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Highlights

► Special edition on carbon stored and sequestered in coastal ecosystems. ► Carbon market options and payment for ecosystem services schemes are analyzed. ► Carbon storage and sequestration science in seagrass ecosystems is synthesized. ► Monitoring techniques for sustainability and coverage of ecosystems are analyzed.

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Editorial

The blue carbon special edition – Introduction and overview

1. Introduction

In May 2010 the United Nations Environment Programme convened a workshop to discuss the opportunities and constraints for developing a marine carbon markets building on experience of the protocols and processes developed for the Reducing Emissions from Deforestation and Forest Degradation (REDD) programme under the United Nations Framework for Climate Change Convention (UNFCCC). The workshop also considered other approaches to realising payment for marine ecosystem services.

This special edition of *Ocean and Coastal Management* presents papers that synthesise the main themes of that workshop and uses the definition of 'blue carbon' provided by Herr et al. (2012): 'carbon stored, sequestered or released from vegetated coastal ecosystems such as tidal salt marshes, mangroves and seagrass meadows'. This definition does not include carbon stored, sequestered or released by the open ocean.

The term 'blue carbon' emerged in discussion of the potential to extend the 'green carbon' REDD programme to apply to prevention or remediation of degradation of marine carbon dioxide metabolism. Given the protocols and processes developed for forest carbon metabolism in REDD it was not practicable to address carbon stored, sequestered or released by the open ocean. Reports by UNEP (Nellemann et al., 2009), IUCN (Laffoley and Grimsditch, 2009) and Duke University (Sifleet et al., 2011) consequently examined the role of coastal ecosystems in the global carbon cycle.

This special edition of *Ocean and Coastal Management* examines some current scientific, methodological and policy aspects of coastal blue carbon and poses questions that it will be necessary to address in order to move towards financing coastal ecosystem management through international carbon markets or payment for ecosystem services schemes. The special edition includes manuscripts on 'Including blue carbon in climate market mechanisms' (Ullman et al.), 'Beyond carbon: conceptualizing payments for ecosystem services in blue forests on carbon and other marine and coastal ecosystem services' (Lau), 'Assessing the capacity of seagrass meadows for carbon burial: current limitations and future strategies' (Duarte et al.), 'What do we need to assess the sustainability of the tidal salt marsh carbon sink?' (Chmura), and 'Mapping of mangrove forest land cover change along the Kenya coastline using Landsat imagery' (Kirui et al.).

2. Carbon storage and sequestration by vegetated coastal ecosystems

Several reports by international organizations and agencies have synthesized, analysed and explored the science, economics and policies surrounding blue carbon, advancing our collective knowledge and greatly increasing visibility of the issues (Nellemann et al., 2009; Laffoley and Grimsditch, 2009; Crooks et al., 2011; O'Sullivan et al., 2011; Murray et al., 2011; Sifleet et al., 2011; Gordon et al., 2011; McLeod et al., 2011). The reports have not only highlighted the potential that coastal ecosystems represent for climate change mitigation but have also highlighted the considerable gaps in our knowledge of these systems and also how vulnerable they are to degradation by anthropogenic activities.

The number of studies on carbon sequestration, storage and emissions in coastal ecosystems remains limited, neither representative of the different coastal ecosystems nor geographical regions. Recent estimates have placed the total estimated emissions from degraded and converted coastal wetlands each year at between 300 and 900 million t CO_2e, approximately equal to the annual CO_2 emissions from energy and industry for Poland and for Germany, respectively (Murray et al., 2011). Coastal ecosystems do have relatively high rates of carbon sequestration and rates of accumulation in sediments, ranging from 18 (intertidal salt marshes) to 1713 (mangroves) $gCm^{-2}\ yr^{-1}$ depending on ecosystem, compared to carbon accumulation rates in soils of temperate, tropical and boreal forests that range from 0.7 to 13.1 $gCm^{-2}\ yr^{-1}$ (McLeod et al., 2011). However, the largest stock of carbon in coastal ecosystems lies buried in the sediments below, which contain more organic carbon than the biomass. Carbon stored in mangrove biomass has been found to range from 25 to 2254 Mg CO_2e ha^{-1} with most estimates falling between 300 and 1000 Mg CO_2e ha^{-1}. In contrast, the carbon stocks in the first metre of mangrove soils has been found to range from 570 to 4712 Mg CO_2e ha^{-1} with most estimates falling between 800 and 3000 Mg CO_2e ha^{-1}. Similarly for intertidal salt marshes, biomass carbon has been found to range from 5.1 to 18.3 Mg CO_2e ha^{-1} while soil carbon ranges from 174 to 6967 Mg CO_2e ha^{-1}. In seagrass meadows, biomass carbon has been found to range from 0 to 13 Mg CO_2e ha^{-1} while soil carbon ranges from 880 to 6000 Mg CO_2e ha^{-1} (Sifleet et al., 2011).

