

The Management of Natural Coastal Carbon Sinks

Edited by Dan Laffoley and Gabriel Grimsditch November 2009

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Foreword

Climate change is arguably one of the biggest issues facing humanity. World leaders now recognise that urgent and significant reductions in our emissions of greenhouse gasses are needed if we are to avoid future dangerous climate change. Alongside such measures is an increasingly strong recognition that there is a need to properly manage particular habitats that act as critical natural carbon sinks. This is to ensure that they retain as much of the carbon trapped in the system as possible, and don't tend to become 'sources' to the atmosphere through poor management. Often the release of trapped carbon as carbon dioxide is accompanied by the release of other powerful greenhouse gases such as methane, and this situation exacerbates an already concerning global climate situation.

In recent decades there has been a significant focus, quite rightly, on major carbon sinks on land such as forests, particular soil types and peatland habitats. These are ecosystems that by their ecology inherently hold vast reservoirs of carbon, and where management can be put in place to attempt to retain such reserves within the natural systems. The challenge is to recognise other carbon sinks that could contribute and ensure that they too are subject to best practice management regimes.

Until now surprisingly little attention appears to have been paid to the ocean, despite the fact that this is a critical part of the carbon cycle and one of the largest sinks of carbon on the planet. This lack of attention may in part be due to a mistaken belief that quantification of discreet marine carbon sinks is not possible, and also in the mistaken belief that there is little management can do to sustain such marine carbon sinks.

The origin of this report lies within IUCN's World Commission on Protected Areas and Natural England in the UK, and a joint enthusiasm to address this issue. This initial enthusiasm sparked the interest of many global partners and scientists when it became apparent that evidence is available that could change the emphasis on the management of carbon sinks. There is an urgent need for the global debate and action now to encompass marine habitats, just as we already value and try to best protect more familiar forests and peatlands on land.

Over the past two years we have sought out and worked with leading scientists to document the carbon management potential of particular marine ecosystems. It turns out that not only are these habitats highly valuable sources of food and important for shoreline protection, but that all of them are amenable to management as on land when it comes to considering them as carbon sinks. In the ocean this management would be through tools such as Marine Protected Areas, Marine Spatial Planning and area-based fisheries management techniques. This report documents the latest evidence from leading scientists on these important coastal habitats.

Given the importance of examining all options for tacking climate change we hope the evidence in this report will help balance action across the land/sea divide so we don't just think about avoiding deforestation, but we also think about similarly critically important coastal marine habitats. We hope this report will, therefore, serve as a global stimulus to policy advisors and decision makers to encompass coastal ecosystems as key components of the wide spectrum of strategies needed to miti

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Scale of Units used

One Gigatonne = 1000 Teragrams One hectare = $10,000$ m²

This report focuses on the management of natural coastal carbon sinks. The production of the report has been stimulated by an apparent lack of recognition and focus on coastal marine ecosystems to complement activities already well advanced on land to address the best practice management of carbon sinks. The production of this report is timely as a number of Governments are now introducing legislation to tackle climate change. In the UK, for example, the Climate Change Act sets out a statutory responsibility to quantify natural carbon sink as part of the overall carbon accounting process. It is important that such quantifications and processes work with the latest science and evidence.

To construct this report we asked leading scientists for their views on the carbon management potential of a number of coastal ecosystems: ti

types. Having comprehensive habitat inventories is critically important and this report highlights the urgent need, alongside recognising the carbon role of such ecosystems, to ensure that such inventories are completed for saltmarsh and kelp forests and then all such inventories are effectively maintained over time.

- These coastal marine ecosystems are also vital for the food security of coastal communities in developing countries, providing nurseries and fishing grounds for artisanal fisheries. Furthermore, they provide natural coastal defences that mitigate erosion and storm action. Therefore, better protection of these ecosystems will not only make carbon sense, but the co-benefits from ecosystem goods and services are clear.
- Significant losses are occurring in the global extent of these critical marine ecosystems due to poor management, climate change (especially rising sea levels), coupled to a lack of policy priority to address current and future threats.
- Certain human impacts notably nutrient and sediment run-off from land, displacement of mangrove forests by urban development and aquaculture, and over-fishing-are degrading these ecosystems, threatening their sustainability and

Introduc on

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As the evidence grows about the effects climate change is having on the environment, so too does the interest in and actions to address the underlying causes – regulation of anthropogenic emissions of greenhouse gases into the atmosphere, avoiding deforestation, management and protection of other natural terrestrial carbon sinks, and the development of fiscal measures that place a value on carbon and therefore provide an economic incentive to reduce emissions.

