations. For example, in the European Union's (EU) Emissions Trading Scheme (ETS) — an example of a 'cap-and-trade' scheme — emitters must stay below a quantity of emissions that is established by EU regulations, and they can use offsets generated by projects that reduce emissions to help achieve this (Bayer and Aklin, 2020). In some jurisdictions (such as in California and New Zealand), credits can also be generated by projects that sequester carbon through improved forest management (Shrestha et al., 2021). Compliance markets can be a central part of a country's emissions reduction policy, in which case the net emissions reductions that they yield are incorporated into the country's GHG inventory. The types of emission reduction activities that are eligible must therefore align with categories defined in the IPCC guidelines.

The nature of compliance markets is such that purchasers tend to favour low-cost credits. The lowest cost credits are usually generated by projects that replace fossil-fuel based energy production with methods based on renewable energy (Hamrick and Gallant, 2017; Donofrio et al., 2020). The costs of projects that involve NCS, such as protection and restoration of blue carbon ecosystems, are typically much higher (de Groot et al., 2013), and so demand for them is unlikely to be substantial in compliance markets. In contrast, buyers in a voluntary market typically do so because they are motivated by reasons other than the need to meet regulatory requirements (Peters-Stanley et al., 2013). In these cases, buyers are often prepared to pay higher prices for the credits, which makes credits generated by coastal blue carbon projects feasible. Indeed, there are now multiple projects in mangrove and tidal marsh ecosystems using methods accredited according to the rules of several different international standards (e.g. Needelman et al., 2018). In addition, these buyers are not necessarily constrained by the need to adhere to the categories used in national GHG inventory (although they can if they choose to), which can lend greater flexibility.

NCS often generate additional benefits beyond their contribution to climate mitigation (usually called 'co-benefits'), such as enhanced fisheries production or reduction in the height of damaging storm waves. These co-benefits are often attractive to buyers in a voluntary market; credits from projects that also generate co-benefits tend to be preferred by buyers, who might also be willing to pay higher prices for the offsets. In general, quantification of these co-benefits is not as well understood as carbon abatement (Palomo et al., 2019; Orth et al., 2020), and warrants further research and development, including methods to value these benefits and the trade-offs among them.

The broad dichotomy between compliance and voluntary markets can be more complicated, because voluntary markets can be part of a broader regulated market (such as in South Africa and Colombia: Hanna and Nicolas, 2019), or they might be completely separate. Also, not all credits are traded on an open market; one of the largest blue carbon projects is a mangrove reforestation project in Sumatra (which generated >270,000 of tCO_2-e by 2019: Anon, 2020) — credits generated by this project are not traded on an open market but are used to offset emissions of the companies which provided the finance for project implementation (Anon, 2015; Herr et al., 2019a).

In both compliance and voluntary markets, there are rules that need to be followed. In regulated markets those rules will typically be established by the regulators (for example in Australia, they must abide by 'offsets integrity standards' that are established in legislation: Bell-James, 2016; Kelleway et al., 2020). In voluntary markets they are established by the organisations that produce voluntary market standards. They tend to share a set of common rules, although there is some variation in the way that these are applied (e.g. Richards and Huebner, 2014). The Taskforce on Scaling Voluntary Carbon Markets (Taskforce on Scaling Voluntary Carbon Markets, 2021) has suggested these be developed into a set of principles that all projects should abide by.

The principles common across standards are that abatement should be real, measurable and credible, that it should be additional (that is, it would not occur without the incentive provided by carbon finance), that the net CO_2 reduction that the credit represents must not be reversed (at least not for a very long period of time; this is called 'permanence'), and that it should not cause an increase in net emissions either in another source or somewhere else (this is called 'leakage'). These principles are designed to ensure that (net) emissions are genuinely reduced. The International Carbon Reduction and Offset Alliance (ICROA) includes all of these in a set of best practice integrity principles[7] for using carbon credits to offset unavoidable emissions. These principles are used by standards that together represent the bulk of offsets traded in the voluntary market, as well as offsets traded under schemes such as the Clean Development Mechanism and Australia's Emissions Reduction Fund.

[7] https://www.icroa.org/resources/Documents/ICROA_cobp_carbon_management_service_executive_summary_2021.pdf

The principle that abatement should be real, measurable and credible means that the methods for calculating the abatement that can be attributed to a particular activity are typically conservative. Often, like the methods for calculating emissions for national GHG inventory described earlier, they can involve a mixture of surrogate data like emissions factors, direct measurements, and models. The models are typically based on extensive data collected at different places, and account for the fact that the rates and net result of processes vary from place to place. They can also be cheaper than methods that require regular (and potentially expensive) measurements.

As described earlier, compliance markets will often be used to reduce emissions in sectors that are covered by a country's GHG inventory, so the eligible sectors and activities will tend to reflect those defined by the IPCC. Voluntary markets might allow greater flexibility, raising the possibility that other sectors or activities might be included. However, they will still need to adhere to the rules applying to carbon accounting; examination of those rules in the context of different ecosystems can reveal why we focus on some ecosystems and not others, and why our ability to include them remains uncertain (**Table 1**).

HOW DO BLUE CARBON PROJECTS FIT INTO CARBON MARKETS?

Many stakeholders (including scientists) are interested in whether projects in different ecosystems might be eligible for carbon market finance. Some ecosystems are covered by methods developed under voluntary carbon market standards. For example, there are several methods produced by the carbon accounting organisation Verra that are applicable to mangrove, tidal marsh and seagrass ecosystems. Of the ecosystems that are not included, it is possible that some could be, but development of methods is hampered by insufficient information. In some offsetting schemes the net emissions reductions need to be linked to a GHG inventory, and so are constrained by the ecosystems and activities that are included in IPCC guidance. Many voluntary market standards don't have this constraint, and so have more flexibility to include other ecosystems or other activities — but they still need to adhere to the same principles. Some ecosystems can be immediately discounted and considering them in the context of the main carbon market principles reveals why (see also Howard et al., 2017; Lovelock and Duarte, 2019).

