AVOID 2

Can we avoid dangerous climate change?

Literature Review of the Potential of “Blue Carbon” Activities to Reduce Emissions

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Key policy points

"Blue Carbon is defined as the carbon stored, sequestered or released from coastal ecosystems of tidal marshes, mangroves and seagrass meadows" (Herr et al 2012).

"Blue Carbon activities refer to a suite of sustainable policy, management and planning activities in coastal ecosystems to reduce emissions from conversion and degradation and to conserve and sustainable manage coastal carbon sinks" (Herr et al 2012).

Coastal wetlands (and ecosystems) are now included in the National Greenhouse Gas Inventories (now including seagrass meadows and tidal marshes as opposed to just mangroves). Guidance has been prepared allowing for reporting emissions and removals in coastal wetlands (Kennedy et al 2014).

Blue Carbon does NOT include carbon stored in the open ocean and its ecosystems and organisms. The generally accepted use is as a subset of the overall ocean carbon cycle, just as tropical forests are a subset of the overall terrestrial carbon cycle. The use of the term and the subset of habitats has primarily been put forward as a way of incorporating these habitats within a REDD+ or equivalent mechanism.

Marine vegetated habitats in combination are responsible for up to 50% of the ocean organic carbon burial in sediments although occupying only 0.2% of the ocean surface area (Duarte et al 2013b).

Seagrass ecosystems are responsible for burying approximately 10% of the annual organic carbon in the oceans, even though they occupy less than 0.2% of the ocean surface (Fourqurean et al 2012).

It is estimated (from a variety of published sources looking at estimates from maps, observations and remote sensing) that 25 to 50% of the area of each type of marine vegetated habitat has been lost over the last 50 to 100 years. This loss equates to a 0.007 to 0.02 $GtCO_2$ loss of sink capacity and annual releases of up to 1 $GtCO_2$, (range of 0.15 to 1.02; Pendleton et al 2012) and the losses are continuing.

Overall, coastal vegetated wetlands are estimated (from a variety of published sources looking at estimates from maps, observations and remote sensing) to be losing 1 to 7% of their global area annually. Should countries begin to report their emissions in this sector under the National Greenhouse Gas Inventory then the estimates might be improved. If these rates of loss continue, 30 to 40% of the seagrass meadows and tidal saltwater wetlands (TSW) and nearly all of the remaining mangroves could be lost in the next 100 years (Pendleton et al. 2012). Thus, there is a significant annual loss of this carbon sink (as well as a potential source of emissions). As with the early stages of REDD, one of the challenges will be determining exactly what the baseline is (year/extent).

Annual land use change related (LUC) emissions from mangrove forest loss is equivalent to 2 to 10% of the total emissions from LUC, even though a smaller areal extent (%) is lost. Overall, LUC emissions from mangrove forest loss is estimated to be on the order of 0.073 to 0.44 $GtCO_2\ yr^{-1}$, or approximately 2 to 10% of the total deforestation emissions (Donato et al 2011).

The central estimate of carbon dioxide releases from annual global 'blue carbon' LUC (0.45 Gt CO_2 yr^{-1}) approaches the annual emissions of the United Kingdom as a whole (Pendleton et al 2012).

If LUC emissions from all coastal vegetated wetlands were to be included in estimates of global deforestation emissions, it is estimated that this would increase the estimate of global deforestation emissions by 3 to 19%. Currently, only terrestrial carbon is included in such estimates of deforestation emissions. However, new guidance allows for the inclusion of coastal ecosystem emissions in National Greenhouse Gas Inventories.

The social cost of carbon from annual LUC 'blue carbon' emissions is 6.1 to 42 billion US$ (central estimate US$18.5 billion based on a central estimate of the social cost of carbon (from a range of published values) being US$41 /ton CO_2, Pendleton et al 2012).

The majority of emissions from mangrove loss could potentially be avoided at a cost of less than $10 per ton of CO_2. This amount is lower than the estimated range of the social cost of carbon (US$12 to US$96) thus avoiding potential damages of climate change in a cost effective manner. While the published analysis only looked at damages from carbon emissions there would also be a wide range of significant co-benefits in terms of fisheries, terrestrial biodiversity and coastal protection. If 'blue carbon' emissions were traded for emissions in another sector, Asia and Oceania were found to have the largest potential offset supply.

A 'blue carbon' offset program would benefit small island states that largely are not able to take significant advantage of REDD+. These islands often have extensive amounts of coastal vegetated habitats.

While remote sensing has provided much better estimates of mangrove forest extent, the estimates for seagrass meadows and TSW are both very large and one of the greatest sources of uncertainty in the analyses.

Macro-algal communities store almost no carbon below ground and are not considered options for sequestration, they may potentially be options for "blue" biofuels, avoiding the food and water security issues that often accompany "green" or terrestrial biofuels.

There may be significant potential to sequester carbon through restoration of blue carbon habitats, but the literature does not currently support a quantification of the potential sequestration benefits. There is evidence that seagrass restoration may be effective within 10 years.

Non-technical summary

A great deal of effort has gone into developing a policy framework around avoiding emissions from deforestation and degradation in tropical forests (REDD/REDD+). However, marine vegetated habitats are significant carbon sinks that are being lost at rates exceeding those of some tropical forests. In 2010, a UNEP workshop examined the potential for developing a policy framework around 'blue carbon', the carbon stored in marine vegetated habitats. There has been a rapid increase in the number of scientific papers examining marine vegetated habitats for their role in mitigation both from maintaining carbon sinks as well as their mitigation potential of maintaining (primarily) or restoring (potentially) these habitats, and the risk of emissions resulting from their loss owing to human activities. The

IPCC (Kennedy et al. 2014) estimates that there are currently the equivalent of 47.7 – 60.2 Gt CO_2 stored within coastal wetlands (~29.4 Gt CO_2 in mangroves; ~2.9 Gt CO_2 in tidal marshes and 15.4 – 30.8 Gt CO_2 in seagrass meadows); these are median estimates and the broader range from the literature can be found in table

This information is provided to help inform policymakers of the potential need to modify existing policy frameworks around avoiding emissions from the loss of coastal vegetated wetlands. Unlike many forests, a much larger fraction of the carbon in marine vegetated habitats is in the soil, and this carbon can have much greater stability than the carbon in terrestrial soils. Research has shown that avoiding emissions from loss of marine vegetation habitats can be done at reasonably low costs (US$10 per ton CO_2) and with fewer of the land tenure and ownership issues often associated with REDD+. There is also potential for sequestering carbon by restoring these habitats. This paper is a review of the published literature on blue carbon, focussing as the 2010 UNEP workshop did, on the potential for including blue carbon within REDD+ and similar carbon markets. It primarily looks at blue carbon from the point of view of reducing emissions from loss.