The ocean is the largest carbon sink on Earth but there has been scant attention paid to coastal and marine ecosystems when considering actions to address climate change concerns. Within that context the production of this report was stimulated by an interest in why coastal habitats were not being considered as important carbon sinks on a global scale – the focus other than in some popular books on the topic seems to be predominantly on terrestrial ecosystems, particularly forests, certain soil types and peatlands. This concern was brought into sharp focus in 2007 - 2008 when undertaking the research for a report by Natural England on Carbon Management by Land and Marine Managers (Thompson, 2008). It rapidly became evident that coastal and marine ecosystems are vital global carbon stores but that it was not easy to find the evidence base to substantiate this claim.

A clear robust rationale was required to progress efforts to include coastal carbon issues in broader climate discussions or heighten the need to manage better and protect these ecosystems. Alongside the Natural England work, in 2008 IUCN's World Commission on

Protected Areas released their global Plan of Action (Laffoley, 2008). This set out the overall framework and direction for the work of the World Commission in marine environments. Within the framework it includes a strategic activity of bringing together work on Marine Protected Areas with actions to address climate change, food security and human health. The development of this report on coastal carbon management is a result of the Natural England and IUCN activities, and a particular contribution to the global Plan of Action for Marine Protected Areas. With ongoing support from the Lighthouse Foundation, the United Nations Environment Programme (UNEP) has also come on board to collaborate with IUCN and Natural England, further adding weight to this innovative report.

The logic behind this report is to attempt to quantify the greenhouse gas implications of the management of particular coastal ecosystems, being careful to choose those whose management can be influenced by application of existing policy agreements and well established area-based management tools and approaches. Only the management of natural carbon sinks can be included in a countries national inventory of greenhouse gas emissions and sequestration and therefore count towards their climate change mitigation commitments.

It follows that if management of such habitats delivers clear and quantifiable greenhouse gas benefits, and tools exist to secure their best management, then this opens up a new range of possibilities for better valuing them in terms of meeting international climate change

objectives. If we want to maximize the potential for natural carbon sequestration, then it is imperative that we draw together the evidence base and protect these valuable coastal marine ecosystems as an additional option to add to our portfolio for mitigating climate change. The challenge, however, is that little concerted attention has previously been applied to this issue, thus hindering the development of national plans that might include recognition and improved protection of coastal carbon sinks.

The focus of this report is therefore on collating and publishing the science of carbon sinks for an initial set of five key coastal ecosystems. These are coastal ecosystems that not only meet the above potential carbon sink and management criteria, but that are already highly valued for their contribution to marine biodiversity and the goods and services that they provide: ti

productive buffer zones that deliver valuable ecosystem goods and services that have significant potential for addressing the adverse effects of climate change." In addressing the needs of these ecosystems additional costs may be incurred, but what are the hidden costs of not achieving carbon reduction goals?

In the following sections we set out the views of on goals?

Tidal Salt Marshes

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Fast facts

- Intertidal ecosystems dominated by vascular plants.
- Occur on sheltered marine and estuarine coastlines from the sub-arctic to the tropics, but most extensive in temperate climates.
- Their soils store 210 g Cm⁻²yr⁻¹. This is a substantial rate and the carbon stored in tidal salt marsh soils of the USA comprises 1-2% of its total carbon sink.
- Each molecule of CO₂ sequestered in soils of tidal salt marshes and their tropical equivalents, mangrove swamps, probably has greater value than that stored in any other natural ecosystem due to the lack of production of other greenhouse gases. In contrast to freshwater wetland soils, marine wetlands produce little methane gas, which is a more potent greenhouse gas than $OQ₁$. The presence of sulphates in salt marsh soils reduces the activity of microbes that produce methane.
- Extensive marsh areas have been lost from dredging, filling, draining, construction of roads and are now threatened by sea level rise.
- Restoration of tidal salt marshes can increase the world's natural carbon sinks. Returning the tides to drained agricultural marsh can also significantly increase this carbon sink.
- Sustainability of marshes with accelerating sea level rise requires that they be allowed to migrate inland. Development immediately inland to marshes should be regulated through establishment of buffer zones. Buffer zones also help to reduce nutrient enrichment of salt marshes, another threat to this carbon sink.