Additionality

The additionality principle is intended to ensure that net emissions reduction occurs because of the implementation of project activities — in a carbon market this in turn means that it could not have been done without the finance generated by the sale of the credits. Additionality is typically assessed from this perspective for an individual project to ensure that activities would not occur without the finance, but in some restoration contexts additionality is assumed because the rate of restoration is lower than the rate of loss for an ecosystem (Needelman et al., 2018; Zeng et al., 2021). This can be complex, and problems include ensuring that protection and restoration would not occur in the absence of finance (which can be particularly difficult to assess for protection), as well as the moral hazard associated with providing more opportunities to those who have been the poorest stewards of nature.

Coral and bivalve reefs, where the process of calcification in seawater produces a net release of CO_2 (**Table 1**: Frankignoulle et al., 1995; Lovelock and Duarte, 2019), would fail to meet the first principle of additionality. Coastal vegetated ecosystems — mangroves, tidal marshes and seagrasses — are composed of photosynthesising vascular plants, producing a net uptake of CO_2, so they could meet this principle, providing that the activities would not otherwise happen without the financial incentive.

Permanence

The principle of permanence requires that the net GHG reduction must not be reversed. This risk tends to be lower for blue carbon ecosystems because they are less susceptible to some of the risks that terrestrial ecosystems are prone to, such as fire — although they are not immune to risks associated with severe weather events, or even climate change itself. The carbon fixed by plants through photosynthesis is stored in their biomass, and some of these meet the principle of permanence — although the duration of time considered 'permanent' varies among standards, it is typically at least 25-30 years, and often 100 years (Richards and Huebner, 2012). The carbon in the sediment these plants grow in can be thousands of years old (Rogers et al., 2019), and so easily passes the test of permanence. In carbon markets, the requirement to demonstrate permanence is typically applied regardless of whether a project sets out to avoid emissions from degradation of the ecosystem, or to enhance sequestration by restoring the ecosystem.

These frameworks assume that carbon removal and sequestration occurs within the boundaries of a defined project

TABLE 1 | Assessment of confidence in coastal ecosystems in the context of principles central to verifying offsets through carbon markets.

Criterion	Existing IPCC guidance	Additionality	Permanence
Mangroves	Y	Y	Y
Tidal marsh	Y	Y	Y
Seagrass	Y	Y	Y
Kelp	N	Y_a I_b	Y_a I_b
Mudflats	N	Y	I
Coral/bivalve reef	N	N	–

*Y, yes; N, no; I, insufficient evidence. a = carbon removals within the project area; b = carbon exported from the project area (see **Box 4**).*

area. Removals can in some cases also include allochthonous organic carbon that is brought into the area (for example by currents or wind), if it can be shown that this organic carbon would have been remineralised and returned to the atmosphere if the project had not occurred (Needelman et al., 2018). Carbon exported from the area is not accounted for, because there is no easy way of knowing its fate — including whether it is additional or permanent. IPCC guidelines recognise that this is a gap in knowledge requiring more information (at least for coastal wetlands, for inland wetlands it is considered to be an emissions source: Hiraishi et al., 2014).

Carbon exported from coastal wetlands might be sequestered elsewhere. This can include small particles originating from mangrove, marsh or seagrass plants as well as dissolved organic or inorganic carbon, and even alkalinity (Huxham et al., 2018; Maher et al., 2018). Extending from methods that focus on measuring the organic carbon sequestered within a project area to methods that can account for carbon fixed in one place and sequestered in another will be challenging. Demonstrating that abatement achieved using such methods is real, measurable and credible will involve overcoming current impediments to quantifying carbon export to and sequestration in distant places. Simple models might be developed that can aid this, but these will require substantial, locally relevant data. This would help resolve the role that unvegetated sediments (such as intertidal and subtidal mudflats and sabkha) might play as NCS: they can contain substantial organic carbon, but most originates elsewhere (Phang et al., 2015; Sasmito et al., 2020). Little is known about permanence of organic carbon in these systems.

Kelp and other seaweed ecosystems pose a challenge from the perspective of permanence (**Table 1**). They photosynthesise and represent substantial carbon fixation. However, they tend to be short-lived — even a long-lived seaweed typically lives for only a few years. In addition, natural kelp stands tend to grow on rock, which doesn't accumulate organic matter (this also creates a challenge to including them in national GHG inventory, because the IPCC guidelines currently only include wetlands as ecosystems with organic or mineral soils. Instead, most kelp carbon is exported from the place where it is fixed, through erosion of fronds or dislodgement of entire individuals (de Bettignies et al., 2013). Nevertheless, it is possible to envisage how methods to account for the emissions reduction potential of kelps (and other seaweeds) might be developed (**Box 4**).

Leakage

Leakage from project areas can be challenging to assess. It requires understanding whether a protection or restoration activity is likely to cause an unintended increase in emissions, either directly from an increase in GHG emissions within the project area, or indirectly through displacement of an activity to somewhere else — say, through construction of aquaculture ponds elsewhere that cause a mangrove forest to be destroyed (Thamo and Pannell, 2016). In the latter case, the risk is assessed through examining the likelihood that the activity will cause such displacement, regardless of whether it is a mangrove, tidal marsh or seagrass.

