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Wil Burns,
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John Gallagher,
University of Tasmania, Australia

*CORRESPONDENCE
Nathalie Hilmi
✉ hilmi@centrescientifique.mc

†PRESENT ADDRESS
Samir Maliki,
University of Western Brittany, UMR 6308 AMURE, Brest, France/ Mecas Laboratory, University of Tlemcen, Tlemcen, Algeria

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Tropical blue carbon: solutions and perspectives for valuations of carbon sequestration

Nathalie Hilmi[1]*, Maria Belen Benitez Carranco[1], David Broussard[1], Maryann Mathew[1], Salpie Djoundourian[2], Sandra Cassotta[3], Alain Safa[4], Samir Maliki[5†], Florence Descroix-Comanducci[6], Denis Allemand[7], Claude Berthomieu[8], Jason M. Hall-Spencer[9] and Christine Ferrier-Pagès[7]

[1]Environnemental Economics, Centre Scientifique de Monaco (CSM), Monaco, Monaco, [2]Department of Economics, Adnan Kassar School of Business, Lebanese American University, Byblos, Lebanon, [3]Department of Law, Aalborg University, Aalborg, Denmark, [4]Université Côte d'Azur, IAE Nice, GRM, Nice, France, [5]Faculty of Economics and Management, University of Tlemcen, Tlemcen, Algeria, [6]IAEA Marine Environment Laboratories, Monaco, Monaco, [7]Department of Marine Biology, Centre Scientifique de Monaco (CSM), Monaco, Monaco, [8]Université Côte d'Azur, MSHS Sud-Est, Nice, France, [9]School of Biological and Marine Sciences, University of Plymouth, Plymouth, United Kingdom

Tropical marine ecosystems provide a wide range of provisioning, regulating, supporting and cultural services to millions of people. They also largely contribute to blue carbon sequestration. Mangroves, seaweeds, and seagrass habitats are important because they store large amounts of organic carbon while fish play a fundamental role in the carbon transport to deep waters. Protecting and restoring tropical marine ecosystems is of great value to society because their decline impairs the vital services they provide, such as coastal protection and seafood supplies. In this marine policy paper, we present options for enhancing blue carbon sequestration in tropical coastal areas. In addition, we outline the economic value of four components of coastal ecosystems (mangroves, seagrass beds, seaweed forests and fish) and discuss the economic levers society can apply to ensure the end of the current gross mismanagement of tropical blue carbon ecosystems. Market-based solutions, such as carbon taxes or fines for violations that use the 'polluter pays' principle, can be very effective in achieving national or international climate agreements. Private investment can also finance the preservation of blue carbon ecosystems. One widely known financing method for blue carbon conservation, particularly of mangroves, is the use of municipal bonds, which can be issued like traditional bonds to finance the day-to-day obligations of cities, states and counties. Non-philanthropic investments can also be used in order to protect these ecosystems, such as debt-for-nature swaps and the improved application of regulatory frameworks. Overall, the protection of tropical marine ecosystems is an ecological imperative and should also be seen as an opportunity for new revenue streams and debt reduction for countries worldwide.

KEYWORDS

tropical blue carbon, ecosystem services, conservation, restoration, market-based solutions

1. Introduction

Maintaining and restoring coastal blue carbon ecosystems is highly beneficial to society because it enhances the ecosystem services they provide, such as biodiversity conservation and seafood provisioning (Hilmi et al., 2021). Blue carbon sequestration is also a nature-based solution to the current climate emergency because marine vegetated habitats help society adapt to climate change by protecting coasts from more frequent storms, sea level rise and coastal erosion, although the effectiveness of blue carbon habitat restoration for carbon sequestration is questionable (Williamson and Gattuso, 2022). The bridge between the knowledge of the benefits of restoring blue carbon ecosystems and the need to prevent their ongoing destruction lies in economic incentives, multi-regulatory frameworks and the financial resources that enable the conservation and restoration of these natural resources (Figure 1). In this paper, we summarize the current state of knowledge to provide a framework that stakeholders can use to support the restoration of severely degraded tropical blue carbon ecosystems.

Calls for a sustained recovery of the world from the COVID 19 crisis are widespread (Laffoley et al., 2021), but these calls have gone unheard. Global CO_2 emissions from fossil fuel combustion increased by 6% in 2020–2021, reaching their highest annual level ever at 36.3 gigatons (Gt) (International Energy Agency, 2022). To avoid the worst impacts of climate change, the world urgently needs to reduce emissions. However, there is also an opportunity to remove CO_2 from the atmosphere through nature-based climate solutions (NbCs). The overall potential for mitigating climate change through the blue carbon approach is estimated to be <1% of current emissions (IPCC, 2021), but the benefits of adapting to climate change are worth. Among NbCs, terrestrial and marine blue carbon ecosystems store > 30,000 Tg C, which could avoid emissions of about 300 carbon dioxide equivalents (CO_2e) per year (Macreadie et al., 2021). Their expansion and restoration could sequester an additional 841 Tg CO_2e per year by 2030, or ∼3% of global emissions overall. Tropical coastal marine ecosystems, which include seagrasses, tidal marshes, and mangroves, are among the most efficient blue carbon ecosystems (Alongi, 2020). They are capable of sequestering 10 times more carbon than terrestrial ecosystems over millennia, whether through natural carbon assimilation during photosynthesis or through the sequestration of sediments and natural debris in their complex root systems (McLeod et al., 2011; Duarte et al., 2013). In addition, these ecosystems are important centers for economic activity due to their diverse resources (aquaculture, agriculture, fisheries, ports, tourism, etc.) and ecosystem services (Mumby et al., 2004; Ayyam et al., 2019). Many of these services are critical to coastal climate change adaptation (Figure 2). These include protection from erosion and sea level rise, provision of habitat for vertebrates and invertebrates, and food security for many communities around the world (Hilmi et al., 2021).

However, these tropical areas are more densely populated than other regions (Von Glasow et al., 2013). They host 40% of the world's population (Ayyam et al., 2019) and this number is expected to increase to 50% by the end of 2030 (Wilkinson, 2014). Increasing urbanization and pollution are therefore threatening mangroves, salt marshes, and seagrasses, resulting in similar or greater habitat loss than tropical forests (Valiela et al., 2001a, 2009). It is estimated that up to 67% of mangroves, 29% of seagrasses, and 35% of intertidal salt marshes have already been lost worldwide (Valiela et al., 2001a; Pendleton et al., 2012). These ecosystems can even go from carbon sinks to carbon sources (Pendleton et al., 2012). Protecting and restoring these ecosystems to avoid emissions is therefore a high priority in climate change mitigation efforts. In addition to help to prevent the erosion of biodiversity, activities to restore and protect blue carbon ecosystems also offer the potential for the development of market-based mechanisms that take advantage of existing carbon offset frameworks. Such financial incentives for blue carbon could also be a way to protect and leverage the other ecosystem services that these habitats provide, such as fisheries.

In this paper, we first briefly summarize the services provided by tropical coastal ecosystems, including carbon storage and sequestration. We then review compensatory measures such as green aquaculture, marine protected areas, and wetland restoration that can enhance carbon storage. Finally, because effective restoration and protection of blue carbon ecosystems require good governance, we discuss different types of governance, including market-based instruments, public investment, partnership initiatives, and community-based management that can be implemented in the future.

2. Services provided by tropical blue carbon ecosystems

Mangroves, seagrass beds and seaweeds are the most important carbon sinks in tropical seas and are referred to as "blue carbon" habitats. Mangroves are taxonomically diverse with around 50–75 woody species (Ellison and Farnsworth, 2001) and cover 135,000 to 150,000 km^2 over 118 countries in Southeast Asia, South America, Africa, and the Caribbean (Donato et al., 2011; Adame et al., 2021). In comparison, seagrasses, which are communities of submerged flowering plants, cover 320,000 km^2 mainly in Southeast Asia (Siikamaki et al., 2013). The coverage of seaweeds is however more difficult to evaluate, as it depends on the cultivation industry. These blue carbon habitats provide a wide range of services that can be classified into four categories: regulating, provisioning, cultural, and supporting (Table 1).

Mangroves provide local communities with timber, firewood, and charcoal, and also provide coastal protection from sea level rise and increased storminess (Duarte et al., 2013; Williamson and Gattuso, 2022). Awareness of the role of mangroves in coastal protection has increased following the 2004 Indian Ocean tsunami, which devastated much of the coastal habitat, as adequate protection of mangroves could have mitigated many of the worst impacts of the tsunami (Mazda et al., 2006; Sanford, 2009). In addition, mangrove ecosystems serve important functions as feeding and spawning areas, and reduce the risk of predation for many fish species (Carrasquilla-Henao et al., 2019). Seaweeds and seagrass beds are also involved in ecosystem regulation by stabilizing sediments, preventing shoreline erosion, and contributing to water purification (Barbier et al., 2011; Cullen-Unsworth and Unsworth, 2013; Lamb et al., 2017;

FIGURE 1
Roadmap for the protection of tropical blue carbon ecosystems.