De ni on and global occurrence

Tidal salt marshes are intertidal ecosystems vegetated by a variety of primary producers such as macroalgae, diatoms and cyanobacteria, but physically dominated by vascular plants. Vascular plants are absent from the tidal flats often found adjacent to the seaward edge of tidal salt marshes. In contrast to eelgrass communities which may be found on the edge of the lowermost intertidal zone, survival of the dominant vascular plants is dependent upon exposure to the atmosphere. During photosynthesis the marsh's vascular plants uptake carbon dioxide from the atmosphere, in contrast to eelgrass which uptakes carbon dioxide dissolved in seawater.

Chapman (1977) described the dominant plant forms of the marsh and how they vary geographically. Perennial grasses such as *Spar na alterni ora* and *Spar na*

patens are dominant along much of the Atlantic coast of North and South America. In some other regions perennial broad-leaved herbaceous plants dominate, such as *Atriplex portuloides* along portions of Europe's coast. Perennial succulents such as the related *Salicornia, Sarcocornia* or *Arthrocnemum* species that grow to shrub size tend to dominate coastlines of Mediterranean climates where, dry, hot summers cause soils to develop hypersaline conditions.

Tidal salt marshes occur on sheltered marine and estuarine coastlines in a range of climatic conditions, from sub arctic to tropical, but are most extensive in temperature climates. Although it is often reported that mangrove trees replace salt marsh vegetation on tropical coasts salt marshes may exist above the higher elevation of the swamp.

are an important source of marsh primary production. Sullivan and Currin (2000) compared the annual production of benthic microflora to vascular plants in salt marshes of the three U.S coastlines. Microfloral production ranged from 8% of vascular plant production in Texas to 140% in a California salt marsh. The biomass of benthic microflora may comprise a significant porti

in elevation, tracking changes in sea level (figure 2). Paleoenvironmental studies of marsh soils (e.g., Shaw and Ceman, 1999) have documented both increase in surface elevation and lateral accretion of marsh soils as marsh plants colonize mudflats to the seaward side and adjacent terrestrial or wetlands environments to disrupt components of the ecosystem, the potential for carbon storage depends on sustainability of marsh accretion, thus maintenance of vegetation cover.

Disruption of coastal food webs can have unanticipated cascade effects that result in increased populations of distance marshes from sites where nutrients are applied and take up nutrients in vegetation and soils, thus reducing the level reaching the marsh. Terrestrial buffers can help ensure sustainability of marshes with accelerating sea level rise, allowing them to migrate inland. Development immediately inland to marshes should be discouraged and, if possible, regulated through establishment of buffer zones.

Restoration of tidal salt marshes is an excellent way to increase the world's natural carbon sinks. Returning the tides to drained agricultural marsh can make a significant increase in the salt marsh carbon sink. The U.K's managed realignment program, to shift embankments inland and restore flooding of agricultural marshes, is a progressive form of coastal management that not only deals with the threat of sea level rise, but promises to enhance carbon sequestration as tidal salt marshes recover. Such policies should be considered in other regions. For example, Connor et al. (2001) estimated that if all of Bay of Fundy marshes "reclaimed" for agriculture could be restored, the rate of carbon dioxide sequestered each year would be equivalent to 4-6% of Canada's targeted reduction of 1990-level emissions under the Kyoto Protocol.

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Mangroves

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De ni on and global occurrence

Mangrove forests are a dominant feature of many tropical and subtropical coastlines, but are disappearing at an alarming rate. The main causes for the rapid destruction and clearing of mangrove forests include urbanization, population growth, water diversion, aquaculture and salt-pond construction (e.g. Farnsworth & Ellison 1997). On a global scale, mangrove plants are found throughout the tropical and subtropical regions of the world, and two species of *Avicennia* have penetrated into the warm temperate areas of both hemispheres. The global distribution of mangroves generally matches the winter 20°C isotherm. Mangroves are trees, shrubs, palms or ground ferns which normally grow above mean sea level in the intertidal zone of marine, coastal, or estuarine environments. Thus, mangrove plants do not form a phylogenetically related group of species but are rather species from very diverse plant groups sharing common morphological and physiological adaptations to life in the intertidal zone, which have evolved independently through convergence rather than common descent. The most recent global data compilation suggests a current global areal extent of about 152,000 km² (FAO 2007), with Indonesia and Australia together hosting about 30% of this area.