Unintended increased emissions of GHG can occur from an activity designed to restore a blue carbon ecosystem. If the increased emissions are in the form of methane or nitrous oxide, both of which have global warming potentials much greater than CO_2 (see **Box 2**; Smith and Wigley, 2000), this could conceivably create leakage. Emissions of these GHG occur naturally in ecosystems (Lovelock et al., 2017). Methane and nitrous oxide are released by microbial decomposition of organic matter, and are influenced by conditions such as temperature, salinity, and the amount of organic matter. Methane emissions tend to be more pronounced where salinity is low, but can sometimes be high in mangrove and tidal marsh ecosystems (Rosentreter et al., 2021), while nitrous oxide emissions can be high in places where nitrogen inputs have been substantial (Roughan et al., 2018). Methane emissions in seagrasses tend to be low, and although nitrous oxide emissions can sometimes be high, one study showed that net abatement of seagrass restoration was still substantial (Oreska et al., 2020). Accounting for GHG emissions in seagrass meadows is further complicated by poor understanding of whether gases dissolved in seawater (where they don't contribute to warming) are transferred to the atmosphere (where they do) in these

BOX 4 | Kelp carbon and carbon markets

Protection and restoration of natural ecosystems carbon market finance is built around a concept in which only GHG emissions avoided or carbon sequestered within a defined project boundary are included. This presents a challenge for building accounting methods for kelp and other seaweed (Luisetti et al., 2020), which tend to be short-lived (years or less), and export carbon to adjacent ecosystems. During transport, some is consumed by organisms from decomposers to herbivores (Ince et al., 2007; Vanderklift and Wernberg, 2008), but a proportion can travel to places where it might be sequestered, on continental shelves or even the deep sea (Krause-Jensen and Duarte, 2016).

It is possible that kelp detritus is sequestered into sediments in these places, but evidence regarding the proportion that might be expected to be sequestered is limited. Evidence of transport to distant areas alone is not sufficient, because kelp detritus is readily consumed by many consumers. It is possible that kelp transported to depths below the pycnocline might be considered permanently sequestered because material at those depths is not readily returned to shallower depths (Krause-Jensen and Duarte, 2016), but the fate of carbon during transport, and even after arriving at those depths, remains poorly understood (Boyd et al., 2019).

These challenges should not present impediments to developing methods for avoided loss of naturally-occurring kelp. In a method for avoided loss, the total carbon stock of all biomass can be included — including components that are typically short-lived (like leaves). In a similar way, the carbon stock in a kelp forest under threat could be accounted for — although this will in many instances be less than that of vascular plant ecosystems because there is no sediment component. Methods for mangrove and seagrass restoration can also account for the total stock restored (e.g. Needelman et al., 2018), which could similarly apply for kelp forests, although again the absence of sediment means that this might be significantly less than that of the blue carbon ecosystems (**Figure 3**).

Farming kelp might also offer opportunities for other ways of reducing net emissions, such as use in biofuels. These possibilities are still in early stages of exploration, and much remains to be understood before they can be deployed as effective solutions.

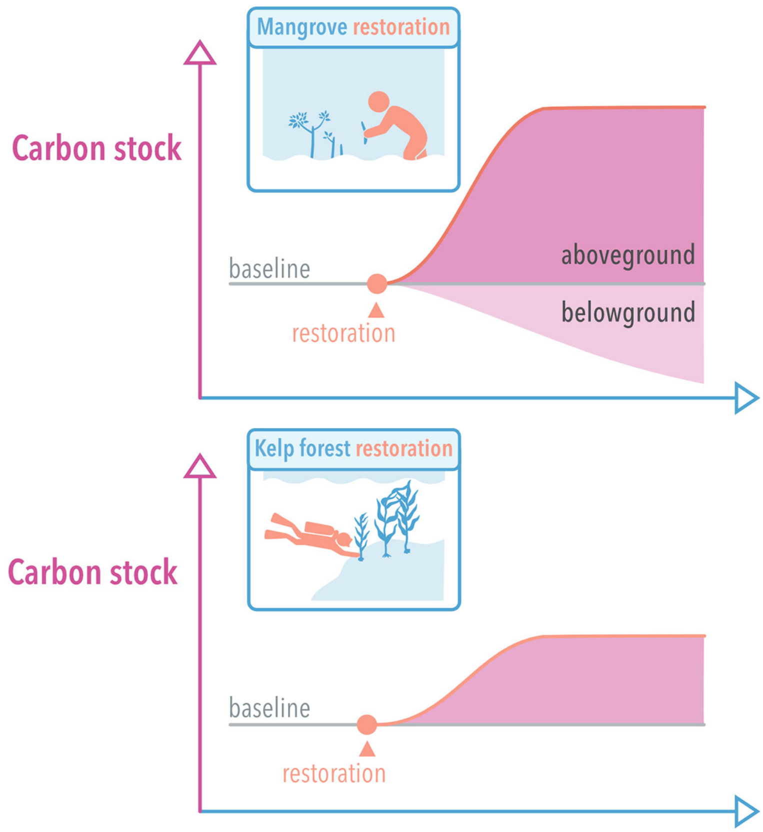

FIGURE 3 | Schematic representation of carbon stock changes for two distinct types of ecosystem (mangrove and kelp) in the context of restoration. The pink shaded area is the carbon that could be attributed to the project activity. Adapted from Olander and Ebeling, 2011.

ecosystems (Van Dam et al., 2021). Transport of detached kelp onto shorelines can result in substantial emissions.

A restoration activity which causes a transition from one ecosystem or land use to another is also likely to generate emissions associated with that transition when the original plants die (Lovelock et al., 2022). Typically, this should be small relative to the amount of sequestration for projects to be feasible.

CONCLUSION

The protection and restoration of coastal blue carbon ecosystems can make a modest but important contribution as natural climate solutions (NCS) for achieving net reductions of greenhouse gas emissions. This potential has generated a lot of interest among scientists, restoration practitioners, policymakers, investors and others — each of whom has different expectations about what the individual and collective benefits are. However, to effectively achieve their potential as NCS, protection and restoration efforts often need to work within policy and finance frameworks — which can mean that the expected benefits are not realised. For example, some activities are not eligible to receive financial support through carbon markets. Or, they might be eligible, but the amount of abatement that they can claim is less than expected because calculations are conservative. This article was intended to explain some of the main international policy and finance frameworks that such projects should consider.