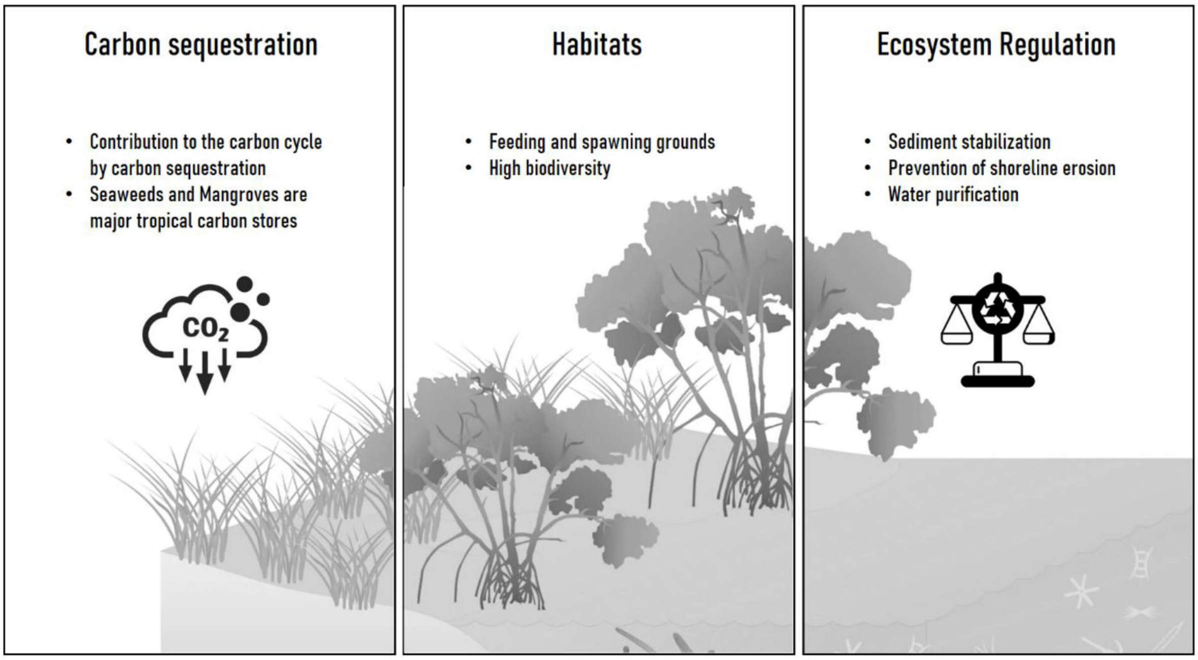

FIGURE 2
Ecological role of blue carbon (Barbier et al., 2011; this figure is a synthesis of Donato et al., 2011; Alongi, 2012; Cullen-Unsworth and Unsworth, 2013; Hasselström et al., 2018; Inoue, 2018; Lamont et al., 2020; Salt Marsh Guide, 2023).

Hasselström et al., 2018). They are important habitats that provide shelter for several hundred species of fish (Cullen-Unsworth and Unsworth, 2013; Hasselström et al., 2018), as well as lobsters and crabs. Other services provided by seagrasses range from food to pharmaceutical material for medicines (Cullen-Unsworth and Unsworth, 2013; Ambo-Rappe et al., 2019). In turn, seaweeds are easily cultivated and aquaculture has become a major industry providing employment and livelihoods for millions of families in rural coastal communities (Msuya and Hurtado, 2017). In addition, research is being conducted on the use of seagrass for biofuel production and as a substitute for plastic packaging (Kim et al., 2017). As a result, seaweed cultivation has developed very rapidly in Asia and the western Indian Ocean, primarily for food production (Calumpong et al., 2021). FAO global fishery and aquaculture

TABLE 1 Global ecosystem services, as classified by Costanza et al. (1997), Millennium Ecosystem Assessment (2005), Barbier (2007), Barbier (2019).

Service	Definition
Provisioning	This service refers to any product that results from the presence of the ecosystem. Examples of provisioning services include the provision of high quality and diverse food, that contributes to people's food security, job creation in the primary and secondary (transformation) sectors, medical resources, genetic resources, and raw materials (timber, water, etc.)
Regulating	Regulatory service refers to any benefits that result from the ecosystem regulation of other ecosystems. Regulation of water quality (removal of pollutants), reduction of inputs of seawater salts to groundwater in coastal areas, regulation of disease, regulation of climate, protection from the effects of hurricanes and storms, contribution to the carbon cycle by sequestering carbon (blue carbon), and protection of coasts from erosion (sediment stabilization, natural flood control, protection from sea level rise) are examples of regulatory services
Supporting	Supporting services have indirect effects on people who depend on certain ecosystems. Examples of supporting services include primary production, production of atmospheric oxygen, and the hydrologic cycle. For example, it provides protection and biodiversity conservation for terrestrial and marine life; it provides suitable reproductive habitat for marine life; and important services such as nutrient cycling.
Cultural	This service is defined by a non-material approach. It includes aesthetics, spiritual enrichment, and recreation through the ecosystem. A primary focus is on cultural, religious, and educational values. These values can vary from community to community and are therefore more difficult to assess. Cultural services also create employment opportunities in services and tourism, which are closely linked to the accessibility of knowledge about biodiversity processes for education and research. In addition, they can impact the wellbeing and health of communities.

statistics show that the global seaweed cultivation increased 1,000-fold between 1950 and 2020, from 34.7 thousand tons to 34.7 million tons, with aquaculture accounting for 97% of the current production (FAO, 2020a,b). However, the impacts of seaweed farms can also be seen as negative, due to habitat degradation (Cabral et al., 2016).

Among the ecosystem services provided by these tropical coastal ecosystems, carbon sequestration is the most important (Donato et al., 2011; Alongi, 2012; Inoue, 2018; Lamont et al., 2020). Mangroves sequester important organic carbon stocks (C_{org}), above (leaves, branches) and below (sediment, roots) the soil, at depths ranging from 30 cm to more than 3 m, providing long-term storage (Donato et al., 2011). Recent estimates of C_{org} accumulation in mangroves are from radiometric analyses and range from 0.17 to 4.3 Mg C ha^{-1} y^{-1} (Kelleway et al., 2017a,b; Lamont et al., 2020). They are within the range of estimates derived from soil carbon measurements, which range from 1.74 Mg C ha^{-1} y^{-1} (Alongi, 2014) to 2.5 Mg C ha^{-1} y^{-1} (Osland et al., 2012; Saintilan et al., 2013; Lunstrum and Chen, 2014; Marchand, 2017). However, the rates of carbon accumulation by roots, ranging from 5.06 to 6.63 Mg C ha^{-1} y^{-1}, are much higher than estimates of mass carbon accumulation by radiometric analyses or soil mass carbon determination (Lamont et al., 2020). These differences are due to the fact that roots are not considered in any of the above measurements. Recent estimates of mangrove litterfall also show higher values for carbon sequestration than radiometric and mass analyses. Carbon sequestration by mangrove litter has been estimated at 3 to 5 Mg C-ha^{-1}-yr^{-1} (Twilley et al., 2017; Ribeiro et al., 2019). Taken together, these values yield a total forest stock of 693 Mg C ha^{-1} and a soil forest stock of 516 Mg C ha^{-1}, considering only the carbon stored in the upper layers of sediments (Alongi, 2022). This stock in soils can increase up to 2,792 Mg C ha^{-1} when deeper layers are considered. Using the median of 627.8 MgC ha^{-1} and the most commonly used estimates of global mangrove areas of 83,495 and 137,760 km^2, Alongi (2022) estimated that the global stock for mangroves ranges from 5.23 to 8.63 Pg C (5.23 and 8.63 x 10^{15}g C). These values also result in 9.6 to 15.8 Tg C y^{-1} of carbon being buried in mangrove forests, i.e. 4–5 times higher than boreal, temperate and tropical upland forests (Alongi, 2022).

The carbon stock of mangroves is much larger than that estimated for seagrass beds (Alongi, 2022). Indeed, seagrass carbon stocks in the uppermost 1 m of sediment range from 12 to 120 Mg C ha^{-1} with a median value of 69.3 Mg C ha^{-1} (Alongi, 2018; Miyajima et al., 2022), with sequestration rates ranging from 94 to 161 kg C ha^{-1} y^{-1} (Miyajima et al., 2022). Recently, however, Van et al. (2021) found that many estimates do not account for other processes, including denitrification, sulfur, and inorganic carbon cycling. These processes represent a source of CO_2 to the atmosphere that can far exceed organic carbon sequestration. Unlike mangroves and seagrasses, seaweeds do not accumulate carbon rich coastal sediment. Instead, most of the organic carbon is in the living biomass. In addition, some of the carbon fixed by seaweeds is buried on the continental shelf and in the deep ocean (Hurd et al., 2022), providing a global carbon sink. Research in Singapore has shown that macroalgae store for up to 650 Mg C of biomass, which is higher than the aboveground carbon found in seagrass meadows but lower than that in mangrove forests whose annual sequestration is estimated at 450 Mg C $year^{-1}$, or 0.77 Mg C ha^{-1} yr^{-1} (Kwan et al., 2022). In addition to these important carbon sinks, the contribution of offshore sediments may be even more important in terms of total organic carbon stored, because of their large area (Legge et al., 2020; Hilmi et al., 2021). Tidal marshes are also carbon sinks, but they tend to be located in temperate and high latitudes, where they cover more than 51,000 km^2 (Chmura, 2013).