Mangrove goods & services

Besides the role mangroves play in the carbon cycle, mangrove ecosystems have a wide range of ecological and socio-economical functions.

For many communities living within or near to mangrove forests in developing countries, mangroves constitute a vital source of income and resources, providing a range of natural products such as wood (for firewood,

to adjacent ecosystems in organic form (dissolved or particulate) where it can either be deposited in sediments, mineralized, or used as a food source by faunal communities.

In the context of O_2 sequest ration, the relevant carbon

fraction (<10%) of the overall net primary production,

assessing whether the functional properties (including carbon sequestration and primary productivity) have been restored through management in regions where restoration/rehabilitation projects have been implemented (e.g., Twilley et al. 1998, Samson & Rollon 2008). Recent reviews indicate that newly created mangrove ecosystems may or may not resemble the structure and function of undisturbed mangrove ecosystems and that objectives should be clearly established before any major small or landscape level rehabilitation is implemented (Kairo et al. 2001, Lewis 2005, Twilley & Rivera-Monroy 2005).

To our knowledge, there is no published information describing projects specifically aiming to enhance carbon sequestration through restoration or rehabilitation. However, a good indicator of potential magnitude of this sink is information reported for mangrove plantations or sites undergoing rehabilitation. Aboveground biomass estimates in replanted mangroves stand have varied from 5.1 Mg ha^{-1}

also have the potential of providing an efficient sink of Ω_2 , both on short and longer time-scales (i.e.
biomass producti **References**

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Global distribution of Seagrasses

Seagrass Meadows

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Fast facts

has been estimated to between 0.6 million km^2 (Charpy-Roubaud & Sournia, 1990) and 0.3 million km² (Green & Short, 2003; Duarte et al., 2005), with the latter estimate taking into account reports of longterm decline rates in seagrass coverage. Although seagrass meadows cover a relatively small portion of the ocean (approx 1%), they play an important role in the coastal zone and provide ecosystem goods and services that have been estimated to be of high value compared with other marine and terrestrial habitats (Costanza et al., 1997). Furthermore, the presence of seagrass meadows is global, unlike mangroves, corals making the role of seagrasses in the oceanic carbon budget proportionally more significant than expected from their cover or primary production alone (Smith, 1981).

Many seagrasses also deposit considerable amounts of carbon in their below-ground tissues with ratios of below-ground to above-ground biomass ranging from 0.005 to 8.56 (Duarte & Chiscano, 1999). Larger seagrass species tend to develop high below-ground biomass and hence have a greater capacity for accumulation of carbon due to the relatively slow turnover of the roots and rhizomes (40 days to 19 years). The seagrass species *Posidonia oceanica* can bury large amounts of the carbon it produces, resulting in partly mineralised, several metres thick, underground *ma es* with an organic carbon content of as much as 40 %. These mattes can persist for millennia, thus representing a long-term carbon sink (Pergent et al., 1994; Romero et al., 1994; Mateo et al., 1997, 2006).

2. Carbon cycling in the ecosystem and its importance as a carbon sink

Fate of carbon: The proportion of biomass produced by seagrasses that is directed into carbon storage is dependent on the extent to which carbon is channelled through herbivory, export and decomposition.

Estimates of herbivory, decomposition and export all vary greatly due to the intrinsic properties of individual species and although carbon fluxes in different species may follow the same general routes, the relative importance of the diff

can be preserved (see Short et al., 2002, Short & Burdick, 2005, Björk et al., 2008). To provide the most favourable conditions a number of requirements must be met. 1. A high water quality, This mean low turbidity waters, low concentrations of coloured dissolved organic matter and low levels of eutrophication. All of these will ensure that the waters support sufficient light penetration for seagrasses to thrive. 2. Good sediment conditions. The sediments should experience only low levels of disturbance/mechanical perturbations, low carbon accumulation rates and low concentrations of sulphide. 3. Maintenance of genetic variability and connectivity with other biological systems, and 4. Favourable water movement

In recent years it has become evident that these requirements cannot be met without creating a public awareness of the purpose of the management plans, and ensuring the participation by stakeholders, both in planning and implementation of management strategies.