Of course, there are many reasons to undertake activities that protect and restore coastal blue carbon ecosystems. Doing so will usually contribute to climate mitigation, and if accounting for carbon is not a primary aim, then these frameworks are less relevant. Such activities will typically also generate other desirable outcomes, from enhancing habitat for a variety of species to supporting livelihoods or creating more enjoyable places to spend time. Sometimes stakeholders might want to formally quantify or seek credit for these benefits (and nascent methods for doing so exist, although they are not as mature as methods for accounting for carbon abatement), but again this need not always be the desired outcome.

Some protection and restoration activities for the three coastal wetlands included in the IPCC guidance (i.e. mangroves, tidal marshes and seagrasses) are well understood and are being increasingly implemented. Other activities, other ecosystems, and even some potential carbon pools are less well understood. More information on these is needed. However, there is sufficient information to support implementation of many activities. One of the most useful at a national level is to incorporate coastal wetlands into national GHG inventory — this is likely to create a variety of incentives for enhancing protection, better management, and restoration of blue carbon ecosystems. NDC can be used to communicate this (as well as other commitments) through the framework of the Paris Agreement. Countries who do so should receive greater benefits both in meeting GHG reduction and in the suite of other benefits that tend to occur alongside. Pilot-scale restoration activities — which can be part of markets if desired — are also a low-risk way of promoting action.

AUTHOR CONTRIBUTIONS

MV and AS contributed to conception and design of the study. All authors wrote sections of the manuscript, contributed to manuscript revision, read, and approved the submitted version.

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REFERENCES

Adame, M. F., Connolly, R. M., Turschwell, M. P., Lovelock, C. E., Fatoyinbo, T., Lagomasino, D., et al. (2021). Future Carbon Emissions From Global Mangrove Forest Loss. *Global Change Biol.* 27, 2856–2866. doi: 10.1111/gcb.15571

Allen, M., Tanaka, K., Macey, A., Cain, M., Jenkins, S., Lynch, J., et al. (2021). Ensuring That Offsets and Other Internationally Transferred Mitigation Outcomes Contribute Effectively to Limiting Global Warming. *Environ. Res. Lett.* 16, 074009. doi: 10.1088/1748-9326/abfcf9

Alongi, D. M. (2014). Carbon Cycling and Storage in Mangrove Forests. *Annu. Rev. Mar. Sci.* 6, 195–219. doi: 10.1146/annurev-marine-010213-135020

Angelsen, A., and McNeill, D. (2012). “The Evolution of REDD+,” in *Analysing REDD+: Challenges and Choices*. Eds. A. Angelsen, M. Brockhaus, W. D. Sunderlin and L. V. Verchot (Bogor, Indonesia: CIFOR).

Anon (2015). *Mangrove Restoration and Coastal Greenbelt Protection in the East Coast of Aceh and North Sumatra Province, Indonesia* (Medan: Project description).

Anon (2020). *Coastal Carbon Corridor: Mangrove Restoration and Coastal Greenbelt Protection in the East Coast of Aceh and North Sumatra Province, Indonesia* (Essen – Germany: Verification Report VCS Version 3).

Atwood, T. B., Connolly, R. M., Almahasheer, H., Carnell, P. E., Duarte, C. M., Ewers Lewis, C. J., et al. (2017). Global Patterns in Mangrove Soil Carbon Stocks and Losses. *Nat. Climate Change* 7, 523–528. doi: 10.1038/nclimate3326

Bayer, P., and Aklin, M. (2020). The European Union Emissions Trading System Reduced CO_2 Emissions Despite Low Prices. *Proc. Natl. Acad. Sci.* 117, 8804–8812. doi: 10.1073/pnas.1918128117

Bell-James, J. (2016). Developing a Framework for ‘Blue Carbon’ in Australia: Legal and Policy Considerations. *UNSW Law J.* 39, 1583–1611.

Bodansky, D., and Rajamani, L. (2018). “The Evolution and Governance Architecture of the United Nations Climate Change Regime,” in *Global Climate Policy : Actors, Concepts, and Enduring Challenges*. Eds. U. Luterbacher and D. F. Sprinz (Cambridge, MA: The MIT Press), 13–66.

Boyd, P. W., Claustre, H., Levy, M., Siegel, D. A., and Weber, T. (2019). Multi-Faceted Particle Pumps Drive Carbon Sequestration in the Ocean. *Nature* 568, 327–335. doi: 10.1038/s41586-019-1098-2

Bridgham, S. D., Cadillo-Quiroz, H., Keller, J. K., and Zhuang, Q. (2013). Methane Emissions From Wetlands: Biogeochemical, Microbial, and Modeling Perspectives From Local to Global Scales. *Global Change Biol.* 19, 1325–1346. doi: 10.1111/gcb.12131

Cook-Patton, S. C., Drever, C. R., Griscom, B. W., Hamrick, K., Hardman, H., Kroeger, T., et al. (2021). Protect, Manage and Then Restore Lands for Climate Mitigation. *Nat. Climate Change* 11, 1027–1034. doi: 10.1038/s41558-021-01198-0

de Bettignies, T., Wernberg, T., Lavery, P. S., Vanderklift, M. A., and Mohring, M. B. (2013). Contrasting Mechanisms of Dislodgement and Erosion Contribute to Production of Kelp Detritus. *Limnol. Oceanogr.* 58, 1680–1688. doi: 10.4319/lo.2013.58.5.1680

de Groot, R. S., Blignaut, J., van der Ploeg, S., Aronson, J., Elmqvist, T., and Farley, J. (2013). Benefits of Investing in Ecosystem Restoration. *Conserv. Biol.* 27, 1286–1293. doi: 10.1111/cobi.12158

Dobush, B.-J., Gallo, N. D., Guerra, M., Guilloux, B., Holland, E., Seabrook, S., et al. (2021). A New Way Forward for Ocean-Climate Policy as Reflected in the UNFCCC Ocean and Climate Change Dialogue Submissions. *Climate Policy*, 22, 1–18. doi: 10.1080/14693062.2021.1990004

Donofrio, S., Maguire, P., Zwick, S., and Merry, W. (2020). *Voluntary Carbon and the Post-Pandemic Recovery* (Washington, DC:Forest Trends Association).