The above numbers of carbon sequestration are rough estimates, as mangroves and seagrass beds are facing increasing threats such as poor water quality and coastal development (aquaculture, timber production...), leading to habitat degradation and rapid loss of the surface and functions of these ecosystems. Dunic et al. (2021) found that the total seagrass area surveyed has declined by 19% since 1880, with particularly large losses in the tropical Atlantic and tropical Indo-Pacific among tropical regions. Mangroves are currently disappearing at a rate of 1–2% per year (Valiela et al., 2001b; Alongi, 2002) and may disappear, at least functionally, in $<$100 years (Duke et al., 2007). Mangroves are also subject to large fluctuations, with both natural reforestation and deforestation occurring (Giri et al., 2014). Overharvesting, and replacement of mangroves by nypa palms, have also been identified as a major cause of deforestation in parts of West Africa (Adanguidi et al., 2020) and South Asia (Islam and Bhuiyan, 2018). As a result, mangroves have shrunk significantly in recent decades (Hamilton and Casey, 2016). Ward et al. (2016) estimated that mangrove forests suffer an average annual loss of 0.18%, with more than 100,100 ha of mangroves removed in Southeast Asia between 2000 and 2012. When mangroves are removed and the land is dredged for economic development, sediments enter the atmosphere or water column, and release rstored carbon back into the atmosphere and ocean (Callaway et al., 2012; Fourqurean et al., 2012). Carbon release from mangrove loss is estimated at 35 million tons/year (Siikamaki et al., 2013). In terms of CO_2 equivalents, Atwood et al. (2017) estimated that global potential CO_2 emissions due to mangrove loss could reach ∼7.0 Tg per year. The countries with the highest potential CO_2 emissions from soils are Indonesia (3,410 Gg CO_2 yr^{-1}) and Malaysia (1,288 Gg CO_2 yr^{-1}). Despite significant losses in mangrove areas, extensive conservation and restoration programs have been implemented in recent years (Lee et al., 2019). Efforts to mitigate global warming and mangrove trade are occurring through community-based restoration, reforestation, integrated coastal ecosystem restoration, and economic approaches (Maulidia et al., 2022). Aheto et al. (2016) found that livelihood and economic benefits are the most important factors motivating local stakeholders to participate in mangrove restoration and management. Therefore, mangrove restoration is expected to reduce the failure of community-based restoration programs (Ranjan, 2019).

3. Economic values of tropical blue ecosystems

Given the increasing interest in the importance of vegetated coastal habitats at global, national, and local scales, it is important that their carbon uptake and storage potential be clearly valued in monetary terms (Hurd et al., 2022)., Such valuation would help raise awareness in the community and among policy makers, it would also help invest in appropriate coastal protection and ecological restoration measures, that could otherwise result in massive economic damage (the cost of inaction).

The value of mangroves for coastal protection and stabilization over a 20-year period is estimated at \$12,263 ha^{-1}, and the damage cost of losing 1 km^2 of mangroves in Thailand is equivalent to approximately \$1,879 ha^{-1} (Barbier, 2006). The annual economic value added to local fisheries for one hectare of mangroves can range from \$42 to \$37,500, depending on location and species value (DebRoy and Jayaraman, 2012; Anneboina and Kavi Kumar, 2017). In addition, the annual economic value added per hectare for penaeid shrimp (the most economically viable fishery associated with mangroves) ranges from US\$91 to US\$5,292. Finally, mangroves also create further value through tourism (Spalding and Parrett, 2019), education (Friess, 2016), and cultural practices (worship). For example, mangroves have been estimated to increase tourism revenue by \$1 million and \$7 million annually in Malaysia and Iran, respectively (Ahmad, 2009; Dehghani et al., 2010), and by \$42,000 annually in Sundarban Reserves in India and Bangladesh (Uddin et al., 2013). In total, taking into account all services, mangroves worldwide have been valued at US\$69.9 billion (Sanford, 2009). Using voluntary carbon markets, mangrove ecosystems have been used to generate income for local communities through the sale of carbon credits equivalent to carbon sequestration (Verra, 2021; Plan Vivo, 2022) and have been identified as strong candidates for payment for ecosystem services (PES) (Locatelli et al., 2014). These mechanisms help finance conservation. However, there are few blue carbon projects that generate carbon credits, as this requires additional climate market mechanisms (Ullman et al., 2013).

Loss of seagrass can result in high economic costs because it is an indirect source of food and pharmaceutical material for medicines. However, such cost has hardly been evaluated. In addition, seagrasses are also a hot-spot of tourism, such as in Indonesia, where tourism directly associated with seagrass ecosystems brings in between \$2,287/ha/year and \$80,226/ha/year (Dewsbury et al., 2016). Finally, the release of carbon dioxide from seagrass degradation, has an estimated global economic cost of \$1.9–\$13.7 billion per year (Cullen-Unsworth and Unsworth, 2013).

Concerning seaweed, a World Bank report identified seaweed aquaculture as a potential climate change mitigation and a source of income in tropical countries (Yarish et al., 2016). It estimated that the production of 500 million tons of seaweed would absorb 135 million tons of carbon (equivalent to 3.2% of the annual carbon addition to seawater from GHG emissions). In addition, seaweed farming reduces community poverty and improves incomes for coastal people. In Malaysia, seaweed aquaculture began in the 1980s and production has increased to 269,431 tons by 2013. During that time Malaysia's contribution to the worldwide seaweed production was 1% and ranked eighth in the world (Hussin and Khoso, 2021). Finally, the majority of seaweed produced in South East Asia is used for the extraction of carrageenan. It's a hydrocolloid that can be found in red seaweed and is used in several food and pharmaceutical products. This industry is steadily growing with a global value of around US\$ 0.5 billion. The major players with 1.3 million tons dry weight in 2016 are Indonesia, the Philippines, Malaysia, United Republic of Tanzania and Vietnam (Nor et al., 2020). Sales of the genera *Kappaphycus* and *Echeuma* accounted for US\$1.9 billion in 2014 (Kim et al., 2017), and these are among the major seaweeds grown in tropical regions globally. In 2012 *Eucheuma* spp. had the highest global value with around US\$1.28 billion and a wet weight of 6.15 million tons. Both *Kappaphycus* and *Echeuma* are predominantly found in tropical waters in Southeast Asia (Hurtado et al., 2017).

4. How can tropical blue carbon ecosystems be protected?

There are several different possibilities to properly implement effective restoration and protection measurements. These include market-based instruments like taxes and fines, public investments, community-based management, government incentives and many more. This section gives an overview of the status quo for the different possibilities mentioned and how they can be implemented.

4.1. Market-based solutions

Economic intervention can take various forms, including the use of pricing systems to alter market outcomes based on efficiency and equity considerations. As a general rule, prices for goods and services must reflect the true cost/benefit of all resources (natural and man-made) used in the production process. If the production and/or consumption process contributes to blue carbon depletion, then this loss of a valuable resource must be incorporated into the market price of the product by assigning a value equal to the carbon produced/displaced per activity that disrupts ecosystem integrity.

Market-based solutions are about finding ways to promote activities that have societal benefits and discourage those that have societal costs. They rely on interventions that change the price of a product to reflect the societal costs or benefits of an activity, not just the private costs or benefits. In the case of mangroves, the fee or price of the activity (industrial development project or fishery) that contributes to their destruction will include the cost of all resources used, including the cost of the ecosystem services that mangroves produce. Interventions include, but are not limited to, taxing activities that damage the blue ecosystem, imposing a carbon tax, granting tax breaks, or subsidizing activities that contribute to blue carbon conservation. Policy instruments can substitute for each other or complement each other. For example, taxes can be used in place of standards or subsidies to achieve the same allocation of resources/outcomes, with potentially different distributional consequences.

Several tools, summarized in the following table (Table 2), can provide an economic incentive for greener development and create incentives for further expansion and exploration of low-carbon technologies, thereby influencing economic growth (Bowen, 2011; World Bank, 2023). Tax break policies usually create incentives to engage in the activities that enable such benefits. When developers or companies are eligible for environmental tax credits, they will consider projects that generate blue carbon as a byproduct and explicitly include the benefits in project costs. It is also important to note that administrative penalties such as fines are generally easier to enforce than criminal penalties. A combination of administrative and criminal penalties appears to be most effective for environmental violations. It is argued that fines are very important for moderately serious cases (Faure and Svatikova, 2012).

Taxing carbon dioxide is much easier to implement than other carbon pricing mechanisms because you only need to build on an existing tax system. They can be easily applied to polluters in all emissions sectors and can create incentives for the development and deployment of low-carbon technologies. Finally, tax reuse could increase public morale and productivity (Harrison, 2010). However, carbon taxation can increase the prices of related products, which can weaken the competitive advantage of energy-intensive firms and thus affect overall economic growth. Polluters may pass on the costs to consumers, which may only increase government tax revenues but have no effect on reducing emissions. Also, public acceptance of carbon taxes may decline if the tax is not recycled, which could further complicate implementation (Baranzini et al., 2000). In addition, the implementation of carbon taxes in developed countries could lead to a shift of emissions to developing countries with looser environmental regulations (Lin and Li, 2011).