Media interest

Preservation and restoration of marine vegetated habitats potentially help preserve some carbon sinks while helping protect coastlines and protect/enhance fisheries and biodiversity at a relatively low cost (especially relatively to the social cost of the carbon).

NERC results

There is no corresponding NERC funded work associated with the research carried out in this report.

Contents

1. Introduction

This short brief provides a summary of the recent findings on 'blue' carbon found in a survey of the major peer-reviewed literature. The papers cited, including the review papers, provide a wide range of values, in part due to potential errors in habitat areal extent derived from remote sensing and other sources. Hence this report provides a synthesis of the values of carbon fluxes and storage in blue carbon habitats. This review is **not** a review of the ocean carbon cycle, nor is it a direct comparison of terrestrial (green) versus coastal vegetated (blue) carbon. It is a review of the current literature on the potential for 'blue' carbon to be treated as method of reducing emissions analogous to reducing emissions from deforestation of tropical forests and how to include blue carbon in existing policy frameworks.

Mangrove forests, salt marshes (tidal saltwater wetlands; TSW), and seagrass meadows (collectively the components of 'blue carbon') are three carbon rich natural habitats. At least some of the reviewed literature estimates that blue carbon has an emission reduction potential along the lines of those of tropical forests as currently thought of in the REDD/REDD+ policy framework. The overall distribution of the components of 'blue carbon' can be seen in Figure 1 (from Pendleton et al. 2012). While mangroves are limited to tropical and sub-tropical waters, seagrasses and TSW are found more broadly. It is estimated that 25%-50% of the area of each type has been lost over the last 50-100 years and that losses are continuing (Table 1) to the extent that 30-40% of the seagrass meadows and TSW and nearly all of the remaining mangroves could be lost in the next 100 years (Pendleton et al. 2012). Rates of loss of marine vegetated habitats is up to ten times faster than in global forests (in Duarte et al 2013b; for comparison, FAO global deforestation rates were estimated at 0.3% yr^{-1} with maximum tropical deforestation rates estimated at 1% yr^{-1} between 2000-2010; thus, global loss rates for salt marshes and mangroves are 1-3x that estimated for tropical forests and 3-10x the estimates for global deforestation) with an overall loss of sink capacity of 0.007-0.02 Gt CO_2 yr^{-1} (Duarte et al 2013b).

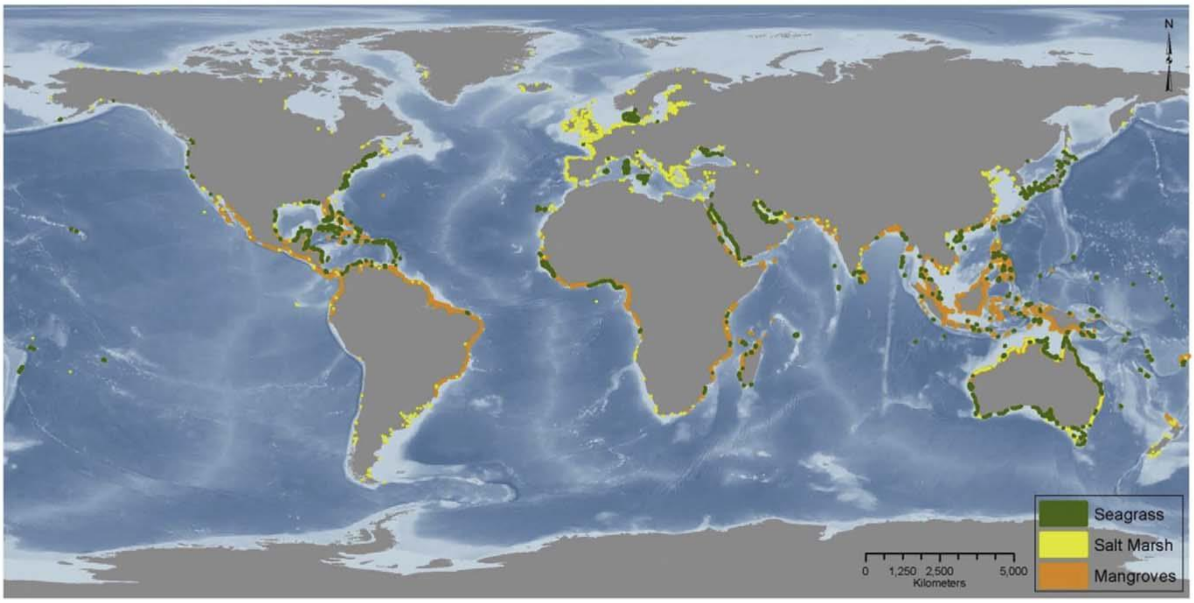

Figure 1. Global distribution of seagrasses, tidal marshes, and mangroves. Source Pendleton et al. 2012.