European Commission Directorate-General for Climate Action (2018). *Study on EU Financing of REDD+ Related Activities, and Results-Based Payments Pre and Post 2020 : Sources, Cost-Effectiveness and Fair Allocation of Incentives* (Publications Office).

Frankignoulle, M., Pichon, M., and Gattuso, J.-P. (1995). “Aquatic Calcification as a Source of Carbon Dioxide,” in *Carbon Sequestration in the Biosphere*. Ed. M. A. Beran (Berlin, Heidelberg: Springer Berlin Heidelberg), 265–271.

French, J. (2019). “Tidal Salt Marshes: Sedimentology and Geomorphology,” in *Coastal Wetlands*. Eds. G. M. E. Perillo, E. Wolanski, D. R. Cahoon and C. S. Hopkinson (Amsterdam:Elsevier), 479–517.

Friess, D. A., Yando, E. S., Alemu, I. J. B., Wong, L. W., Soto, S. D., and Bhatia, N. (2021). Ecosystem Services and Disservices of Mangrove Forests and Salt Marshes. *Oceanogr. Mar. Biol.: Annu. Rev.* 58 58, 107–141.

Fuss, S., Lamb, W. F., Callaghan, M. W., Hilaire, J., Creutzig, F., Amann, T., et al. (2018). Negative Emissions-Part 2: Costs, Potentials and Side Effects. *Environ. Res. Lett.* 13, 102083. doi: 10.1088/1748-9326/aabf9f

Green, C., Lovelock, C., Sasmito, S., Hagger, V., and Crooks, S. (2021). *Coastal Wetlands in National Greenhouse Gas Inventories: Advice on Reporting Emissions and Removal From Management of Blue Carbon Ecosystems*.

Griscom, B. W., Adams, J., Ellis, P. W., Houghton, R. A., Lomax, G., Miteva, D. A., et al. (2017). Natural Climate Solutions. *Proc. Natl. Acad. Sci.* 114, 11645–11650. doi: 10.1073/pnas.1710465114

Hamrick, K., and Gallant, M. (2017). *Unlocking Potential: State of the Voluntary Carbon Markets* (Washington DC: E. Marketplace).

Hanna, W.-H., and Nicolas, K. (2019). The Potential Impacts of a Domestic Offset Component in a Carbon Tax on Mitigation of National Emissions. *Renewable Sustain. Energy Rev.* 101, 453–460. doi: 10.1016/j.rser.2018.11.026

Herr, D., Blum, J., Himes-Cornell, A., and Sutton-Grier, A. (2019a). An Analysis of the Potential Positive and Negative Livelihood Impacts of Coastal Carbon Offset Projects. *J. Environ. Manage.* 235, 463–479. doi: 10.1016/j.jenvman.2019.01.067

Herr, D., Chagas, T., Krämer, N., Conway, D., and Streck, C. (2018). *Coastal Blue Carbon and Article 6: Implications and Opportunities* (Amsterdam, The Netherlands:IUCN).

Herr, D., and Hamilton, J. (2021). *Building on the Ocean-Climate Dialogue: Options for Strengthening Action on the Ocean Under the UNFCCC*.

Herr, D., and Landis, E. (2016). *Coastal Blue Carbon Ecosystems: Opportunities for Nationally Determined Contributions* (Switzerland:IUCN).

Herr, D., Vegh, T., and Von Unger, M. (2019b). “State of International Policy for Blue Carbon Actions,” in *A Blue Carbon Primer: The State of Coastal Wetland Carbon Science, Practice, and Policy*. Eds. L. Windham-Myers, S. Crooks and T. G. Troxler (Boca Raton: CRC Press), 199–215.

Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M., et al. (2014). *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories* (Wetlands. Switzerland:IPCC).

Howard, J., Sutton-Grier, A., Herr, D., Kleypas, J., Landis, E., McLeod, E., et al.

(2017). Clarifying the Role of Coastal and Marine Systems in Climate Mitigation. *Front. Ecol. Environ.* 15, 42–50. doi: 10.1002/fee.1451

Huxham, M., Whitlock, D., Githaiga, M., and Dencer-Brown, A. (2018). Carbon in the Coastal Seascape: How Interactions Between Mangrove Forests, Seagrass Meadows and Tidal Marshes Influence Carbon Storage. *Curr. Forest. Rep.* 4, 101–110. doi: 10.1007/s40725-018-0077-4

Ince, R., Hyndes, G. A., Lavery, P. S., and Vanderklift, M. A. (2007). Marine Macrophytes Directly Enhance Abundances of Sandy Beach Fauna Through Provision of Food and Habitat. *Estuar. Coast. Shelf. Sci.* 74, 77–86. doi: 10.1016/j.ecss.2007.03.029

IPCC (1990). *Climate Change: The IPCC Scientific Assessment* (Cambridge: Intergovernmental Panel on Climate Change).

IPCC (1996). *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (Geneva:I- IPCC/OECD/IEAI).

IPCC (2013). *Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*. Eds. T. Hiraishi, T. Krug, K. Tanabe, N. Srivastava, J. Baasansuren, M. Fukuda and T. G. Troxler (Geneva).

IPCC (2019a). *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*. Eds. E. Calvo Buendia, K. Tanabe, A. Kranjc, J. Baasansuren, M. Fukuda, S. Ngarize, A. Osako, Y. Pyrozhenko, P. Shermanau and S Federici (Geneva).