4.2. Financing blue carbon preservation and maintenance

Currently, one of the biggest problems is the inadequate provision of funding for the protection and restoration of blue carbon ecosystems. In order to receive funding, projects must demonstrate their effectiveness while having a low financial risk. More than 80% of Clean Development Mechanism (CDM) funding goes to sustainable energy and only 1% to reforestation. The voluntary market currently appears to be the largest source where buyers can purchase so-called offsets that target their own social responsibility (Vanderklift et al., 2019). This market is estimated to reach US$50 billion in 2030 (Favasuli and Sebastian, 2021). Vanderklift et al. (2019) argue that publicly funded blue carbon projects would be one way to improve the risk and reward profile of these activities. They provide an example of guaranteed minimum prices for blue carbon credits that could address the risks of price volatility. The legal and policy framework for blue carbon projects is fraught with uncertainty. As a result, many public funds for blue carbon ecosystem conservation are being cut, affecting the cash flow for these projects (Vanderklift et al., 2019).

Gordon et al. (2011) provide an overview of 14 different funding sources related to blue carbon project financing. Much of the money currently allocated to the funds goes to REDD + (Reducing Emission from Deforestation and forest Degradation) planning and pilot projects. REDD + is a framework under the United Nations Framework Convention on Climate Change (UNFCCC) and includes projects aimed at reducing emissions from deforestation and forest degradation (United Nations Climate Change, 2023). It also includes potential funding for blue carbon (Gordon et al., 2011). Examples of these funding sources that provide funding for REDD + projects include the Hatoyama Initiative ($158 million), the Amazon Fund ($133.3 million), and the Global Environment Facility Trust Fund ($105), to name a few (Gordon et al., 2011).

According to Earth Security (2020), philanthropic money is very important for private sector funding for blue carbon. They cite an example from Tahiry, Madagascar, where the MacArthur Foundation provided over $1 million to Blue Ventures. This enabled funding for project preparation studies for blue carbon credits totaling 1,300 metric tons. The innovation that comes with philanthropic investments is also an important factor. They can often contribute to the research and development of business models that indirectly impact blue carbon conservation. Philanthropies and other funders can help attract private investors and minimize their risk. One example is a partial debt guarantee and $6 million investment from the Global Environment Facility and the U.S. International Development Finance Corporation, which led to additional investment from large private investors such as JPMorgan Chase and Encourage Capital.

One widely used financing method for blue carbon conservation, particularly mangroves, is municipal bonds. Municipal bonds can be issued like any other bond, but their purpose is to fund the day-to-day obligations of cities, states, and counties. The funds typically go toward building schools, highways, and more (U.S. Securities and Exchange Commission, n.d.). In the U.S., several coastal cities have begun issuing $400

TABLE 2 Possible economic interventions.

Economic intervention	Description
Carbon taxes	Carbon taxes or carbon prices use the market mechanism to internalize the external costs of greenhouse gas emissions in order to discourage such emissions, protect the environment, combat climate change, and comply with various national or international climate agreements (Baranzini et al., 2000; Vincent, 2013). This mechanism is based on the polluter pays principle, which shifts the burden for the destructive consequences of greenhouse gas emissions back to the responsible parties or polluters (Khan, 2015). Managing authorities set a direct, predetermined price on GHG emissions and require participants to account (or be accountable) for each ton of carbon produced (Aldy and Stavins, 2012). This incentive encourages players to reduce their emissions by switching to cleaner technologies. The carbon price sends an economic signal to polluters that gives them a choice to either change their activities and thereby reduce their GHG emissions, resulting in a lower carbon payment, or maintain similar emission patterns and pay for the emissions (Baranzini et al., 2000).
Fines for violation	Fines serve as punitive measures for violating norms or certain rules of conduct. Fines may or may not depend on the amount produced or consumed. An important aspect of fines for violating environmental laws is the implementation and enforcement process. According to OECD (2009), environmental law violations can be punished by courts withholding wages if payment is refused. However, in an article on punishing polluters, Pedersen (2019) points out that the size of the fines is very important because large companies, which are responsible for the vast majority of polluting activities, can easily pay the current fines. They also note that regardless of the level of fines, strict enforcement of penalties has led to an increase in so-called "enforcement commitments." Under this process, a company commits to changing its polluting activities while admitting to having caused unintended harm. The focus is thus on improving behavior rather than paying fines.
Emissions Trading	The Emissions Trading Scheme (ETS) is a system in which emitters can trade units of permits to emit greenhouse gasses. Here, the system or competent authority issues limited permits with different emission quotas, creating supply and demand for the units. The cap-and-trade system requires that agencies set the overall quota based on the desired level of GHG emissions and allow individual emitters' quotas to be traded through auctions or other means (Bowen, 2011). The baseline-and-credit system does not require the establishment of a fixed quota. Instead, agencies set the baseline, and emissions reductions allow companies to purchase credits and trade them with others through the carbon offset mechanism (OECD, n.a.). Carbon offsetting is a mechanism by which emitting companies can offset their greenhouse gas emissions by purchasing carbon credits that are sold in various carbon markets. The carbon credits come from projects that enable the sequestration of greenhouse gasses (e.g., mangrove ecosystems in an MPA) and are accredited by a certification body (Alongi, 2011; World Bank, 2023).
Results-based climate finance	(RBCF) is a mechanism whereby companies receive funds if they achieve certain pre-determined climate-related targets, such as a specified reduction in emissions, as verified by independent auditors. This mechanism incentivizes companies to reduce their emissions to meet climate targets and is a catalyst for private sector investment in climate projects (World Bank Group Frankfurt School of Finance Management, 2017; World Bank, 2023).
Internal carbon pricing	Internal carbon pricing allows governments, businesses, and other organizations to incorporate the value of carbon production and/or savings into all investment-related decisions to incentivize investment in low-carbon technologies and guide organizations' decision-making processes regarding climate change impacts (Harpankar, 2019; World Bank, 2023).

million in bonds (U.S. Securities and Exchange Commission, n.d.), including $192 million for mangrove protection and restoration (Earth Security, 2020). Green bonds allow you to raise money for environmental projects (e.g., pollution reduction, sustainable agriculture, ecosystem protection, etc.) by issuing financial instruments specifically dedicated to these projects. In addition, they can be issued with tax incentives to make them more attractive to investors (Segal, 2022). This mechanism is often used by the World Bank to support climate-related projects (World Bank, 2021).

Another method of financing blue carbon reserves is to use debt-for-nature swaps to reduce or offer preferential terms on national or local debt. By 2020, countries' debt levels have increased enormously. According to the International Monetary Fund (2020), general government debt is at post-World War II levels. Small island developing countries are particularly vulnerable (Grigoryan et al., 2021). For this reason, Thomas and Theokritoff (2021) propose debt-for-nature/debt-for-climate swaps. In this financial mechanism, a creditor country forgives a debtor country's debt through an intermediary that buys the debt at a deep discount in exchange for conservation investments.

4.3. Regulatory frameworks applicable to coastal blue carbon conservation and restoration

The conservation of mangrove forests, as well as the restoration of some already destroyed forests, is a challenge from a legal perspective. Mangroves are regulated by a multi-layered set of rules at the international, regional, and national levels, composed of various legal sources and policies, both hard law and soft law. Typical legal instruments include, for example, standards, principles (such as the polluter pays principle), concepts, regulatory decision-making tools such as environmental impact assessments (EIAs), treaties, declarations, targets, and goals (such as the SDGs). These legal instruments have been implemented by various countries, and there are current legal frameworks that provide good tools for mangrove protection and conservation. However, all of these instruments suffer from the problems of "traditional environmental law," such as lack of enforcement, human and financial constraints, and unclear government mandates. International instruments can be both hard and soft law and are often used in combination with incentives and financial instruments. These instruments are cross-sectoral, meaning that they do not address a single area of law, but rather multiple areas that overlap and intersect to respond to the various threats identified above.

International hard law instruments applicable to Coastal Blue Carbon include the biodiversity frameworks, such as the Ramsar Convention on Wetlands,[1] the World Heritage Convention,[2] and the Convention on Biological Diversity.[3] The latter is particularly relevant to mangroves, as it requires Parties to integrate biodiversity considerations into sectoral programs and provide incentives for conservation. It also includes the Aichi Biodiversity Targets,[4] which are specific goals. In addition, climate change frameworks are relevant to respond to the challenges faced by mangroves, such as the United Nations Framework Convention on Climate Change (UNFCCC)[5] the Paris Agreement,[6] and the framework on Reducing Emissions from Deforestation and Forest Degradation (Redd +),[7] as mangroves are subject to flexible mechanisms established by the UNFCCC, such as the CDM, a mechanism that promotes carbon sequestration. Under the CDM, countries can receive outcome-based payments for forest conservation and management.

Other conventions that address challenges to mangroves include the Convention on Migratory Species (CITES), (see text footnote[1]) which provides a framework for agreements between states with migratory species, and the United Nations Convention on the Law of the Sea (UNCLOS) (see text footnote[2]), which provides for the protection and conservation of the marine environment in areas under its jurisdiction, which may include an obligation to protect mangroves and regulate activities. Standards are increasingly used as soft law instruments, such as the recent International Union for Conservation of Nature (IUCN) Global Standards of 2020 (see text footnote[3]), World Bank and Center for Tropical Ecosystem Research codes of conduct, and finally environmental impact assessments. Since most mangroves thrive in brackish water, they usually grow where the river meets the sea. Therefore, mangroves also fall under international water frameworks such as the United Nations Water Convention (UN Convention) (see text footnote[4]) and the UN Convention on the Right of Non-Nautical Uses of International Watercourses (UN Watercourse Convention) (see text footnote[5]).