‘Blue carbon’ is defined as the carbon sequestered by vegetated coastal ecosystems, usually taken to refer to mangrove forests, TSW, and seagrass meadows but occasionally expanded to include macro-algal communities (Grimsditch et al 2013). *Blue carbon does not include the overall carbon sequestered in the open ocean.* The possibility of developing marine (blue) carbon markets, similar to those for tropical forests, within the UNFCCC framework was discussed at a workshop in 2010. While REDD/REDD+ was originally discussed as a model for a ‘blue carbon’ framework, it formerly was not seen as a vehicle for blue carbon financing. Thus, many of the published papers on ‘blue carbon’ are published as encouragement and justification for the potential development of a mitigation policy framework. However, more current analyses suggests that REDD+ could potentially be expanded to incorporate blue carbon (Herr et al 2012). While REDD could include mangrove forests, it only included the aboveground biomass. Given the relative carbon sequestration potential of aboveground biomass in tropical terrestrial forests versus tropical marine forests, little attention would likely be paid to mangrove forests under those circumstances. However, vegetated coastal ecosystems are thought to hold comparatively larger amounts of carbon in both their belowground biomass and in the surrounding soils. It is this total amount of carbon that makes the preservation and restoration of vegetated coastal ecosystems potentially important as part of any new mitigation policy framework. It is also the combination of the non-forested nature of much of the aboveground biomass, and the large below ground carbon storage that potentially makes it more desirable to ensure that it be included in any policy framework. The increasing interest in the subject of blue carbon, particularly as to its potential for emissions reductions, can be seen in the increase in the number of scientific papers on the subject – from 30 papers in 2005 to 110 papers in 2012 (Duarte et al 2013b).

2. Blue carbon natural sequestration potential

Coastal vegetated wetlands are estimated to bury 0.37 $GtCO_2yr^{-1}$ in marine sediments (Hopkinson et al 2012; Table 1 overall range is 0.19 – 0.609). “Marine vegetated habitats (seagrasses, salt-marshes, macro-algae and mangroves) occupy 0.2% of the ocean surface area, but contribute 50% of carbon burial in marine sediments” (Duarte et al 2013b). Table 1 provides estimates of the size of wetlands, rates of loss, ‘blue carbon storage and annual estimates of blue carbon releases.

Table 1. Overview of total 'blue' carbon storage (in marine sediments in the three key blue carbon habitats, mangroves, saltmarshes and seagrass meadows), annual natural 'blue' carbon storage and annual releases of carbon owing to human induced loss of these habitats (values represent a synthesis of the range of values provided in Donato et al 2011; Duarte et al 2010, 2013a,b; Hopkinson et al. 2012; Kennedy et al 2010; Mcleod et al. 2011; Fourqurean et al. 2012; Pendleton et al 2012).

System	Global Area (km^2)	Global total C Stock in Soil ($GtCO_2$)	Total Natural C Burial Rate ($GtCO_2$ yr^{-1})	Global Loss Rate (% yr^{-1})	Carbon emissions owing to habitat loss[2] ($GtCO_2$ yr^{-1})	Economic cost of carbon emissions due to annual habitat loss (billion US$ per yr^{-1})[3]
Mangroves	138000 - 200000	14.67 – 73.34	0.0825 - 0.166	0.7 – 3	0.073-0.45	3.6-18.5
Tidal Saltwater Wetlands	22000 – 400000	1.47 – 23.84	0.0177 - 0.032	1 – 2	0.02-0.24	0.64-9.7
Seagrass Meadows	177000 - 600000	15.40 – 72.61	0.089 - 0.411[1]	0.4 – 5	0.05-0.33[5]	1.9-13.7
Total	-[4]	31.54 – 169.79	0.1892-0.609		0.15-1.02	6.14-41.9

[1]The 0.411 $GtCO_2$ comes from estimates including seagrass and non-seagrass organic carbon in soils as opposed to the seagrasses alone (Kennedy et al. 2010); [2]Excludes the indirect consequences of loss as a future carbon sink; [3]Based on using a central estimate of the social cost of carbon of US$41 and assuming that without policy intervention current rates of loss will continue into the future (Pendleton et al. 2012; see economics section, below). [4]Area not summed as there is overlap in habitats in some areas. [5]Estimates here are those from Pendleton et al 2012 as they were used for the economic values, estimates of potential emissions from loss of seagrass meadows could be as high as 1.09 owing to differences in estimates of carbon emissions from soils (Forquorean et al. 2012). Values in Table 1 are based on the full range of values synthesized from the literature. Ranges reflect uncertainty in the areal extent of habitats obtained from remote sensing and other sources; and the fact that some literature treats soil carbon in different ways. The accompanying text utilises both these ranges as well as the figures from individual citations.

Mangroves

The global area of mangrove forests has been estimated by various authors (see Table 1 caption) to be 138,000 – 200,000 km^2. The most up to date research, based on Landsat imagery from 1997-2000 gives a potential total acreage of 137,760 km^2 in 118 countries; 75% of occurring in just 15 countries (see Table 2; Giri et al 2010). However, Table 1 contains the entire range of possible areal extent mentioned in the literature. The range is large because of potential errors in remote sensing studies, and so sources based on non-remote data are also included. There is also a potential that some areas reported as lacking mangroves could have lost their mangroves owing to natural causes (e.g., typhoons, hurricanes) that may recover. If the remote sensing data is accurate, then the amount of carbon still stored in mangroves is on the low end of the values in Table 1. Overall, mangrove forests represent 0.7% of global tropical forested extent (Giri et al 2010) and ~2%

of the marine environment area (Breithaupt et al 2012). Approximatively 50% of the mangrove forests have been lost in the last 50 years, 35% of them from 1980 to 2000 (in Giri et al 2010). Deforestation rates are currently estimated to continue at the rate of 1-3% per year.

Table 2. The fifteen most mangrove rich countries (from Giri et al 2010).