IPCC (2019b). "Summary for Policymakers," in *Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems*. Eds.P. R. Shukla, J. Skea, E.C. Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R.v. Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J.P. Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi and J. Malley

Jobbagy, E. G., and Jackson, R. B. (2000). The Vertical Distribution of Soil Organic Carbon and its Relation to Climate and Vegetation. *Ecol. Appl.* 10, 423–436. doi: 10.1890/1051-0761(2000)010[0423:TVDOSO]2.0.CO;2

Kauffman, J. B., Arifanti, V. B., Hernández Trejo, H., Carmen Jesús García, M., Norfolk, J., Cifuentes, M., et al. (2017). The Jumbo Carbon Footprint of a Shrimp: Carbon Losses From Mangrove Deforestation. *Front. Ecol. Environ.* 15, 183–188. doi: 10.1002/fee.1482

Kelleway, J. J., Serrano, O., Baldock, J. A., Burgess, R., Cannard, T., Lavery, P. S., et al. (2020). A National Approach to Greenhouse Gas Abatement Through Blue Carbon Management. *Global Environ. Change* 63, 102083. doi: 10.1016/j.gloenvcha.2020.102083

Krause-Jensen, D., and Duarte, C. M. (2016). Substantial Role of Macroalgae in Marine Carbon Sequestration. *Nat. Geosci.* 9, 737–742. doi: 10.1038/ngeo2790

Kroeger, K. D., Crooks, S., Moseman-Valtierra, S., and Tang, J. (2017). Restoring Tides to Reduce Methane Emissions in Impounded Wetlands: A New and Potent Blue Carbon Climate Change Intervention. *Sci. Rep.* 7, 11914. doi: 10.1038/s41598-017-12138-4

Kuyper, J., Schroeder, H., and Linnér, B.-O. (2018). The Evolution of the UNFCCC. *Annu. Rev. Environ. Resour.* 43, 343–368. doi: 10.1146/annurev-environ-102017-030119

Lashof, D. A., and Ahuja, D. R. (1990). Relative Contributions of Greenhouse Gas Emissions to Global Warming. *Nature* 344, 529–531. doi: 10.1038/344529a0

Lecerf, M., Herr, D., Thomas, T., Elverum, C., Delrieu, E., and Picourt, L. (2021). *Coastal and Marine Ecosystems as Nature-Based Solutions in New or Updated Nationally Determined Contributions*. Ocean & Climate Platform, Conservation International, IUCN, GIZ, Rare, The Nature Conservancy and WWF.

Liu, Z., Deng, Z., Davis, S. J., Giron, C., and Ciais, P. (2022). Monitoring Global Carbon Emissions in 2021. *Nat. Rev. Earth Environ* 3, 217–219. doi: 10.1038/s43017-022-00285-w

Lovelock, C. E., Adame, M. F., Bradley, J., Dittman, S., Hagger, V., Hickey, S. M., et al. (2022). An Aus tralian blue carbon me thod to e stimate climate change mitigation be ne fits of coastal wetland restoration. *Restoration Ecology*. doi: 10.1111/rec.13739

Lovelock, C. E., Atwood, T., Baldock, J., Duarte, C. M., Hickey, S., Lavery, P. S., et al. (2017). Assessing the Risk of Carbon Dioxide Emissions From Blue Carbon Ecosystems. *Front. Ecol. Environ.* 15, 257–265. doi: 10.1002/fee.1491

Lovelock, C. E., and Duarte, C. M. (2019). Dimensions of Blue Carbon and Emerging Perspectives. *Biol. Lett.* 15, 20180781. doi: 10.1098/rsbl.2018.0781

Luisetti, T., Ferrini, S., Grilli, G., Jickells, T. D., Kennedy, H., Kroger, S., et al. (2020). Climate Action Requires New Accounting Guidance and Governance Frameworks to Manage Carbon in Shelf Seas. *Nat. Commun.* 11, 4599. doi: 10.1038/s41467-020-18242-w

Maher, D. T., Call, M., Santos, I. R., and Sanders, C. J. (2018). Beyond Burial: Lateral Exchange is a Significant Atmospheric Carbon Sink in Mangrove Forests. *Biol. Lett.* 14, 20180200. doi: 10.1098/rsbl.2018.0200

McLeod, E., Chmura, G. L., Bouillon, S., Salm, R., Bjork, M., Duarte, C. M., 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, 552–560. doi: 10.1890/110004

Menéndez, P., Losada, I. J., Torres-Ortega, S., Narayan, S., and Beck, M. W. (2020). The Global Flood Protection Benefits of Mangroves. *Sci. Rep.* 10, 4404. doi: 10.1038/s41598-020-61136-6

Michel, J., Kallweit, K., and von Pfeil, E. (2016). "Reduced Emissions From Deforestation and Forest Degradation (REDD)," in *Tropical Forestry Handbook*. Eds. L. Pancel and M. Köhl (Berlin, Heidelberg: Springer Berlin Heidelberg), 3065–3091.

Murdiyarso, D. (2019). "The Nexus Between Conservation and Development in Indonesian Mangroves," in *A Blue Carbon Primer: The State of Coastal Wetland Carbon Science, Practice, and Policy*. Eds. L. Windham-Myers, S. Crooks and T. G. Troxler (Boca Raton: CRC Press), 295–305.