Management aimed at preserving especially high carbon storage capacity: There are certain features of seagrasses that can enhance their potential to act as important sites for carbon storage. The low nutrient concentrations and high proportion of structural carbon in seagrass tissues, enhance carbon accumulation in the meadow by slowing down the destruction of organic carbon, and the large proportion of below ground biomass enhance carbon accumulation in the meadow by burying organic carbon quickly, before it can be exported from the meadow. It follows that the greatest proportion of organic carbon preserved in the sediments will be found in meadows consisting of slow growing species with a high allocation of biomass to the growth of below ground organs.

Of all the seagrasses studied, *Posidonia oceanica* probably represents one of the best species for carbon storage; it is also the best studied species in terms of carbon burial and probably provides the best estimate of the size of the carbon sink in at least one area of our coastal oceans. *Posidonia oceanica* is widespread and endemic to the Mediterranean and sustains carbon burial rates of 17-191 g Cm-2 yr-1, forming a *ma e* that can be thousands of years old. The thickness of the *ma e* in one bay of the NW Mediterranean has been recently estimated using high-resolution seismoacoustic imaging (Iacono et al., 2008), allowing the carbon accumulation to be calculated at 0.18 Mg m⁻². Given that *Posidonia oceanica* is thought to cover

 0.035 million km² of the Mediterranean, the sediments below *Posidonia oceanica* meadows could represent a store of ~6 x 1015 tonnes of carbon, with a carbon accumulation rate of between 0.6-7 MgC yr¹ or 2-24% of global seagrass burial.

Although *Posidonia oceanica* may appear to make the Mediterranean a hot spot in terms of carbon burial, other seagrass species may, although today undiscovered, have similar potential for carbon burial. Even species with a lower carbon burial but a more widespread distribution may actually make a larger overall contribution to global carbon storage. Thus to make accurate predictions concerning the fate of seagrass production on a global scale, reliable estimates of the distribution and density of the dominating seagrass species in all different biogeographical regions and the potential of each species for carbon burial would be needed. These figures for seagrasses are not currently available as shown in a review of the literature on seagrass ecology (Duarte 1999). Of the papers reviewed in this study, 25% related to the ecology of just two of the seagrass species (*Thalassia testudinium* + *Posidonia oceanica*) and there was a geographic bias in published results, with 50% of the studies being undertaken in Caribbean and Mediterranean seagrass meadows.

Thus today, although we can only approximate the current importance of seagrass meadows as a carbon sink, the recent focus within the scientific community on global change and the importance of natural carbon sinks has resulted in a large number of research projects aiming at making it possible to incorporate the biogeography of seagrass species and their propensity for carbon storage into an accurate global carbon budget.

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Geographic distribu on of kelp forests in surface (green line) and deep (red line) waters, reproduced from Santelices - Santelices, B., 2007. The discovery of kelp forests in deep-water habitats of tropical regions, PNAS, 104 (49), 19163 – 19164 by kind permission of Proceedings of the Na onal Academy of Sciences (PNAS).

De ni on and global occurrence Kelp forests consist of conspicuous assemblages of up to 3 m in height, while low-lying prostrate species form a canopy covering the bottom. Mann (2000) characterized kelp forests by their dominant genera and recognized three general types, those dominated by *Laminaria*, *Ecklonia*, and *Macrocys s. Laminaria* is the dominant genera in the eastern and western Atlantic and western Pacific. *Ecklonia* is prevalent in Austral Asia and South Africa, and the giant kelp *Macrocys s* dominates in the eastern Pacific off the coasts of North and South America.

Although kelps are technically restricted to the order Laminariales, large brown algae in the Order Fucales are occasionally referred to as kelps. Much like kelps, these fucalean algae (commonly referred to as rockweeds) occur world wide, but unlike kelps they are most diverse in the Southern Hemisphere where they form dense forests subtidally (Schiel and Foster 1986).