One of the greatest challenges in formulating policy for coastal areas is the coordination between the legal and administrative frameworks for marine water and freshwater on the mainland. The example of mangroves clearly shows that this is a cross-cutting issue. To set an example at the regional and European level, the Water Framework Directive (WFD) (see text footnote[1]) provides objectives for good status not only for continental waters, but also for coastal waters, which include transitional waters (estuaries and lagoons). In these areas, the physico-chemical, biological and hydromorphological components of good status are highly dependent on both land-based and marine influences. Specifically, this means that river basin mechanisms (monitoring, basin planning, governance, and funding) must be coordinated and provide tremendous leverage for coastal mechanisms in an integrated water management perspective. This framework also applies to "overseas territories" (OVTs), which have a special regulatory status, and in this context, using the example of the tropical area (see text footnote[2]).

However, the WFD is not legally binding in overseas countries and territories, i.e., jurisdictions characterized by a dependent relationship with an EU member state without being part of the EU. In French Guiana, for example, mangrove management requires local coordination to comply with European legislation for both marine and freshwater. In practice, funding allocated to WFD monitoring and planning is also being used to improve knowledge of downstream coastal areas in several watersheds in the country (see text footnote[1]).

Another example is found in Africa, where the Senegalese Ministry of Environment (responsible for coastal zone management) is currently working with the Ministry of Water and Sanitation (responsible for river basin planning) to better protect the Somone Coastal Basin Conservation Area. In the downstream part of the watershed, there is a remarkable mangrove that provides ecosystem services (protection, economic activities with tourism and seafood, biodiversity, carbon storage, etc.). However, due to excessive use of water resources in the upstream part of the basin (with increasing demographics, industry, and agricultural exports), freshwater runoff to the reserve is lower, sedimentation and salinity are increasing, resulting in immediate loss of mangrove areas and biodiversity. The conservation and restoration of mangrove forests requires a good interaction between the environment and water resources, which is currently being prepared with a new concertation mechanism (Committee for the Management and Planning of Waters in Somone - SC-GPE) (see text footnote[2]).

From all of the foregoing, it is clear that there is no comprehensive, globally binding legal framework focused on mangrove conservation, but rather a set of international instruments, tools, and standards that can be used if properly implemented. At the national level, mangroves may fall under different legislations due to the fact that they belong to different ecosystems: Forests, Marine and Coastal Law, as well as Water and Wetlands, Aquaculture, and Climate Change. Moreover, since mangroves are key to valuable ecosystem mechanisms, various "tagging-based instruments" are an option for mangrove protection. The national level of regulation is closely linked to the international level, as laws and regulations at the national level must consider the principles, concepts, and standards contained in international treaties, and thus the national level must implement global environmental treaties. For the protection of mangroves, the legal framework at the national level can use executive decrees, regulations, legal decisions, taxes, and strategic instruments. The national level is not free from various obstacles, such as governance, land tenure, and rights. At the national level, countries do not have "specific mangrove laws" but have various legal provisions that regulate the activities of other sectors (such as extractive

1 United Nations Convention on Wetlands of International Importance Especially as Waterfowl Habitat, 1975.

2 World Heritage Convention of 1975.

3 Convention on Biological Diversity of 1993.

4 Aichi Biodiversity Targets of 2020.

5 United Nations Framework Convention on Climate Change of 1992.

6 The Paris Agreement of 2015.

7 Reducing Emissions from Deforestation and Forest Degradation of 2013.

industries, fisheries, and agriculture). Of importance are planning and permitting regulations, which may be private or public in nature and may take into account principles of good governance (such as access to information, public participation, and access to justice). Planning also involves communities in governance and people at the village level in programmes for social forestry, land use, etc. Other legal tools used at the national level include marine protected areas (MPAs), marine special planning (MSP), integrated coastal zone management (ICZM), and ecosystem-based management (EMB).

4.4. Governance, incentives, and enforcement's challenges

Mangrove ecosystems produce useful and sometimes crucial resources and services for nature and humans (Slobodian et al., 2023). These resources and services can be sustainably monetized to support mangrove conservation through payments for ecosystem services, product certification, carbon offsets, and REDD + and fiscal incentives and disincentives. Mangrove interests have sought opportunities to monetize stored carbon through REDD + and the sale of carbon offsets in the voluntary market. Such opportunities depend on legal conditions that do not exist in many countries (i.e., legal definition of ownership of mangrove areas and their ecosystem services, legal definition of carbon property rights, and standards for carbon valuation). There are also legal problems in applying carbon offset schemes to mangrove forests. For example, the definition of "forest" is not the same in every country, which creates problems when trying to implement the flexible mechanisms introduced by the UNFCCC. Fiscal incentives and disincentives can be used to change behaviors and make choices that support conservation and sustainability. The main challenges for mangroves are institutional coordination, governance issues, lack of community participation, and land tenure issues, as well as poor articulation between responses to land-based (freshwater river basin management, issues of contaminations, uses of sedimentation and impacts on hydromorphology) and marine-based challenges, considering that mangrove are influenced by both processes. Transparency in governance, accountability, and rule of law participation are very important to ensure citizen participation. The main problems in implementation are the lack of institutional capacity and financial resources. Meanwhile, enforcement challenges are mainly due to corruption, lack of capacity building, and poorly functioning bureaucratic mechanisms at the national level. To meet the challenges of future climate change and achieve the goals of global and regional agreements and strategies, both new legal instruments and legal measures should be redesigned to anticipate implementation, enforcement, and compliance problems and create proactive rather than reactive law. To promote enforcement of the law, the issue of ownership is key. Coastal management strategies and their decisions for ecosystem conservation, protection, and restoration face the major challenge of appropriation. To mediate between a top-down and bottom-up perspective, integrated planning and community participation in prioritizing pressures and actions are needed. For this reason, local governance and participatory management involving stakeholders (communities and citizens, local authorities, regional and national governments and their local representatives, economic sectors, non-governmental organizations, science and universities) is useful to jointly diagnose the state of these ecosystems, find answers and implement measures for protection, conservation and restoration. In this way, more economic resources can also be mobilized for these ecosystems, increasing willingness to pay. In conclusion, from an institutional and regulatory point of view, we can mention here that the joint effort to develop an integral management of coastal ecosystems is an effort/action that should not be regretted because it remains relevant regardless of the expected reality of climate change and also brings benefits to territorial development in general.

5. Conclusion

The protection of tropical blue carbon ecosystems is of great importance, not only for carbon storage but also for the preservation of the many other ecosystem services associated with them. In particular, provisioning and regulating services have an impact on society in terms of economic value and ecosystem health. As we have seen, preserving tropical blue carbon ecosystems can be an opportunity to create new sources of revenue and reduce debt through innovative financing mechanisms. This is directly related to the United Nations Sustainable Development Goals that are being targeted. Incentives to achieve these goals can come from governance, regulatory frameworks, market-based solutions, and other financing mechanisms. International governmental cooperation will be required to preserve the ecosystem and its health. Timing is also a vital element in ensuring sustainability in protection. Finally, blue carbon ecosystems are complex so that there is the need to improve our knowledge on the biology of these ecosystems, to reduce the uncertainties about their role as carbon sinks. Indeed, a very recent study showed that seaweed ecosystems may finally not mitigate CO_2 emissions, and may even be CO_2 emitters (Gallagher et al., 2022). In this case, there is a real risk of investments in natural climate solutions that, ultimately, have little climate benefit.

Author contributions

NH designed the paper and led the process and wrote the first draft with JH-S and CF-P who drafted the science sections. MB, DB, and MM contributed to the sections, tables, and supplementary material under the NH's supervision. SD, AS, SM, and CB contributed to the economic sections. SC contributed to the governance sections. FD-C, DA, JH-S, and CF-P contributed to the science sections. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

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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. *Glob. Chang. Biol.* 27, 2856–2866. doi: 10.1111/gcb.15571

Adanguidi, J., Padonou, E. A., Zannou, A., Houngbo, S. B. E., Saliou, I. O., and Agbahoungba, S. (2020). Fuelwood consumption and supply strategies in mangrove forests—Insights from RAMSAR sites in Benin. *For Policy Econ.* 116, 102192. doi: 10.1016/j.forpol.2020.102192

Aheto, D. W., Kankam, S., Okyere, I., Mensah, E., Osman, A., Jonah, F. E., et al. (2016). Community-based mangrove forest management: Implications for local livelihoods and coastal resource conservation along the Volta estuary catchment area of Ghana. *Ocean Coastal Manag.* 127, 43–54. doi: 10.1016/j.ocecoaman.2016.04.006

Ahmad, S. (2009). Recreational values of mangrove forest in Larut Matang, Perak. *J. Trop. Forest Sci.* 21, 81–87. Available online at: https://www.jstor.org/stable/23616638

Aldy, J. E., and Stavins, R. N. (2012). The Promise and PRoblems of Pricing Carbon. *The J. Envi. Dev.* 21, 152–180. doi: 10.1177/1070496512442508

Alongi, D. M. (2002). Present state and future of the world's mangrove forests. *Envir. Conserv.* 29, 331–349. doi: 10.1017/S0376892902000231

Alongi, D. M. (2011). Carbon payments for mangrove conservation: Ecosystem constraints and uncertainties of sequestration potential. *Environm. Sci. Policy.* 14, 462–470. doi: 10.1016/j.envsci.2011.02.004

Alongi, D. M. (2012). Carbon sequestration in mangrove forests. *Carbon Manag.* 3, 313–322. doi: 10.4155/cmt.12.20

Alongi, D. M. (2014). Carbon cycling and storage in mangrove forests. *Ann. Rev. Mar. Sci.* 6, 195–219. doi: 10.1146/annurev-marine-010213-135020

Alongi, D. M. (2018). *Seagrass Meadows*. Cham: Blue Carbon. Springer Briefs in Climate Studies. Springer.