The numbers presented here are from limited studies – 62 mangrove sites, 126 intertidal salt marshes and 160 seagrass sites (Sifleet et al., 2011) with uneven geographical distribution.

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Geographical areas that lack representation in the current scientific literature are Africa, South America and South Asia, and it is recommended that research into blue carbon in these vast geographical areas is promoted and supported. This limitation inhibits understanding of the relative capacities of tropical and high latitude coastal vegetated habitats in carbon capture, storage and release. However, the number of studies is not insignificant. Although variability across the world has not been fully documented, we are beginning to understand the overall importance of coastal ecosystems in the global carbon cycle (Duarte et al., 2004).

Over decades, these ecosystems sequester carbon in above-ground biomass (branches, stems and leaves), below-ground biomass (roots) and non-living biomass (litter and dead wood). Over millennia carbon is stored in the sediments beneath these ecosystems. Sediments in healthy coastal ecosystems continue to accrete vertically as sea levels rise and do not become saturated with organic carbon, unlike terrestrial ecosystems that often reach soil carbon equilibrium within decades or centuries (McLeod et al., 2011). Thus vegetated coastal sediments are often extremely rich in organic carbon and contain the majority of blue carbon. However, when these systems are degraded or destroyed they become significant sources of carbon dioxide emissions, due to the oxidization of carbon in biomass and organic soil. The rate of carbon dioxide emissions is particularly high in the decade immediately after disturbance, but continues as long as oxidation of sediment occurs, releasing carbon that has been stored in sediments for up to millennia (McLeod et al., 2011).

The vast majority of coastal carbon lies in the sediments, which are at risk of being oxidized and released into the atmosphere when ecosystems are degraded and destroyed. Coastal lands generally are under substantial pressure driven largely by human activities such as conversion, coastal development and over-harvesting. Current global rates of global loss of mangroves, seagrass beds and salt marshes are 0.7–2% per year; among the highest rate of loss of any ecosystem on the planet (Murray et al., 2011). In view of the valuable ecosystem services they provide and the carbon they store and sequester this is of considerable concern for climate change mitigation globally as well as for the wellbeing of coastal communities locally.

Vegetated coastal ecosystems also provide a host of valuable regulating services (protection of beaches and coastlines from storm surges, waves and floods; reduction of beach and soil erosion; stabilization of land by trapping sediments; water quality maintenance; and climate regulation), provisioning services (subsistence and commercial fisheries; honey; fuelwood; building materials; and traditional medicines), cultural services (tourism and recreation; and spiritual appreciation) and supporting services (cycling of nutrients; and habitats for species) (Millennium Ecosystem Assessment, 2005).

3. Blue carbon and ecosystem services market approaches to management

International carbon markets or payment for ecosystem services schemes could potentially fund action and management that help to reverse trends in the global loss and degradation of coastal vegetated habitats.

Mangroves can be included in national REDD projects depending on national definitions of what a forest is. The text in the UNFCCC Cancun Agreement, defines REDD activities as (a) reducing emissions from deforestation; (b) reducing emissions from forest degradation; (c) conservation of forest carbon stocks; (d) sustainable management of forest; (e) enhancement of forest carbon stocks. The REDD programme can provide bilateral financing for these activities in mangroves, but for this to occur it is important that appropriately robust scientific methodologies and frameworks are developed and put in place for mangroves to become part of national REDD strategies and thus access this financing. RED D criteria cannot so readily be extended to tidal salt marshes or seagrass meadows and there is a consequent need to develop methodologies and policy frameworks that can make the full range of blue carbon ecosystems a viable option for carbon markets or payment for ecosystem services schemes.