Goods and services

Economically, kelp forests are one the most important marine ecosystems in temperate regions. They are the primary habitat for many commercial and recreational fisheries that include a wide diversity of mollusks, crustaceans, and finfish (Foster and Schiel 1985, Mann 2000, Graham et al. 2007b). Kelp itself is harvested for a wide range of uses such as food, food additives, pharmaceutical and cosmetic applications, animal fodder, and biofuel (Neushul 1987, Leet et al. 1992). In addition, vast amounts of kelp are grown commercially in marine farms in many parts of the world where it is harvested for human and animal consumption (Tseng 1981, Gutierrez et al. 2006).

In addition to provisioning services, kelp forests provide many regulating and cultural services as well. Importantly, they constitute one of the most diverse marine systems in temperate regions. As foundation species (*sensu* Dayton 1975) kelps provide the main source of food and shelter for many forest inhabitants (Schiel and Foster 1986), and they exert a profound influence on the abundance and distribution of the vast number of species that associate with them

(Eckman and Duggins 1991, Graham 2004, Arkema et al. 2009). As such kelp forests play a critically important role in the conservation of biodiversity; a ecological service that has long been recognized (Darwin 1839). The trophic importance of kelp, however, is not limited to the area within kelp forests as the majority of kelp biomass can be exported out of the forest to adjacent habitats where it has been shown to be an important dietary component of terrestrial, intertidal and deep sea food webs (Polis and Hurd 1996, Harrold et al. 1998, Dugan et al. 2003).

Kelp forests also have high recreational value for fishing, diving, and boating, and they are a favorite area for sightseeing and photographing marine birds and mammals. Importantly, kelp forests provide many opportunities for education. They are a popular exhibit at most public aquaria, and they serve as a natural laboratory and classroom for training marine scientists and the general public at large, which enhances stewardship of the ocean and its resources.

Biomass and produc on

Kelps dominate the autotrophic biomass and production of shallow rocky substrates in temperate and artic regions of the world (Mann 2000). A complete survey of the world's kelp forest has never been done. The length of all coastlines where kelp forests are expected to occur has been estimated at 58,774 km of which about 30,000 km are believed to have significant kelp forests (de Vouys 1979). Deriving estimates of the global standing crop of kelp on these coastlines is challenging because the biomass density and crossshore width of kelp forests vary greatly with species, time (both seasonally and inter-annually), and location (both within and among sites). If one was to assume that kelp forests were restricted to coastlines with significant kelp and had an average biomass density of $500 g$ Cm⁻² (Table 1), and an average forest width of 500 m, then the global kelp standing crop would be ~7.5 Tg C. Understory algae associated with kelp forests may increase the standing crop of the ecosystem by 20%

Table 1. Es mates of standing biomass for three common kelp genera and for understory algae within MacrocysƟ s *forests (other than* MacrocysƟ s*). Dry wt was assumed to be 15% of wet wt for* Laminaria *and* Ecklonia *and 10% for* MacrocysƟ s *and its associated understory; carbon wt was assumed to be 30% of dry wt for all species (Mann 1972, Rassweiler et al. 2008).*

or more (Table 1). This estimate does not account for deep (30 m – 200 m) kelp in unexplored tropical waters, which Graham et al. (2007) estimated at $> 23,500$ $km²$ using an oceanographic-ecophysiological model that accurately identified known kelp populations. If their model predictions are accurate, then the global standing crop of kelp could be as much as 20 Tg C.

Kelps are among the fastest growing autotrophs in the world with growth rates averaging up to 2 to 4% of the standing biomass per day (Wheeler and Druehl 1986; Reed et al. 2008). The high growth rate of kelps is principally responsible for the high rates of primary production recorded for kelp forests, which rank as one of the most productive ecosystems on earth (Table 2). The methods used to measure primary production in

Kelp Forests

affecting the standing crop of kelps (Dayton 1985, Schiel and Foster 1986). It has been suggested that the deep water forests in tropical regions may serve as a spatial refuge for kelp during extended periods of climate change (Santelices 2007). In any case, climate related changes will undoubtedly affect the entire forest community of kelp, algal competitors, invertebrate grazers, and vertebrate predators. The impacts of climate change on kelp will undoubtedly be influenced by direct and indirect interactions involving a suite of forest inhabitants.