Murdiyarso, D., Purbopuspito, J., Kauffman, J. B., Warren, M. W., Sasmito, S. D., Donato, D. C., et al. (2015). The Potential of Indonesian Mangrove Forests for Global Climate Change Mitigation. *Nat. Climate Change* 5, 1089–1092. doi: 10.1038/nclimate2734

Needelman, B. A., Emmer, I. M., Emmett-Mattox, S., Crooks, S., Megonigal, J. P., Myers, D., et al. (2018). The Science and Policy of the Verified Carbon Standard Methodology for Tidal Wetland and Seagrass Restoration. *Estuar. Coast.* 41, 2159–2171. doi: 10.1007/s12237-018-0429-0

Newell, P., and Paterson, M. (2010). *Climate Capitalism: Global Warming and the Tranformation of the Global Economy* (Cambridge: Cambridge University Press).

Olander, J., and Ebeling, J. (2011). "Building Forest Carbon Projects: Step-by-Step Overview and Guide," in *Building Forest Carbon Projects*. Eds. J. Ebeling and J. Olander (Washington, D.C: Forest Trends).

Oreska, M. P. J., McGlathery, K. J., Aoki, L. R., Berger, A. C., Berg, P., and Mullins, L. (2020). The Greenhouse Gas Offset Potential From Seagrass Restoration. *Sci. Rep.* 10, 7325. doi: 10.1038/s41598-020-64094-1

Orth, R. J., Lefcheck, J. S., McGlathery, K. S., Aoki, L., Luckenbach, M. W., Moore, K. A., et al. (2020). Restoration of Seagrass Habitat Leads to Rapid Recovery of Coastal Ecosystem Services. *Sci. Adv.* 6, eabc6434. doi: 10.1126/sciadv.abc6434

Palomo, I., Dujardin, Y., Midler, E., Robin, M., Sanz, M. J., and Pascual, U. (2019). Modeling Trade-Offs Across Carbon Sequestration, Biodiversity Conservation, and Equity in the Distribution of Global REDD+ Funds. *Proc. Natl. Acad. Sci.* 116, 22645–22650. doi: 10.1073/pnas.1908683116

Pascual, U., Phelps, J., Garmendia, E., Brown, K., Corbera, E., Martin, A., et al. (2014). Social Equity Matters in Payments for Ecosystem Services. *BioScience* 64, 1027–1036. doi: 10.1093/biosci/biu146

Perugini, L., Pellis, G., Grassi, G., Ciais, P., Dolman, H., House, J. I., et al. (2021). Emerging Reporting and Verification Needs Under the Paris Agreement: How can the Research Community Effectively Contribute? *Environ. Sci. Policy* 122, 116–126. doi: 10.1016/j.envsci.2021.04.012

Peters-Stanley, M., Gonzalez, G., and Yin, D. (2013). *Covering New Ground State of the Forest Carbon Markets 2013* (Washington, DC:Forest Trends' Ecosystem Marketplace).

Phang, V. X. H., Chou, L. M., and Friess, D. A. (2015). Ecosystem Carbon Stocks Across a Tropical Intertidal Habitat Mosaic of Mangrove Forest, Seagrass Meadow, Mudflat and Sandbar. *Earth Surf. Proc. Landf.* 40, 1387–1400. doi: 10.1002/esp.3745

Putz, F. E. (2010). The Importance of Defining 'Forest': Tropical Forest Degradation, Deforestation, Long-Term Phase Shifts, and Further Transitions. *Biotropica* 42, 10–20. doi: 10.1111/j.1744-7429.2009.00567.x

Rakotomahazo, C., Ravaoarinorotsihoarana, L. A., Randrianandrasaziky, D., Glass, L., Gough, C., Georges, G., et al. (2019). Participatory Planning of a Community-Based Payments for Ecosystem Services Initiative in Madagascar's Mangroves. *Ocean. Coast. Manage.* 175, 43–52. doi: 10.1016/j.ocecoaman.2019.03.014

Richards, G. P., and Evans, D. M. W. (2004). Development of a Carbon Accounting Model (FullCAM Vers. *1.0) Aust. Contin. Aust. Forest.* 67, 277–283. doi: 10.1080/00049158.2004.10674947

Richards, K. R., and Huebner, G. E. (2012). Evaluating Protocols and Standards for Forest Carbon-Offset Programs, Part A: Additionality, Baselines and Permanence. *Carb. Manage.* 3, 393–410. doi: 10.4155/cmt.12.38

Richards, K. R., and Huebner, G. E. (2014). Evaluating Protocols and Standards for Forest Carbon-Offset Programs, Part A: Additionality, Baselines and Permanence. *Carb. Manage.* 3, 393–410. doi: 10.4155/cmt.12.38

Rogers, K., Kelleway, J. J., Saintilan, N., Megonigal, J. P., Adams, J. B., Holmquist, J. R., et al. (2019). Wetland Carbon Storage Controlled by Millennial-Scale Variation in Relative Sea-Level Rise. *Nature* 567, 91–95. doi: 10.1038/s41586-019-0951-7

Romano, A. A., Scandurra, G., Carfora, A., and Ronghi, M. (2018). *Climate Finance as an Instrument to Promote the Green Growth in Developing Countries* (Cham, Switzerland: Springer).

Romijn, E., Ainembabazi, J. H., Wijaya, A., Herold, M., Angelsen, A., Verchot, L., et al. (2013). Exploring Different Forest Definitions and Their Impact on Developing REDD+ Reference Emission Levels: A Case Study for Indonesia. *Environ. Sci. Policy* 33, 246–259. doi: 10.1016/j.envsci.2013.06.002

Rosentreter, J. A., Al-Haj, A. N., Fulweiler, R. W., and Williamson, P. (2021). Methane and Nitrous Oxide Emissions Complicate Coastal Blue Carbon Assessments. *Global Biogeochem. Cycle.* 35, e2020GB006858. doi: 10.1029/2020GB006858

Roughan, B. L., Kellman, L., Smith, E., and Chmura, G. L. (2018). Nitrous Oxide Emissions Could Reduce the Blue Carbon Value of Marshes on Eutrophic Estuaries. *Environ. Res. Lett.* 13, 044034. doi: 10.1088/1748-9326/aab63c