Alongi, D. M. (2020). Carbon balance in salt marsh and mangrove ecosystems: a global synthesis. *J. Mar. Sci. Eng.* 8, 767. doi: 10.3390/jmse8100767

Alongi, D. M. (2022). Impacts of climate change on blue carbon stocks and fluxes in mangrove forests. *Forests* 13, 149. doi: 10.3390/f13020149

Ambo-Rappe, R., La Nafie, Y. A., Cullen-Unsworth, L. C., and Unsworth, R. K. (2019). Perspectives on seagrass ecosystem services from a coastal community. *IOP Conf. Ser.* 370, 012022. doi: 10.1088/1755-1315/370/1/012022

Anneboina, L. R., and Kavi Kumar, K. S. (2017). Economic analysis of mangrove and marine fishery linkages in India. *Ecosyst. Serv.* 24, 114–123. doi: 10.1016/j.ecoser.2017.02.004

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. Clim. Chang.* 7, 523–528. doi: 10.1038/nclimate3326

Ayyam, V., Palanivel, S., and Chandrakasan, S. (2019). *Coastal Ecosystems of the Tropics - Adaptive Management*. Berlin: Springer. doi: 10.1007/978-981-13-8926-9

Baranzini, A., Goldemberg, J., and Speck, S. (2000). A future of carbon taxes. *Ecol.Econ.* 32, 395–412. doi: 10.1016/S0921-8009(99)00122-6

Barbier, E. B. (2006). Natural barriers to natural disasters: Replanting mangroves after the tsunami. *Front. Ecol. Environ.* 4, 124–131. doi: 10.1890/1540-9295(2006)0040124:NBTNDR2.0.CO;2

Barbier, E. B. (2007). Valuing ecosystem services as productive inputs. *Econ. Policy* 22, 178–229. doi: 10.1111/j.1468-0327.2007.00174.x

Barbier, E. B. (2019). "The Value of Coastal Wetland Ecosystem Services," in *Coastal Wetlands*. p. 947–964. doi: 10.1016/B978-0-444-63893-9.00027-7

Barbier, E. B., Hacker, S. D., Kennedy, C., Koch, E. W., Stier, A. C., and Silliman, B. R. (2011). The value of estuarine and coastal ecosystem services. *Ecol. Monogr.* Elsevier: Amsterdam. 81, 169–193. doi: 10.1890/10-1510.1

Bowen, A. (2011). *The Case for Carbon Pricing*. Policy Brief, Grantham Research.

Cabral, P., Levrel, H., Viard, F., Frangoudes, K.,Girard, S., and Scemama, P. (2016). Ecosystem services assessment and compensation costs for installing seaweed farms. *Marine Policy.* 71, 157–165. doi: 10.1016/j.marpol.2016.05.031

Callaway, J. C., Borgnis, E. L., and Turner,R. E., Milan, C.S. (2012). Carbon sequestration and sediment accretion in SanFrancisco Bay tidal wetlands. *Estuaries Coasts.* 35,1163–1181 doi: 10.1007/s12237-012-9508-9

Calumpong, H., Kirkman, H., Yokoya, N. Y., Hall-Spencer, J. M., Osman, N. A. R., Park, C., et al. (2021). "Chapter 6G Marine plants and macroalgae," in *The Second World Ocean Assessment* United Nations, New York, NY: United Nations publication. p. 224–248

Carrasquilla-Henao, M., Ban, N., Rueda, M., and Juanes, F. (2019). The mangrove-fishery relationship: A local ecological knowledge perspective. *Marine Policy.* 108, 103656. doi: 10.1016/j.marpol.2019.103656

Chmura, G. L. (2013). What do we need to assess the sustainability of the tidal salt marsh carbon sink? *Ocean Coastal Manag.* 83, 25–31. doi: 10.1016/j.ocecoaman.2011.09.006

Costanza, R., d'Arge, R., Groot, R., Farber, S., Grasso, M., and Hannon, B. (1997). The value of the world's ecosystem services and natural capital. *Nature.* 387, 253–260. doi: 10.1038/387253a0

Cullen-Unsworth, L., and Unsworth, R. (2013). Seagrass Meadows, Ecosystem Services, and Sustainability. *Environ. Sci. Policy.* 55, 14–28. doi: 10.1080/00139157.2013.785864

DebRoy, P., and Jayaraman, R. (2012). "Economic valuation of mangroves for assessing the livelihood of fisherfolk: A case study in India," in *Visible Possibilities: The Economics of Sustainable Fisheries, Aquaculture and Seafood Trade: Proceedings of the Sixteenth Biennial Conference of the International Institute of Fisheries Economics and Trade, July 16-20, Dar es Salaam, Tanzania*, ed A. L. Shriver (Corvallis, OR: International Institute of Fisheries Economics and Trade).

Dehghani, M., Farshchi, P., Danekar, A., Karami, M., and Aleshikh, A. A. (2010). Recreation value of Hara biosphere reserve using willingness-to-pay method. *Int. J. Environm. Res.* 4, 271–280.

Dewsbury, B. M., Bhat, M., and Fourqurean, J. W. (2016). A review of seagrass economic valuations: gaps and progress in valuation approaches. *Ecosyst. Serv.* 18, 68–77. doi: 10.1016/j.ecoser.2016.02.010

Donato, D. C., Kauffman, J. B., Murdiyarso, D., Kurnianto, S., Stidham, M., and Kanninen, M. (2011). Mangroves among the most carbon-rich forests in the tropics. *Nature Geosci.* 4, 293–297. doi: 10.1038/ngeo1123

Duarte, C. M., Losado, I. J., Hendriks, I. E., and Mazarrasa, I. (2013). The role of coastal plant communities for climate change mitigation and adaptation. *Nature Clim Chang.* 3, 961–968. doi: 10.1038/nclimate1970

Duke, N. C., Meynecke, J. O., Dittmann, S., Ellison, A. M., Anger, K., Berger, U., et al. (2007). A world without mangroves. *Science.* 317: 41–42 doi: 10.1126/science.317.5834.41b

Dunic, J. C., Brown, C. J., Connolly, R. M., Turschwell, M. P., Côt, é, and Isabelle, M. (2021). Long-term declines and recovery of meadow area across the world's seagrass bioregions. *Glob. Chang. Biol.* 27, 4096–4109. doi: 10.1111/gcb.15684

Earth Security (2020). *Financing the Earth's Assets - The Case for Mangroves as a Nature-Based Climate Solution.* Available online at: https://www.blueclimateinitiative.org/sites/default/files/2021-01/Earth%20Security%20Group-mangrove-12.2020.pdf (accessed February 15, 2023).

Ellison, A. M., and Farnsworth, E. J. (2001). "Marine Communities," in *Marine Community Ecology,* Bertness, M. D., Gaines, S., and Hay, M. E. (eds.). Sunderland, Massachusetts, United States: Sinauer Press. p. 423–442.

FAO (2020a). *Global Forest Resources Assessment 2020.* Rome: FAO.

FAO (2020b). *The State of World Fisheries and Aquaculture 2020. Sustainability in Action.* Rome: FAO.

Faure, M. G., and Svatikova, K. (2012). Criminal or administrative law to protect the environment? Evidence from Western Europe. *J. Environm. Law.* 2, 253–286. doi: 10.1093/jel/eqs005

Favasuli, S., and Sebastian, V. (2021). *Voluntary Carbon Markets: How They Work, How They're Priced and Who's Involved. S&P Global.* Available online at: https://www.spglobal.com/platts/en/market-insights/blogs/energy-transition/061021-voluntary-carbon-markets-pricing-participants-trading-corsia-credits

Fourqurean, J. W., Duarte, C. M., Kennedy, H., Marba, N., Holmer, M., Mateo, M. A., et al. (2012). Seagrass ecosystems as a globally significant carbon stock. *Nature Geosci.* 5, 505–509. doi: 10.1038/ngeo1477

Friess, D. (2016). Ecosystem services and disservices of mangrove forests: insights from historical colonial observations. *Forests.* 7, 183. doi: 10.3390/f7090183

Gallagher, J. B., Shelamoff, V., and Layton, C. (2022). Seaweed ecosystems may not mitigate CO_2 emissions. *ICES J. Marine Sci.* 79, 585–92. doi: 10.1093/icesjms/fsac011

Giri, S., Mukhopadhyay, A., Hazra, S., Mukherjee, S., Roy, D., Ghosh, S., et al. (2014). A study on abundance and distribution of mangrove species in Indian Sundarban using remote sensing technique. *J. Coast. Conserv.* 18, 359–367. doi: 10.1007/s11852-014-0322-3

Gordon, D., Murray, B. C., Pendleton, L., and Victor, B. (2011). *Financing Options for Blue Carbon: Opportunities and Lessons From the REDD+ Experience.* Durham, NC: Nicholas Institute for Environmental Policy Solutions, Duke University. Available online at: https://nicholasinstitute.duke.edu/sites/default/files/publications/financing-options-for-blue-carbon-paper.pdf