Management

The most prudent approach to managing the world's kelp forests is to avoid, prevent, or limit habitat degradation and loss caused by humans. Kelp forests require good water quality and suitable hard substrate for attachment. Consequently, management practices aimed at protection should focus on policies that preserve water quality and rocky habitats in areas where kelp forests are found. Chief among these should be policies that restrict the chronic discharge of municipal and industrial waste waters into the nearshore, and land use practices that elevate the concentrations of sediments, nutrients and pollutants in runoff delivered to the ocean. Degradation of kelp forests caused by the direct and indirect effects of fishing are best managed by restricting the harvest of kelp and associated biota, which can be done using tradi

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Smith and Ga uso show from ocean chemistry that coral reefs are not a sink for the greenhouse gas carbon dioxide. The point is we cannot count on reefs to clean the atmosphere of our carbon dioxide emissions. We have to act decisively and do it right now, before it is too late.» - Richard B. Aronson, Florida Institute of Technology and President of the International Society for Reef Studies.

Coral reefs support the highest marine biodiversity in the world, containing an estimated 25% of all marine species (Roberts, 2003). More than 500 million people worldwide depend on them for food, storm protec

instantaneous. The distribution of the various forms of dissolved inorganic carbon among $H_2\text{CO}_3$, $H\text{CO}_3^$ and \mathcal{O}_3^2 is dependent upon hydrogen ion ac

of $CO_a²$ (see equations 3, 4 and 7; also Figure 1). As a result of this pH shift, equation 7 is modified to the general form:

$$
Ca^{2+} + 2HOQ_3 \quad CaCO_3 + CO_2 \quad + H_2O \quad \rightarrow \Uparrow \quad (8)
$$

So a curious characteristic of CaCO₂ precipitation from water (whether by inorganic precipitation or calcification) is that the inorganic carbon used in the reaction is the HCO in the water, not CO_o in the atmosphere. The calcification process thus actually releases CO₂ from the water back to the atmosphere, rather than removing it from the atmosphere. It will be pointed out below that Eq. 8 does not quite explain the real world quantitatively.

First we wish to point out the reason for the counter intuitive result represented by Eq. 8 (Gattuso et al., 1999a). The long-term (geological time scale; millions of years) $CO₂$ cycle involves release of $CO₂$ from the Earth interior into the atmosphere. This delivery is geochemically significant, but is a small fraction of the fluxes among the Earth Surface System reservoirs. As the volcanic $CO₂$ emissions are introduced into the atmosphere, they induce weathering of volcanically derived silicate minerals also emanating from the Earth interior. The igneous rocks are chemically unstable and react (by chemical weathering) with $CO₂$ and water. Igneous rocks are diverse in chemical composition; but to relate the carbonate and silicate cycles, we use CaSO₃ (wollastonite) as an example of reacting silicate minerals:

$$
CaSO_3 + 2OO_2 + H_2O \t Ca^{2+} + 2HOO_3 + SO_2 \t A9)
$$

This and similar reactions account for both the DIC and the dissolved positive ions (cations) in seawater. The HCO_s — rich water reacts with $Ca²⁺$ according to Eq. 8 to form CaCO₃. So the summed effect of Eqs. 9 and 8 is:

$$
CaSO3 + CO2 \quad CaCO3 + SO2 \qquad \rightarrow \qquad (10)
$$

The chemically igneous silicate minerals are chemically unstable at Earth Surface temperature and pressure. These minerals react with $CO₂$ in the presence of water to form the more stable sedimentary minerals CaCO₂ and SO₂. The atmosphere is the source of $CO₂$ that dissolves in the water during weathering. That dissolved CO₂ hydrates and dissociates (primarily to HCO₂, at oceanic pH: Figure 2) and is the source of the C that enters CaCO₂; the process of forming that CaCO₂ also delivers CO₂ from the oceanic DIC back to the atmosphere. The important points to this analysis, are (a) the demonstration that CaCO precipitation taken alone (Eq. 8) is an atmospheric O , source, not a sink, and (b) the geochemical explanation for this result.