SN	Country	Area (ha)	% of global total	Cumulative %	Region
1	Indonesia	3,112,989	22.6	22.6	Asia
2	Australia	977,975	7.1	29.7	Oceania
3	Brazil	962,683	7.0	36.7	South America
4	Mexico	741,917	5.4	42.1	North and Central America
5	Nigeria	653,669	4.7	46.8	Africa
6	Malaysia	505,386	3.7	50.5	Asia
7	Myanmar (Burma)	494,584	3.6	54.1	Asia
8	Papua New Guinea	480,121	3.5	57.6	Oceania
9	Bangladesh	436,570	3.2	60.8	Asia
10	Cuba	421,538	3.1	63.9	North and Central America
11	India	368,276	2.7	66.6	Asia
12	Guinea Bissau	338,652	2.5	69.1	Africa
13	Mozambique	318,851	2.3	71.4	Africa
14	Madagascar	278,078	2.0	73.4	Africa
15	Philippines	263,137	1.9	75.3	Asia

An analysis of carbon fluxes in mangroves found that greater than 50% of the carbon burial, export and mineralization from mangrove NPP was unaccounted for in previous studies (Bouillon et al. 2008), amounting to ~0.411 $GtCO_2$ yr^{-1}. An analysis of the overall movement of carbon in and out of the system found that mineralization of carbon was underestimated and that mangroves moved a large amount of carbon to adjacent waters as dissolved inorganic carbon (op cit). The unaccounted for proportion was estimated to be equivalent to "30-40% of the global riverine organic carbon input to the coastal zone" (op cit). Taking into account carbon assimilated by crabs and other organisms, Bouillon et al. estimate that ~0.653 (±0.605) $GtCO_2$ $yr^{-1}$was potentially exported tidally as inorganic carbon. This export of carbon is not included in the overall soil carbon storage for mangroves. Table 1 reflects these findings.

Mangroves not only store carbon in their aboveground biomass (woody material and leaves) but also in their belowground biomass (roots and fine root structures). The total carbon stored in mangrove soils is estimated to be 14.67-17.34 $GtCO_2$. (Table 1). Furthermore, approximately 25% of the leaf litter may also be trapped in the sediments (Jennerjahn and Ittekot 2002, *in* Breithaupt et al 2012). Mangroves also trap significant amounts of suspended sediments helping retain transported carbon in soils. While the overall percentages vary depending on the tidal flow, geographic location and underlying soil type, mangroves generally have been found to store greater amounts of carbon belowground than aboveground. While there are generally low carbon turnover rates in intact mangrove forests, it can be released relatively quickly if converted to other uses (e.g., aquaculture).

Salt marshes

Tidal saltwater wetlands (TSW) are estimated to occupy 200,000 – 400,000 km^2 (in Hopkinson et al. 2012; table 1 value of 22,000 – 400,000). TSWs have undergone a 25% loss since the 1800s and are currently being lost at the rate of 1-2% per year (Mcleod 2011). A large percentage of primary production of TSWs is belowground, forming deposits up to 8 m deep (Chmura et al 2003). Unlike freshwater wetlands, the presence of sulphates generally hinders CH_4 production, especially in polyhaline environments. Thus, TSWs are generally not CH_4 sources and may potentially be CH_4 sinks (Chmura et al. 2003, Poffenbarger et al. 2011). Using a value of 203,000 km^2 for the combined extent of salt marshes and mangrove swamps, Chmura et al (2003) estimated that 0.156 $GtCO_2$ yr^{-1} are sequestered annually in salt marsh soils(Table 1 values 0.0825-0.166 for mangroves and 0.0177-0.032 for other TSWs). The total carbon stored in TSW soils is estimated to be 1.47-23.84 $GtCO_2$. (Table 1).

Seagrass meadows

Seagrass meadows are estimated to occupy an area of 177,000 – 600,000 km^2 (in Hopkinson et al. 2012). It is estimated than 29% of seagrass meadows have been lost over the 20th century (50% of that since the1990s, Mcleod et al. 2011) and that losses continue at the rate of 0.9 – 5% per year. A highly productive ecosystem, seagrass meadows are estimated to bury 0.1 $GtCO_2$ yr^{-1}(0.089-0.411 overall range from all sources, Table 1). As much of seagrass meadow carbon (two-thirds) is belowground biomass and thus is in soils, it can be preserved for long periods of time (millennia). The largest known pool of seagrass carbon is in the Mediterranean but data are sparse from many parts of the world, especially in the southern hemisphere. Overall the carbon storage in seagrass meadow soils can potentially be twice that per hectare than that of terrestrial soils (Fourqurean et al. 2012) and approximately 2/3 of the seagrass meadows studied are active carbon sinks (Duarte et al 2013). Depending on the assumed thickness of C pools in the soil estimates of total carbon stored in seagrass meadow soils is estimated to be as high as 35.94 – 72.61 $GtCO_2$ (Fourqurean et al. 2012; Table 1 range 15.4 – 72.61) equal or greater to the total carbon stored in mangrove and TSW soils (Fourqurean et al. 2012). A comparison of living biomass and soil organic carbon can be found in figure 2.

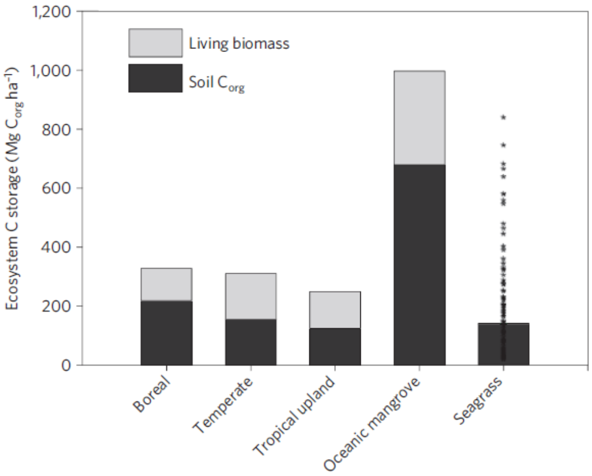

Figure 2. Comparison of C storage in living biomass and the upper metre of soils in a variety of habitats. There is very little C in living biomass in seagrass, the dots indicating the range of estimates. From Forquorean et al. 2012. Note that this is per hectare and not a total.