Grigoryan, E., Hasannudin, Z. A., Isgut, A. E., Morris, D., and Martin, P. (2021). *Debt-for-climate swaps as a tool to support the implementation of the Paris Agreement.* Available online at: https://hdl.handle.net/20.500.12870/3875

Hamilton, S. E., and Casey, D. (2016). Creation of a high spatio-temporal resolution global database of continuous mangrove forest cover for the 21st century (CGMFC-21). *Global Ecol. Biogeograp.* 25, 729–738. doi: 10.1111/geb.12449

Harpankar, K. (2019). Internal carbon pricing: Rationale, promise and limitations. *Carbon Manag.* 10, 219–225. doi: 10.1080/17583004.2019.1577178

Harrison, K. (2010). The comparative politics of carbon taxation. *Ann. Rev. Law Social Sci.* 6, 507–529. doi: 10.1146/annurev.lawsocsci.093008.131545

Hasselström, L., Visch, W., Gröndahl, F., Nylund, M., and Pavia, H. (2018). The impact of seaweed cultivation on ecosystem services - a case study from the west coast of Sweden. *Mar. Pollut. Bull.* 133, 53–64. doi: 10.1016/j.marpolbul.2018.05.005

Hilmi, N., Chami, R., Sutherland, M. D., Hall-Spencer, J. M., Lebleu, L., Benitez, M. B., et al. (2021). The role of Blue Carbon in climate change mitigation and Carbon Stock Conservation. *Frontiers in Clim,* 3, 710546. doi: 10.3389/fclim.2021.710546

Hurd, C. L., Law, C. S., Bach, L. T., Britton, D., Hovenden, M., Paine, E. R., et al. (2022). Forensic carbon accounting: Assessing the role of seaweeds for carbon sequestration. *J. Phycol.* 58, 347–363. doi: 10.1111/jpy.13249

Hurtado, A. Q., Critchley, A. T., and Neish, I. C. (2017). "Tropical seaweed farming trends, problems and opportunities," in *Focus on Kappaphycus and Eucheuma of Commerce.* Cham, Switzerland: Springer (Developments in applied phycology 9).

Hussin, H., and Khoso, A. (2021). Migrant Workers in the Seaweed Sector in Sabah, Malaysia. *SAGE Open.* 11, 215824402110457. doi: 10.1177/21582440211047586

Inoue, Y. (2018). "Ecosystem carbon stock, atmosphere, and food security in slash-and-burn land use: a geospatial study in mountainous region of Laos," in *Land-Atmospheric Research Applications in South and Southeast Asia.* Cham: Springer. p. 641–665.

International Energy Agency (2022). *Global Energy Review: CO_2 Emissions in 2021. IEA, Paris.* https://www.iea.org/reports/global-energy-review-co2-emissions-in-2021-2

International Monetary Fund (2020). *Fiscal Monitor: Policies for the Recovery.* Washington, DC : International Monetary Fund, October. Available online at: https://www.imf.org/en/Publications/FM/Issues/2020/09/30/october-2020-fiscal-monitor (accessed February 15, 2023).

IPCC (2021) "Climate Change 2021: The Physical Science Basis," in *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, [Masson-Delmotte, V., Zhai, A., Pirani, S. L., Connors, C., Péan, S., Berger, N., et al. (eds.)] Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Islam, S. M. D.-U., and Bhuiyan, M. A. H. (2018). Sundarbans mangrove forest of Bangladesh: Causes of degradation and sustainable management options. *Environ. Sustainab.* 1, 113–131. doi: 10.1007/s42398-018-0018-y

Kelleway, J. J., Cavanaugh, K., Rogers, K., Feller, I. C., Ens, E., Doughty, C., et al. (2017b). Review of the ecosystem service implications of mangrove encroachment into salt marshes. *Glob. Chang. Biol.* 23, 3967–3983. doi: 10.1111/gcb.13727

Kelleway, J. J., Saintilan, N., Macreadie, P. I., Baldock, J. A., Heijnis, H., Zawadzki, A., et al. (2017a). Geochemical analyses reveal the importance of environmental history for blue carbon sequestration. *J. Geophysical Res.: Biogeosci.* 122, 1789–1805. doi: 10.1002/2017JG003775

Khan, M. (2015). Polluter-Pays-Principle: The Cardinal Instrument for Addressing Climate Change. *Laws* 4, 638–653. doi: 10.3390/laws4030638

Kim, J. K., Yarish, C., Hwang, E. K., Park, M., and Kim, Y. (2017). Seaweed aquaculture: cultivation technologies, challenges and its ecosystem services. *Algae.* 32, 1–13. doi: 10.4490/algae.2017.32.3.3

Kwan, V., Jenny, F., Chin Soon Lionel, N., and Danwei, H. (2022). Temporal and Spatial Dynamics of Tropical Macroalgal Contributions to Blue Carbon. *Sci. Total Environm.* 828, 154369. doi: 10.1016/j.scitotenv.2022.154369

Laffoley, D., Baxter, J. M., Amon, D. J., Claudet, J., Hall-Spencer, J. M., Grorud-Colvert, K., et al. (2021). Evolving the narrative for protecting a rapidly changing ocean, post-COVID-19. *Aquatic Conservat.* 31, 1512–1534 doi: 10.1002/aqc.3512

Lamb, J. B., van de Water, J. A. J. M., Bourne, D. G., Altier, C., Hein, M. Y., Fiorenza, E. A., et al. (2017). Seagrass ecosystems reduce exposure to bacterial pathogens of humans, fishes, and invertebrates. *Science.* 355, 731. doi: 10.1126/science.aal1956

Lamont, K., Saintilan, N., Kelleway, J., Mazumder, D., and Zawadzki, A. (2020). Thirty-year repeat measures of mangrove above- and below- ground biomass reveals unexpectedly high carbon sequestration. *Ecosystems.* 23, 370–382. doi: 10.1007/s10021-019-00408-3

Lee, S. Y., Hamilton, S., Barbier, E. B., Primavera, J., and Lewis, R. R. (2019). Better restoration policies are needed to conserve mangrove ecosystems. *Nat. Ecol. Evol.* 3, 870–872. doi: 10.1038/s41559-019-0861-y

Legge, O., Martin, J., Natalie, H., Tim, J., Markus, D., John, A., et al. (2020). Carbon on the Northwest European Shelf: Contemporary Budget and Future Influences. *Front. Marine Scie.* 7, 143. doi: 10.3389/fmars.2020.00143

Lin, B., and Li, X. (2011). The effect of carbon tax on per capita CO_2 emissions. *Energy Policy* 39, 5137–5146. doi: 10.1016/j.enpol.2011.05.050

Locatelli, T., Binet, T., Kairo, J. G., King, L., Madden, S., Patenaude, G., et al. (2014). Turning the tide: how blue carbon and payments for ecosystem services (pes) might help save mangrove forests. *Ambio.* 43, 981–995. doi: 10.1007/s13280-014-0530-y

Lunstrum, A., and Chen, L. (2014). Soil carbon stocks and accumulation in young mangrove forests. *Soil Biol. Biochem.* 75, 223–232. doi: 10.1016/j.soilbio.2014.04.008

Macreadie, P., Costa, M. D., P., Atwood, B., Friess, D. A., Kelleway, J. J., and Kennedy, H. (2021). Blue carbon as a natural climate solution. *Nat. Rev. Earth Environ.* 2, 826–839. doi: 10.1038/s43017-021-00224-1

Marchand, C. (2017). Soil carbon stocks and burial rates along a mangrove forest chronosequence (French Guiana). *For. Ecol. Manage.* 384, 92–99. doi: 10.1016/j.foreco.2016.10.030

Maulidia, V., Akbar, A. A., Jumiati, J., Arifin, A., and Sulastri, A. (2022). The value of mangrove ecosystems based on mangrove carbon sequestration in West Kalimantan. *J. Wetlands Environm. Manag.* 10, 12–25. doi: 10.20527/jwem.v10i1.279

Mazda, Y., Magi, M., Ikeda, Y., Kurokawa, T., and Asano, T. (2006). Wave reduction in a mangrove forest dominated by Sonneratia sp. *Wetl Ecol Manag.* 14, 365–378. doi: 10.1007/s11273-005-5388-0

McLeod, E., Chmura, G. L., Bouillon, S., Salm, R., and Björk, C. M. (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

Millennium Ecosystem Assessment (2005). *Ecosystems and Human Wellbeing.* Washington, D.C.: Island Press United States of America. Available online at: http://www.bioquest.org/wp-content/blogs.dir/files/2009/06/ecosystems-and-health.pdf (accessed February 15, 2023).