Some of the questions that need to be addressed for seagrass meadows and intertidal salt marshes are discussed by Duarte et al. in 'Assessing the capacity of seagrass meadows for carbon burial: current limitations and future strategies', and by Chmura in 'What do we need to assess the sustainability of the tidal salt marsh carbon sink?'. These papers discuss issues relating to the possibilities for blue carbon in international carbon markets and in payment for ecosystem services schemes. They address the scientific questions that need to be answered in order to progress blue carbon in these market options, and to develop potential tools that can be used to monitor and assess the sustainability of blue carbon sinks.

The challenges of realizing the monetary value of coastal ecosystems through carbon markets and payment for ecosystem services are substantial. Ullman et al. discuss the market economic considerations for including blue carbon in current markets in 'Including blue carbon in climate market mechanisms'. Lau takes this further and discusses other potential opportunities for monetization of a wide range of ecosystem services in 'Beyond carbon: conceptualizing payments for ecosystem services in blue forests on carbon and other marine and coastal ecosystem services'.

Ullman et al. and Lau show that international carbon markets are currently more developed than payment for ecosystem services schemes. Of the existing carbon markets Ullman et al. identify regulated cap-and-trade schemes such as the UNFCCC or the European Union Emissions Trading System (EU ETS) as the most promising avenue for major investment in blue carbon due to the high volume of transactions they represent. However there is a risk associated with the UNFCCC because of the dependence on the Kyoto and subsequent negotiations for deciding the regulations and existence of this international carbon market. Regulated markets are being created in California, Brazil and Japan, opening up further opportunities for blue carbon trading, but as yet they have not been realized. Each potential new market opportunity should be analysed and feasibility assessed as it emerges. Currently the only carbon market that is ready for blue carbon credits is the voluntary carbon market, where Ullman et al. show that the volume of transactions is significantly lower than in the regulated markets and can currently only mobilize funding for smaller scale project activities.

Non-market values are often not taken into account and schemes set up to pay for ecosystem services present us with an option for addressing this market failure. Coastal ecosystem services are of high value, but they are usually not accounted for or they are undervalued in traditional financial and business strategies. Lau looks beyond revenue from carbon markets and points out that coastal ecosystems also provide a wide range and variety of ecosystem services such as coastal protection, fish nursery, water purification, recreational, cultural and marine biodiversity that could potentially be monetized. Schemes for payment for ecosystem services in marine and coastal settings have the potential to generate market-scale payments, similar to carbon payments and to create incentives for behavioural change, reversal of biodiversity degradation and the capturing of non-market values.

An option might be design of projects that could address the combined ecosystem services and carbon market values and thus potentially increase the value of these carbon credits sold on the voluntary market. Above-market prices can sometimes be attained

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for carbon credits that have measurable positive impacts on local communities affected by the project activities. Prices of high quality voluntary offsets are now trading higher than regulated market carbon credits with steady demand from North America and large corporations seeking to reduce carbon footprints. These projects are seen as "charismatic" by buyers, especially if they generate a range of benefits to the world's poorest communities, besides cutting carbon, and they combine high levels of environmental integrity as well as providing a strong contribution to sustainability (e.g. through maintaining ecosystem services). Although voluntary offsets are by far the smallest segment of the global carbon market, they are the most accessible to the general public, as they can be used to offset household energy use, road travel and air travel (McGarrity, 2012). Measuring ecosystem services in the context of the carbon markets in a cost-effective and accurate manner presents a challenge and it will be important to develop appropriate methodologies and frameworks that can be approved by independent international bodies in order to ensure that they are globally standardized.

4. Monitoring, assessment and research priorities for blue carbon markets

There is an urgent need to develop appropriate frameworks and methodologies for assessment and monitoring for the full extent of possible blue carbon market mechanisms. The only methodologies that exist for the regulated market thus far have been developed for monitoring, reporting and verifying carbon from mangrove afforestation and reforestation for the Clean Development Mechanism under the Kyoto Protocol Methodologies. Methodologies for coastal wetlands are also being developed for the voluntary market, and small-scale pilot projects for mangrove restoration do exist (Kairo, 2011) but there are still large gaps in our scientific knowledge of these ecosystems and their carbon storage and sequestration capacity.