Seagrass meadows not only store carbon derived from aboveground and belowground biomass, they also trap transported sediments which increases their carbon store Isotopic analyses of soils from seagrass meadows and surrounding areas found that non-seagrass organic material forms a large component of seagrass meadow soils, in some cases in excess of 50% (Kennedy et al. 2010). In some meadows, much of this carbon originated in terrestrial sources.

3. Emissions from 'blue carbon' land-use change

Much of the work on blue carbon has centred on the overall amount of carbon stored with fewer papers published that estimate the annual emissions from habitat loss (land-use change). In part, this is owing to uncertainty as to the amount of carbon released annually from the soils with the loss. Overall, the estimated annual blue carbon emissions from land-use change are 0.15 – 1.02 $GtCO_2$ yr^{-1} (central estimate 0.45 $GtCO_2$ yr^{-1}; Pendleton et al. 2012). For comparison, this is approximately equivalent to the annual emissions of the U.K. in 2013. Thus, avoiding these losses (reduced emissions from deforestation) are the equivalent of avoiding the emissions of a country the equivalent of the U.K. This total is higher than previous estimates that looked only at annual sequestration or lost sequestration potential (loss of sink). These emissions are estimated to be contribute an additional 3-19% to estimates of emissions from deforestation globally (5.5 $GtCO_2$ yr^{-1} in Pendleton et al. 2012 with ranges from 3 – 10 elsewhere) with estimated annual emission damages (the social cost of carbon (SCC)) of US$6-42 billion (Pendleton et al 2012; based on an SCC central estimate of US$41 ton CO_2). New guidance allowing countries to estimate their emissions from losses of coastal wetland ecosystems may improve these overall estimates. Emissions come not only from the direct loss of aboveground biomass but also from losses to the surface soil carbon pool. There are also losses from deeper soil carbon pools but these are not included in the estimates. Losses from TSW largely come from conversion to arable land, leading to long-term losses of carbon from soils. Losses to mangroves come from development of tourism and aquaculture with soil excavations also leading to oxidation of soils and release of carbon, as well as to releases of NO_2 if the conversion was to aquaculture. Seagrass meadows loss is generally from reductions in water quality which will lead to soil losses over longer time periods. Some losses also occur due to dredging, trawling, filling and anchorages.

Other emission estimates from various land-use changes include 2900 tC per km^2 for mangrove peatlands in Belize (Lovelock et al 2011), 1500-1700 tC per km^2 for mangroves damaged in hurricanes (although these will recover over time, so can be considered a transient loss) and loss to aquaculture (with additional emissions from NO_2). Overall, LUC emissions from mangrove forests average 112-392 tC per hectare (Donato et al. 2011) for a total annual release of 0.073-0.44 $GtCO_2\ yr^{-1}$ (Donato et al. 2011; full range in Table 1 0.073-0.45 $GtCO_2\ yr^{-1}$), or approximately 2-10% of the total deforestation emissions.

Ongoing losses of seagrass meadows are estimated to lead to 0.041 – 0.083 GtCO2 yr^{-1} being returned to the ocean-atmosphere system from seagrass biomass, and an additional 0.23-1.09 $GtCO_2\ yr^{-1}$ eventually leaking in the system from oxidation of soils. This is on top of the estimated loss of 0.022-0.088 $GtCO_2\ yr^{-1}$ r loss of sequestration potential since the beginning of the 20th century. Overall the authors estimate that seagrass loss may be 'contributing as much of 10% of the 0.5-2.7 GtC yr^{-1} released from changes in land use' (Forquorean et al. 2012 relative to the values in IPCC 2007. Note that Table 1 reports only the lower values from Pendleton et al. 2012 for emissions from seagrass meadow loss of 0.05-0.33 $GtCO_2\ yr^{-1}$ to retain consistency with the economic cost data shown in Table 1, and derived from these particular estimates).

4. Stability ('permanence') of 'blue carbon'

Most losses to coastal vegetated wetlands are due to human activities, either from direct LUC or changes tied to pollution (including eutrophication) (Hopkinson et al. 2012). These systems can also be disturbed by natural processes, for example tsunamis, cyclonic events (including hurricanes and typhoons), flooding, pests and diseases but can recover relatively quickly if left undisturbed. However, sea level rise (SLR), changes in global temperatures, 'hard' coastal adaptation (armouring) and inland land use changes and adaptation (e.g., dams and shifting agriculture and erosion) will play a role on permanence of these habitats and their carbon in the future. Mangrove forests are especially prone to disturbance from tropical storms (hurricanes, cyclones, typhoons) (Barr et al 2012). While there is initial loss of aboveground carbon and carbon sequestration, and some release from soils, it is possible for the habitat to recover; recovery time depending on the degree of the damage. In cases where the aboveground biomass is completely lost, then subsequent wave actions can lead to collapse of soils and release of large amounts of carbon, especially from peat soils.

TSWs and mangroves can keep pace with moderate levels of SLR through soil accumulation (accretion) and, in some areas, by expanding inland. The slow rate of SLR since the last ice age has allowed TSW to accumulate large amounts of sediment, in some cases 6 m thick (Chmura 2013). This comes not only from vegetation but also from trapped sediments from tidal flows. To the extent that accretion can keep up with SLR (including subsidence in some areas) then the TSW can remain intact. In some TSW, rising sea levels actually stimulates production in the dominant plant species (Chmura 2013). However, as in other coastal vegetated habitats the rate of SLR (especially taking into account local land movements) can exceed the capacity of the wetland to keep up. Once that occurs there is a loss of wetland and a release, over time, of the carbon held in the soils. The other main response of TSW to SLR is inland migration, where possible. However, in many areas "coastal squeeze" will not allow for inland migration. This includes placement of roads and cities (e.g., most of South San Francisco Bay), as well as coastal armouring to avoid storm surges or to protect from SLR. Finally, inland adaptations, such as the building of dams for water storage, hydropower or flood control can block the transport of sediments downstream and limit the ability of coastal habitats to accrete adequate sediment to keep up with SLR.