Miyajima, T., Hamaguchi, M., and Hori, M. (2022). Evaluation of the baseline carbon sequestration rates of Indo-Pacific temperate and tropical seagrass meadow sediments. *Ecol. Res.* 37, 9–20. doi: 10.1111/1440-1703.12263

Msuya, F. E., and Hurtado, A. Q. (2017). The role of women in seaweed aquaculture in the Western Indian Ocean and South-East Asia. *Eur. J. Phycol.* 52, 482–494. doi: 10.1080/09670262.2017.1357084

Mumby, P. J., Edwards, A. J., Ernesto Arias-Gonzalez, J., Lindeman, K. C., Blackwell, P. G., Gall, A., et al. (2004). Mangroves enhance the biomass of coral reef fish communities in the Caribbean. *Nature.* 427, 533–536. doi: 10.1038/nature02286

Nor, A. M., Gray, T. S., Caldwell, G. S., and Stead, S. M. (2020). A value chain analysis of Malaysia's seaweed industry. *J. Appl. Phycol.* 32, 2161–2171. doi: 10.1007/s10811-019-02004-3

OECD (2009). *Determination and Application of Administrative Fines for Environmental Offences: Guidance for Environmental Enforcement Authorities in EECCA Countries*. Available online at: https://www.oecd.org/env/outreach/42356640.pdf

OECD (n.a.). *Emission Trading System.* Available online at: https://www.oecd.org/env/tools-evaluation/emissiontradingsystems.htm

Osland, M. J., Spivak, A. C., Nestlerode, J. A., Lessmann, J. M., Almario, A. E., Heitmuller, P. T., et al. (2012). Ecosystem development after mangrove wetland creation: plant–soil change across a 20-year chronosequence. *Ecosystems.* 15, 848–866. doi: 10.1007/s10021-012-9551-1

Pedersen, O. (2019). *Punishing the polluters: why large fines are an important step towards cleaner corporations. The Conversation*. Available online at: https://theconversation.com/punishing-the-polluters-why-large-fines-are-an-important-step-towards-cleaner-corporations-115727 (accessed February 15, 2023).

Pendleton, L., Donato, D. C., Murray, B. C., Crooks, S., Jenkins, W., and Aaron, S. (2012). Estimating global "blue Carbon" emissions from conversion and degradation of vegetated coastal ecosystems. *PLoS ONE.* 7, e43542. doi: 10.1371/journal.pone.0043542

Plan Vivo (2022). *Tahiry Honko–Madagascar*. Available online at: https://www.planvivo.org/tahiryhonko#:$\sim$:text=Tahiry%20Honko%20is%20the%20world's, mangrove%20forests%20in%20southwest%20Madagascar

Ranjan, R. (2019). Optimal mangrove restoration through community engagement on coastal lands facing climatic risks: The case of Sundarbans region in India. *Land Use Policy*. 81, 736–749. doi: 10.1016/j.landusepol.2018.11.047

Ribeiro, R. D. A., Rovai, A. S., Twilley, R. R., and Castañeda-Moya, E. (2019). Spatial variability of mangrove primary productivity in the neotropics. *Ecosphere.* 10, e02841. doi: 10.1002/ecs2.2841

Saintilan, N., Rogers, K., Mazumder, D., and Woodroffe, C. (2013). Allochthonous and autochthonous contributions to carbon accumulation and carbon store in southeastern Australian coastal wetlands. *Estuar. Coast. Shelf Sci.* 128, 84–92. doi: 10.1016/j.ecss.2013.05.010

Salt Marsh Guide (2023). *Guide to the Salt Marshes and Tidal Creeks of the Southeastern United States- ECOSYSTEM SERVICES*. Available online at: https://www.saltmarshguide.org/ (accessed February 15, 2023).

Sanford, M. P. (2009). Valuating mangrove ecosystems as coastal protection in post-tsunami South Asia. *Natural Areas J.* 29, 91–95. doi: 10.3375/043.029.0111

Segal, T. (2022). *Green Bond, Guide to Green Investing. Investopedia*. Available online at: https://www.investopedia.com/terms/g/green-bond.asp (accessed February 15, 2023).

Siikamaki, J., Sanchirico, J. N., Jardine, S., McLaughlin, D., and Morris, D. (2013). Blue carbon: coastal ecosystems, their carbon storage, and potential for reducing emissions. *Environment.* 55, 14–29. doi: 10.1080/00139157.2013.843981

Slobodian, L. Rodriguez, C., Mariamalia Nguyen L. T. P., and Rakotoson L. N. (2023). *Legal Frameworks for Mangrove Governance, Conservation and Use: Assessment Summary*. International Union for Conservation of Nature. Available online at: https://policycommons.net/artifacts/1375590/legal-frameworks-for-mangrove-governance-conservation-and-use/1989854/

Spalding, M., and Parrett, C. L. (2019). Global patterns in mangrove recreation and tourism. *Marine Policy.* 110, 103540. doi: 10.1016/j.marpol.2019.103540

Thomas, A., and Theokritoff, E. (2021). Debt-for-climate swaps for small islands. *Nat. Clim. Chang.* 11, 889–891. doi: 10.1038/s41558-021-01194-4

Twilley, R. R., Castañeda-Moya, E., Rivera-Monroy, V. H., and Rovai, A. (2017). "Productivity and carbon dynamics in mangrove wetlands," in *Mangrove ecosystems: a global biogeographic perspective.* Cham: Springer. p. 113–162. doi: 10.1007/978-3-319-62206-4_5

U.S. Securities and Exchange Commission (n.d.). *Municipal Bonds*. Available online at: https://www.investor.gov/introduction-investing/investing-basics/investment-products/bonds-or-fixed-income-products-0 (accessed February 15, 2023).

Uddin, M.d. S., de Ruyter van Steveninck, E., Stuip, M., and Shah, M. A. R. (2013). Economic valuation of provisioning and cultural services of a protected mangrove ecosystem: a case study on Sundarbans Reserve Forest, Bangladesh. *Ecosyst. Serv.* 5, 88–93. doi: 10.1016/j.ecoser.2013.07.002

Ullman, R., Bilbao-Bastida, V., and Grimsditch, G. (2013). Including blue carbon in climate market mechanisms. *Ocean and Coastal Manag.* 83, 15–18. doi: 10.1016/j.ocecoaman.2012.02.009

United Nations Climate Change (2023). *REDD+*. Available online at: https://unfccc.int/topics/land-use/workstreams/reddplus (accessed February 15, 2023).

Valiela, I., Bowen, J. L., Cole, M. L., Kroeger, K. D., Lawrence, D., Pabich, W. J., et al. (2001b). Following up on a Margalevian concept: interactions and exchanges among adjacent parcels of coastal landscapes. *Scientia Marina.* 65, 215–229. doi: 10.3989/scimar.2001.65s2215

Valiela, I., Bowen, J. L., and York, J. K. (2001a). Mangrove forests: one of the world's threatened major tropical environments. *Bioscience.* 51: 807–815. doi: 10.1641/0006-3568(2001)0510807:MFOOTW2.0.CO;2

Valiela, I., Kinney, E., Culbertson, J., Peacock, E., and Smith, S. (2009). *Global Losses of Mangroves and Salt Marshes*. Fundación BBVA. 107–138.

Van, D., Bryce, R., Zeller, M. A., Lopes, C., Smyth, A. R., Böttcher, E., et al. (2021). Calcification-driven CO_2 emissions exceed "Blue Carbon" sequestration in a carbonate seagrass meadow. *Sci. Adv.* 7, eabj1372. doi: 10.1126/sciadv.abj1372

Vanderklift, M. A., Marcos-Martinez, R., Butler, J. R. A., Coleman, M., Lawrence, A., and Prislan, H. (2019). Constraints and opportunities for market-based finance for the restoration and protection of blue carbon ecosystems. *Marine Policy.* 107, 103429. doi: 10.1016/j.marpol.2019.02.001

Verra (2021). *Blue Carbon Project Gulf Of Morrosquillo "Vida Manglar*." Available online at: https://registry.verra.org/app/projectDetail/VCS/2290 (accessed February 15, 2023).

Vincent, D. P. (2013). *Internalizing Externalities: An Economic and Legal Analysis of an International Carbon Tax Regime*. Oregon Law Review.

Von Glasow, R., Jickells, T. D., Baklanov, A., Carmichael, G. R., Church, T. M., Gallardo, L., et al. (2013). Megacities and large urban agglomerations in the coastal zone: interactions between atmosphere, land, and marine ecosystems. *Ambio.* 42, 13–28. doi: 10.1007/s13280-012-0343-9

Ward, R. D., Friess, D. A., Day, R. H., and Mackenzie, R. A. (2016). Impacts of climate change on mangrove ecosystems: a region by region overview. *Ecosys. Health Sustainab.* 2, e01211. doi: 10.1002/ehs2.1211

Wilkinson, A. (2014, June 29). Expanding tropics will play greater global role, report predicts. *Science*. Available online at: https://www.science.org/content/article/expanding-tropics-will-play-greater-global-role-report-predicts#:~:text=By%202050%2C%20half%20of%20the,a%20hefty%20report%20released%20today.

Williamson, P., and Gattuso, J.-P. (2022). Carbon removal using coastal blue carbon ecosystems is uncertain and unreliable, with questionable climatic cost-effectiveness. *Front. Clim.* 4, 853666 doi: 10.3389/fclim.2022.853666

World Bank (2021). *The World Bank Impact Report, Sustainable Development Bonds and Green Bonds*. Available online at: https://issuu.com/jlim5/docs/world_bank_ibrd_impact_report_2021_web_ready_r01?fr=sYTBhOTM4NTM3MTk (accessed February 15, 2023).

World Bank (2023). *What is Carbon Pricing?* Available online at: https://carbonpricingdashboard.worldbank.org/what-carbon-pricing (accessed February 15, 2023).

World Bank Group and Frankfurt School of Finance and Management (2017). *Results-Based Climate Finance in Practice*. Washington, DC: World Bank.

Yarish, B., Hansen, B., Valderrama, S., Radulovich, D., Capron, F., and Goudey, H. (2016). *Seaweed Aquaculture for Food Security, Income Generation and Environmental Health in Tropical Developing Countries.* World Bank Group.