Rovai, A. S., Twilley, R. R., Castañeda-Moya, E., Riul, P., Cifuentes-Jara, M., Manrow-Villalobos, M., et al. (2018). Global Controls on Carbon Storage in Mangrove Soils. *Nat. Climate Change* 8, 534–538. doi: 10.1038/s41558-018-0162-5

Sala, E., Mayorga, J., Bradley, D., Cabral, R. B., Atwood, T. B., Auber, A., et al. (2021). Protecting the Global Ocean for Biodiversity, Food and Climate. *Nature* 592, 397–402. doi: 10.1038/s41586-021-03371-z

Sasmito, S. D., Kuzyakov, Y., Lubis, A. A., Murdiyarso, D., Hutley, L. B., Bachri, S., et al. (2020). Organic Carbon Burial and Sources in Soils of Coastal Mudflat and Mangrove Ecosystems. *Catena* 187, 104414. doi: 10.1016/j.catena.2019.104414

Schneider, H. (2019). "The Role of Carbon Markets in the Paris Agreement: Mitigation and Development," in *Climate Change and Global Development: Market, Global Players and Empirical Evidence*. Eds. T. Sequeira and L. Reis, 109–132. Switzerland: Springer Nature

Schoene, D., Killmann, W., Lüpke, H.v, and LoycheWilkie, M. (2007). Definitional Issues Related to Reducing Emissions From Deforestation in Developing Countries. *Forest. Climate Change Work. Pap.* 5, pp 29.

Seddon, N., Chausson, A., Berry, P., Girardin, C. A. J., Smith, A., and Turner, B. (2020). Understanding the Value and Limits of Nature-Based Solutions to Climate Change and Other Global Challenges. *Philos. Trans. R. Soc. B.: Biol. Sci.* 375, 20190120. doi: 10.1098/rstb.2019.0120

Shrestha, A., Eshpeter, S., Li, N., Li, J., Nile, J. O., and Wang, G. (2021). Inclusion of Forestry Offsets in Emission Trading Schemes: Insights From Global Experts. *J. Forest. Res.* 33, 279–287. doi: 10.1007/s11676-021-01329-5

Smith, S. J., and Wigley, M. L. (2000). Global Warming Potentials: 1. Climatic Implications of Emissions Reductions. *Clim. Change* 44, 445–457. doi: 10.1023/A:1005584914078

Steven, A. D. L., Vanderklift, M. A., and Bohler-Muller, N. (2019). A New Narrative for the Blue Economy and Blue Carbon. *J. Indian Ocean. Reg.* 15, 123–128. doi: 10.1080/19480881.2019.1625215

Streck, C. (2020). Who Owns REDD Plus ? Carbon Markets, Carbon Rights and Entitlements to REDD Plus Finance. *Forests* 11, 15. doi: 10.3390/f11090959

Taskforce on Scaling Voluntary Carbon Markets (2021). *Taskforce on Scaling Voluntary Carbon Markets: Final Report*.

Thamo, T., and Pannell, D. J. (2016). Challenges in Developing Effective Policy for Soil Carbon Sequestration: Perspectives on Additionality, Leakage, and Permanence. *Climate Policy* 16, 973–992. doi: 10.1080/14693062.2015.1075372

Troxler, T. G., Kennedy, H. A., Crooks, S., and Sutton-Grier, A. E. (2019). "Introduction of Coastal Wetlands Into the IPCC Greenhouse Gas Inventory Methodological Guidance," in *A Blue Carbon Primer: The State of Coastal Wetland Carbon Science, Practice, and Policy*. Eds. L. Windham-Myers, S. Crooks and T. G. Troxler (Boca Raton: CRC Press), 217–234.

UNFCCC (2009). *UNFCCC Resource Guide for Preparing the National Communications* of Non-Annex I Parties: Module 3 - National Greenhouse Gas Inventories.

UNFCCC (2016). *Compendium on Greenhouse Gas Baselines and Monitoring: National-Level Mitigation Actions*.

Van Dam, B., Polsenaere, P., Barreras-Apodaca, A., Lopes, C., Sanchez-Mejia, Z., Tokoro, T., et al. (2021). Global Trends in Air-Water CO2 Exchange Over Seagrass Meadows Revealed by Atmospheric Eddy Covariance. *Global Biogeochem. Cycle.* 35, e2020GB00684. doi: 10.1029/2020GB006848

Vanderklift, M. A., Marcos-Martinez, R., Butler, J. R. A., Coleman, M., Lawrence, A., Prislan, H., et al. (2019). Constraints and Opportunities for Market-Based and Protection of Blue Carbon Ecosystems. *Mar. Policy* 107, 103429. doi: 10.1016/j.marpol.2019.02.001

Vanderklift, M. A., and Wernberg, T. (2008). Detached Kelps From Distant Sources are a Food Subsidy for Sea Urchins. *Oecologia* 157, 327–335. doi: 10.1007/s00442-008-1061-7

Vinh, T. V., Allenbach, M., Joanne, A., and Marchand, C. (2019). Seasonal Variability of CO_2 Fluxes at Different Interfaces and Vertical CO_2 Concentration Profiles Within a *Rhizophora* Mangrove Forest (Can Gio, Viet Nam). *Atmos. Environ.* 201, 301–309. doi: 10.1016/j.atmosenv.2018.12.049

Windham-Myers, L., Crooks, S., and Troxler, T. G. (2018). *A Blue Carbon Primer: The State of Coastal Wetland Carbon Science, Practice, and Policy* (Boca Raton: CRC Press).

Zeng, Y., Friess, D. A., Sarira, T. V., Siman, K., and Koh, L. P. (2021). Global Potential and Limits of Mangrove Blue Carbon for Climate Change Mitigation. *Curr. Biol.* 31, 1737–1743.e1733. doi: 10.1016/j.cub.2021.01.070

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