Better data are needed in order to adequately assess regions for permanence in the face of SLR. This includes not only better information on local rates of SLR and land movements but primarily better information on vertical elevations of wetlands and surrounding terrestrial areas. Existing topographic products (TOPO30, SRTM) are inadequate for these purposes as their vertical resolution is on the order of 1 m or greater. LIDAR technology provides vertical resolution on the order of 0.1 m or less. However, LIDAR is not readily available for most of the world, especially developing countries and LIDAR acquisition costs are estimated at US$2.34 per acre (Chmura 2013).

Seagrass meadows can be lost through dredging and filling but also from eutrophication and increases in turbidity. Thus most seagrass meadows are lost as a side-effect of onshore activities such as deforestation.

As the standards for blue carbon funding in the various carbon markets (voluntary and UNFCCC related) are relatively new, there have been relatively few pilots on the success or failure of restoration in sequestration. In the peer-reviewed literature there is a report on a large-sale seagrass meadow restoration in Virginia, U.S.A. This study, the first of its kind, measured carbon accumulation for 10 years, From the studies' accumulation curves the authors estimate that found that "within 12 years of seeding, the restored seagrass meadows are expected to accumulate carbon at a rate that is comparable to measured ranges in natural seagrass meadows" (Greiner et al 2013).-reviewed literature there is a report on a large-sale seagrass meadow restoration in Virginia, U.S.A. This study, the first of its kind, measured carbon accumulation for 10 years, From the studies' accumulation curves the authors estimate that found that "within 12 years of seeding, the restored seagrass meadows are expected to accumulate carbon at a rate that is comparable to measured ranges in natural seagrass meadows" (Greiner et al 2013). It would be expected that mangrove restoration would take much longer, but there is no literature which has assessed sequestration in restored mangroves. However numerous projects are attempting to restore mangroves, some succeeding and others failing, but this is for purposes other carbon sequestration (e.g. coastline protection and fisheries enhancement).

5. Potential economic pathways to achieve 'blue carbon' success

Economic benefits of mangroves may be greater than those of coral reefs, continental shelves and the open ocean but less than estuaries and seagrass meadows (Alongi 2011). Globally, mangroves were previously estimated to have an annual economic value of US$900,000 per km^2 (UNEP-WCMC 2006).

Mechanisms for potentially funding 'blue carbon' programs range from payments for ecosystem services (PES) to cap-and-trade mechanisms analogous to current REDD programs (Alongi 2011; Lau 2013; Ullman et al 2013). PES looks not only at the carbon sequestration benefits but also fisheries, biodiversity, fuel resources, sediment depository, and coastal protection. One of the main issues with any of the funding schemes would be that of permanence (see below), but this can also be an issue in some tropical forests.

In mangrove systems, reforestation may have some benefits, and afforestation few benefits, with the ***greatest benefit being maintenance of current forests, especially older forests*** (greater carbon stocks in soils) (Alongi 2011). Mangrove forests not only sequester carbon but they also provide coastal protection, enhance fisheries, and provide other biodiversity protection (Lau 2013). Seagrass meadows also assist with nutrient cycling, enhance fisheries, reduce turbidity and provide some coastal protection (Lau 2013). Thus, PES potentially provides for greater and/or more diverse streams of funding than carbon payments alone would. Table 3 outlines some of the potential ecosystem services that could be used in a PES scheme.

Table 3. Examples of ecosystem services potentially contributing to a PES scheme (from Lau 2013).

Type of service	Type of ecosystem		
	Mangroves[a]	Seagrass[b]	Salt marshes[c]
Carbon Sequestration	Store carbon in aboveground tree biomass as well in belowground roots and soils	Store carbon in belowground root matrix and soil	Store carbon in belowground root system and soils
Shoreline Protection	Absorb wave and wind energy; reduce erosion and storm surges; accrete sediment for adaptation to sea level rise	Absorb wave energy	Absorb wave energy; accrete sediment for adaptation to sea level rise
Fish Nursery	Serve as nursery habitats, refugia, and feeding grounds for many tropical fish species and invertebrates	Serve as nursery habitats, refugia, and feeding grounds for many fish species	Serve as nursery habitats for fish, shellfish, and crustaceans
Biodiversity	Maintain important biodiversity on land (e.g., birds), coasts (fish and invertebrates), and oceans (e.g., coral reefs)	Sustain filter-feeding invertebrate species and particularly the endangered dugong	Provide feeding grounds for migratory birds and waterfowl and home to invertebrate species
Water Quality	Filter pollution and waste; treat excess nutrients (e.g., nitrogen and phosphorus from land); trap sediments	Filter sediment from water column; reduce turbidity	Treat and filter excess nutrients (e.g., nitrogen and phosphorus from land); trap sediments

One of the large differences and potential benefit between REDD and blue carbon revolves around land ownership as many marine areas are in the public domain (although at least parts of mangrove forests would still have land ownership issues). This is in contrast with REDD where land tenure and ownership/land rights has been a significant issue in some areas and in the negotiations.

Discussions of ‘blue carbon’ as a policy often use REDD or REDD+ as an example of a potential policy or economic scheme that could be used to either reduce emissions or protect sequestered carbon. As such, a cap and trade scheme may be an effective way of approaching financing such a system (Ullman et al. 2013). This could easily be done of ‘blue carbon’ emissions were part of the overall cap. A more likely alternative (and the one discussed below) is through the use of offsets as opposed to caps. In an offset, an economic incentive is used to trade avoiding ‘blue carbon’ emissions for emissions from a different sector (e.g., travel emissions, power production). Currently, the most likely offset schemes that could support ‘blue carbon’ projects are voluntary and California’s cap-and-trade which specifically includes ‘blue carbon’ (Ullman et al. 2013). One issue with voluntary markets is that the current average price per ton of CO_2e is US$6 (at time of paper publication), possibly adequate to reduce emissions from mangrove losses in the Americas and Caribbean but less than the amount estimated to be most effective in Asia and Oceania (Siikamaki et al 2012). However, opening any of the currently regulated markets to ‘blue carbon’ could provide sufficient estimated capital (Ullman et al 2013, Siikamaki et al 2012). The main advantage of the voluntary markets is that they currently exist and so could potentially be easily put to use for ‘blue carbon’ projects.