Ullman et al. identify over-arching questions that need to be addressed for each of the three blue carbon ecosystems:

1. the rate at which carbon is naturally sequestered in the ecosystem;
2. the stock of sequestered carbon in the ecosystem;
3. the extent, rate and duration of release of the previously-sequestered stock of carbon when the ecosystem is destroyed or degraded;
4. the areal extent and latitudinal variation of coastal ecosystems and how they change over time;
5. how changes in the rates of sequestration and emission can be independently and accurately measured and monitored; and
6. the natural variation in the carbon pools of coastal ecosystems; and
7. how the permanence of carbon stocks are affected by natural variations as well as degradation caused by climate change and anthropogenic activities.

Duarte et al. specifically identify gaps in knowledge for seagrass meadows which are the least well understood of the three ecosystems when it comes to carbon sequestration and storage. They identify possible variability in seagrass carbon sink capacities related to species assemblages and habitats. They also show that the total global extent of seagrass area is often underestimated due to the fact that these ecosystems are always submerged, sometimes down to 90 m below sea-level, and there are difficulties with assessing its cover using remote sensing data. Duarte et al. point to the need for improved integration of data sets collected in different regions in the world in order to have a fuller global overview of areal extent of seagrasses and for improving models to identify suitable areas for seagrass growth. The issues of remote sensing, ground truth validation, improved data integration and modelling for better understanding apply to each of the coastal ecosystems and should provide the basis for blue carbon research strategies.

The research priorities identified by Duarte et al. mirror those identified by Ullman et al., with major questions related to carbon emissions from habitat degradation; rates of natural sequestration; areal extents of ecosystem cover; factors affecting variability of carbon sequestration and storage; and how to measure carbon sequestration and storage accurately.

Kirui et al. discuss the issue of measuring the areal extent of coastal ecosystems and how they change over time, focussing on a case study of Kenyan mangroves. They present a change analysis of Landsat satellite imagery over 25 years from 1985 to 2010. An 18% cover loss was recorded, and the paper concludes that freely available Landsat images, in conjunction with on-the-ground data validation by experts, prove to be adequate to detect changes in mangrove cover at the sub-national level and could thus be used to monitor carbon projects effectively. They demonstrate that the scale and distribution of the coastal ecosystems are such that remote sensing is a crucial component of cost effective assessment and monitoring but that data validation by experts in the field is necessary to evaluate and improve the accuracy of remote sensing data sets.

Carbon crediting systems require sinks be 'permanent' and sustainable for ~100 years, but increasing sea levels due to climate change threaten the permanence of many blue carbon sinks. Chmura presents a possible technique using high resolution elevation data from Lidar (light detection and ranging) technology for assessing the permanence of tidal salt marshes in the face of sea-level rise. This is also significant because coastal ecosystems can survive rises in sea-level if they are allowed to migrate inland so the potential for the success of inland migration must be assessed when designating areas for projects.

5. Potential for developing blue carbon mechanisms

Coastal ecosystems are rich in carbon and the papers in this special edition of *Ocean and Coastal Management* show that blue carbon has the potential to leverage economic support for their management and protection.

Capturing the monetary value of carbon credits on the international carbon market blue carbon could potentially provide a significant source of investment in the management and protection of coastal ecosystems. Regulated cap-and-trade markets such as the United Nations Framework for Climate Change Convention (UNFCCC) or the European Union Emissions Trading System (EU ETS) markets are presented as the major target due to potential revenues and the opportunity to reverse global trends in ecosystem degradation. The voluntary carbon credit market is currently significantly smaller than the regulated markets but is also currently more developed for blue carbon and can mobilize funding for smaller scale project activities. However, carbon market projects for coastal ecosystems have high transaction, direct and opportunity costs and these make them more costly and difficult to implement. Start-up funding from non-governmental organizations is often necessary, although higher carbon prices would make them more viable. Ullman et al. therefore argue that the ultimate target for blue carbon should be the international regulated carbon markets.

Looking beyond carbon markets the options for monetizing other ecosystem services separately and in combination with carbon markets may offer viable ways forward but any solutions will depend upon development and implementation of appropriate

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assessment and monitoring methodologies and institutional frameworks. A combination of both carbon market and ecosystem services credits could potentially attract the highest investment and allow for economically viable projects that conserve blue carbon as well as maintain ecosystem services for coastal communities.

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