The most complete analysis of the economic potential of blue carbon developed high-resolution estimates of potential carbon emissions from mangrove loss and looked at the cost curves (regional and global) for avoiding these emissions (Siikamaki et al 2012). The authors found that the majority of the emissions could be avoided at a cost of less than US$10 per ton of CO_2. Approximately two-thirds of the potential offset supply is in Asia and Oceania (including India) with the remainder evenly split between Africa and the Middle East and the Americas and Caribbean. This study used a range of potential land use conversion rates to in order to better estimate the range of potential offset available (note this is specifically targeted to avoided deforestation and not carbon maintenance). The conversion rates are widest in Asia and Oceania, and the shapes of the supply curves are very similar, thus a similar offset price would largely intersect the inflection point of each curve (especially the midpoint and high conversion rates). Based on these parameters, the cost of avoiding emissions could be as low as US$5 ton in Africa and the Middle East, US$5-US$10 in the Americas and Caribbean and around US$10 a ton in Asia and Oceania (all in 2005 US$). Even the most unfavourable assumptions in the models only added US$1 per ton to the cost. The exceptions to these values were in some parts of Asia with either conversion to oil palm or aquaculture where the price per ton would need to be greater. These values are far below the estimated damages from the social cost of carbon (using a central estimate of SCC of US$41 per ton CO_2 (published range US$12 – US$96 per ton of CO_2).

Different countries would have different difficulties in implementing offset programs, potentially leading to greater costs and constraints on the potential size of offsets. Taking into account governance effectiveness, the amount of potential offsets available is reduced by up to 75% (assuming insurmountable governance issues in 50% of the countries). In this analysis Africa and the Middle East was the region found to be the most sensitive to exclusions based on governance considerations.

Co-benefits – The analysis examined the costs of potentially targeting regions with high terrestrial biodiversity for the offsets (but did not look at fisheries, potentially a much more important co-benefit). They found that the additional cost of taking a co-benefit approach would be <US$1 ton. Overall, the authors found that reducing emissions from LUC in mangrove forests is less than that of reducing emissions from regulated GHG industries and less than the potential damages from doing nothing.

<u>Case study – Brazil (Estrada et al 2014):</u>

Guarantiba State Biological Reserve is located in Sepetiba Bay on the southeast coast of Brazil near Rio de Janeiro. The reserve is composed of 3356 ha of mangrove forests. The monetary value of carbon storage and sequestration was estimated using various levels of payments, with and without the inclusion of other ecosystem services (PES; based on the Climate, Community and Biodiversity certificate as well as the Verified Carbon Standard certificate programs used in some REDD activities). In this study the authors only considered the aboveground biomass (as is standard in REDD) and not the belowground biomass and soil storage. Valuations used ranged from US$5 to US$18. Based on the various figures, the authors estimated that the Guarantiba mangroves had a value of up to US$455,827 per year. Considering the carbon in aboveground storage alone, this equated to a potential value of US$3.5 million (substantially increased if belowground storage was included). The annual maintenance cost (or rental tax) of this carbon storage was thus estimated to be in the range of US$104,000 to US$209,000 per year.

Macroalgal communities store almost no carbon belowground and are not options for sequestration but are options for “blue” biofuels, avoiding the food and water security issues that often accompany “green” or terrestrial biofuels (Duarte et al 2013b).

The Blue Carbon Policy Framework 2.0 (Herr et al 2012), from the International Blue Carbon Policy Working Group, examined various options for financing blue carbon activities. Those revolving around REDD+ and other UNFCCC frameworks (e.g., adaptation funding; CDM) will be discussed below. However, the framework also examined the potential for carbon markets to include blue carbon activities in their portfolios. These include the Verified Carbon Standard; the American Climate Registry; the Climate, Community, and Biodiversity Standard, the CarbonFix Standard; and the Plan Vivo Systems and Standard. Many of the issues around including blue carbon activities into this voluntary carbon markets are the same as in tropical forests. These include baseline and monitoring, additionality, permanence and leakage. As the REDD process as matured, so have the guidelines and methodology around these issues, as well as much better quantification of carbon estimates and co-benefits (as well as risks and social issues). The International Blue Carbon Science Working Group is preparing a ‘best practice’ guide in how to address these issues within the blue carbon context. Additionally, the American Climate Registry and Verified Carbon Standard have both developed preliminary guidelines for crediting wetlands projects, including restoration

6. Policy Issues – Is a new policy mechanism needed?

When blue carbon activities were first being proposed for inclusion under the UNFCCC (including under Article 4(c)) it was felt that REDD was not an adequate mechanism for financing blue carbon activities. While mangroves are a forest type and could be included in REDD, it was only for the aboveground biomass. As seagrass meadows have no aboveground biomasses and seagrass meadows and salt marshes are not forests, neither of these ecosystems could have been included in existing frameworks. Therefore, there were suggestions that a new framework might be necessary for dealing with blue carbon activities.

The Blue Carbon Policy Framework 2.0 (BCPF2; Herr et al 2012) has five policy objectives –

“1) Integrate Blue Carbon activities fully into the international policy and financing processes of the UNFCCC as part of mechanisms for climate change mitigation;

2) Integrate Blue Carbon activities fully into other carbon finance mechanisms such as the voluntary carbon market as a mechanism for climate change mitigation;

3) Develop a network of Blue Carbon demonstration projects;

4) Integrate Blue Carbon activities into other international, regional and national frameworks and policies, including coastal and marine frameworks and policies;

5) Facilitate the inclusion of the carbon value of coastal ecosystems in the accounting of ecosystem services.”

Thus, many existing policy mechanisms could be made to work for blue carbon activities (especially for potentially obtaining financing for activities). Under the UNFCCC this includes REDD+, National Appropriate Mitigation Actions (NAMA), as well as some LULUCF activities including under the Clean Development Mechanism (CDM). One of the key needs for the inclusion of Blue Carbon activities is recognizing and taking into account the full measure of carbon stored – above and belowground (including soils). Some countries (e.g., Costa Rica, Tanzania, Indonesia and Ecuador) already include mangroves in their REDD+ plans under UN-REDD. Several countries (e.g., Ghana, Sierra Leone and Eritrea) have included coastal wetland related NAMAs to assist in receiving international aid for reducing deforestation emissions in this sector. Other countries could also potentially include reducing loss of coastal wetland ecosystems in their NAMAs. This may be most appropriate in Small Islands Developing States as they are not typically REDD+ countries. Climate change adaptation funds have also been identified as a potential source for funding of blue carbon activities as many of the co-benefits of reducing loss of coastal wetland ecosystems also have adaptation benefits (e.g., 'soft' armouring, fisheries, biodiversity maintenance). Reforestation and afforestation of mangroves is already potentially fundable under the CDM.

There may also be possible mechanisms through other international agreements than the UNFCCC. These include the Convention on Biological Diversity (CBD), RAMSAR, Rio+20, as well as more regional bodies (EU, South Pacific Regional Environment Programme). The CBD has already encouraged countries to include marine and coastal biodiversity into their national climate change activities and it would potentially be possible to secure funding for some of these through the Global Environment Facility (GEF). Indeed, the GEF has previously funded work to develop best practices for mangrove restoration (J. Price pers. Comm.). RAMSAR sites are also eligible to receive funding through the GEF and this funding could potentially be used for Blue Carbon Activities. Rio+20 provides opportunities for small island states, for example, to 'keep the green economy blue' and this could include reducing degradation of coastal wetland ecosystems. Within the EU, the EU Biodiversity Strategy to 2020, the Green Infrastructure Strategy and the BEST initiative (ecosystem services) may all provide frameworks for funding blue carbon activities.

In addition to the treaty based policy frameworks the BCPF2 recommends efforts to better incorporate coastal ecosystems and blue carbon benefits into Integrated Coastal Zone Management (ICZM) and Marine Spatial Planning, especially around Marine Protected Areas (MPAs). It is felt that the inclusion of carbon sink management into coastal zone planning is another opportunity to potentially reduce deforestation or even encourage restoration in these sectors. Unlike REDD+ which is largely limited to tropical countries, many of these other frameworks may be applicable more globally, including the UK and its extensive tidal saltwater wetlands.

7. Conclusion

Blue carbon, or mitigation obtained largely through maintaining the carbon sinks in mangrove forests, seagrass ecosystems and tidal saltwater wetlands has been proposed as an additional mechanism for mitigating climate change. The amount of peer-reviewed literature on this topic has greatly increased in recent years. A review of the most recent literature, including several review articles was used in preparing this report, including the meta-analysis of the combined paper's findings found in Table 1.

Overall, marine vegetated habitats, in combination, are estimated to be responsible for up to 50% of the ocean carbon burial in sediments while occupying only 0.2% of the ocean surface area (Duarte et al 2013b). Of this, seagrass ecosystems are responsible for burying approximately 10% of the yearly organic carbon in the oceans (Fourqurean et al 2012).

It is estimated that 25%-50% of the area of each type of marine vegetated habitat has been lost over the last 50-100 years equating 0.007-.02 $GtCO_2$ loss of sink capacity and annual releases of up to 1 $GtCO_2$, (0.15-1.02; Pendleton et al 2012). These losses are continuing with coastal vegetated wetlands estimated to be losing 1% - 7% of their area annually due to human activities. This means that 30-40% of the seagrass meadows and tidal saltwater wetlands (TSW) and nearly all of the remaining mangroves could be lost in the next 100 years (Pendleton et al. 2012). This represents a significant annual, and potentially avoidable, loss of this carbon sink (and a source of emissions). Blue Carbon Activities are analogous to REDD – both are attempting to reduce emissions from deforestation and degradation (with the definition of deforestation expanded to other habitats in blue carbon).

Annual LUC emissions from mangrove forest loss is equivalent to 2-10% of the total emissions from deforestation, even though a smaller areal extent (%) is lost. Overall, LUC emissions from mangrove forest loss is estimated to be on the order of 0.073-0.44 $GtCO_2$ yr^{-1}, or approximately 2-10% of the total deforestation emissions (Donato et al 2011).

Annual LUC emissions from all coastal vegetated wetlands is 3-19% in ADDDITION to those from terrestrial deforestation globally. The overall central estimate of carbon dioxide releases from annual 'blue carbon' LUC (0.45 Mt CO_2 yr^{-1}) approaches the annual emissions of the United Kingdom as a whole (Pendleton et al 2012).

The social cost of carbon from annual LUC 'blue carbon' emissions is US$6.1 – US$42 billion (central estimate US$18.5 billion based on a central estimate of the social cost of carbon being US$41 ton CO_2, Pendleton et al 2012). The majority of emissions from mangrove loss could be avoided at a cost of less than $10 per ton of CO_2. This amount is lower than the estimated range of the social cost of carbon (US$12 – US$96) thus avoiding potential damages of climate change in a cost effective manner. While the analysis only looked at carbon emissions there would also be a wide range of significant co-benefits in terms of fisheries, terrestrial biodiversity and coastal protection. Asia and Oceania were found to have the largest potential offset supply. A 'blue carbon' offset program would benefit small island states that largely are not able to take significant advantage of REDD+. These islands often have extensive amounts of coastal vegetated habitats.

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