As was the case for primary production (Eq. 5) and respiration (Eq. 6), the back reaction of Eq. 8 occurs (CaCO₃ dissolution), is a sink for atmospheric $CO₃$, and draws CO₂ out of the atmosphere:

$$
CaCO3 + CO2 + H2O
$$

$$
Ca2+ + 2HCO3
$$
 \longrightarrow (11)

However, equation 8 does not quantitatively describe what happens when CaCO_n is precipitated from seawater (Smith, 1985; Ware et al, 1991 and Frankignoulle et al, 1994). Consider seawater with pCO₂ in equilibrium with the overlying atmosphere (equation 1). Precipitating CaCO₂ quantitatively according to equation 8, that is, one mole of gaseous CO₂ release for each mole of CaCO₂ precipitation does not apply to seawater due to its buffering effect. Put simply, some of the $CO₂$ generated by calcification is scavenged by the $CO₃²$ ions according to:

$$
OQ_2 + OQ_3^2 + H_2O \rightarrow 2HOQ_3
$$
 (12)

Removing equimolar amounts of C as CO₂ and CaCO₃ from seawater open to the atmosphere would cause pCO₂ (water) to drop below pCO₂ (air). Yet the physical process that drives the CO₂ gas out of seawater is the pOQ , differential between the water and air; gas moves from the higher-pressure to the lowerpressure reservoir, so gas evasion occurs only if there is a positive gradient from water to air. This constraint places an upper limit on the ratio of $CO₂$ evasion as gas to Cprecipitation in CaCO₂.

At an atmospheric pOQ , of about 350 ppmv, it was

Reef Area and Metabolism **Area**

We use a nominal area of $600,000$ km², as being a round-number intermediate in estimates used for coral reef area studies (Smith, 1978; Kleypas, 1997; Spalding and Grenfell, 1997; Spalding et al., 2001) and recognize that inclusion of other shallow to intermediate depth tropical to high-laƟ tude bej 9 0 0 tabolism **Area**

Coral Reefs

Over the last two hundred years, the concentration of carbon dioxide (OQ_2) in the Earth's atmosphere has increased by more than 30% (IPCC 2007). This increase has been driven by the combustion of fossil fuels, deforestation, destruction of other biological carbon reserves, cement production and other human sources of $CO₂$. The current rate of $CO₂$ increase in the atmosphere is at least an order of magnitude faster than has occurred for millions of years (Doney & Schimel 2007), and the current atmospheric CO concentration is greater than the Earth has experienced in at least 800,000 years (Luthi et al. 2008). These changes have dramatic and longterm consequences for the Earth's climate – both atmospheric and oceanic – and for all life on Earth. Resulting shifts in the distribution and population of species and impacts on human communities from the Equator to the poles have already being observed (Parmesan 2006).

The Oceans and CO₂ Sequestra on

Nearly a third of the anthropogenic $CO₂$ added to the atmosphere has been absorbed by the oceans (Sabine et al. 2004). Currently, the ocean and land absorb similar amounts of \mathcal{O}_{2} from the atmosphere (Bender et al. 2005). However, projections suggest that $CO₂$ absorption by land sinks may decrease during this century (Friedlingstein et al., 2006), while the oceanic absorption of atmospheric CO₂ will continue to grow (Orr et al. 2001). The oceans are therefore critical as the ultimate sink for anthropogenic $CO₂$.

The long term implications of climate change for both terrestrial and marine systems have lead to strong international recognition of the need to stabilize the concentration of atmospheric $CO₂$ and other greenhouse gases. To achieve this, both dramatic decreases in the rate of greenhouse gas emissions and increases in the sequestration of atmospheric $CO₂$ must be rapidly implemented. Ongoing development of artificial and geo-engineering methods of carbon sequestration include techniques for CO_o injection into the deep ocean, geological strata, old coal mines and oil wells, and aquifers along with mineral carbonation of CO₂. These techniques have potential for sequestering vast quantities of CO., However, these techniques are expensive, have leakage risks, significant potential environmental risk and will likely not be available for routine use until 2025 or beyond (Lal 2008). In contrast, preservation and restoration of naturally occurring biological carbon reservoirs represent CO sequestration options that are immediately applicable, cost-effective, have numerous ancillary benefits, and are publicly acceptable. Biological reservoirs of carbon are, however, finite in capacity, making it likely that a combination of biological and artificial mechanisms of carbon sequest ration will be required.

Currently approximately 8.5 x 10¹⁵ g C yr¹ is emitted by fossil fuel combustion and 1.6 x 10¹⁵ g C yr⁻¹ by changes in biological systems resulting from the anthropogenic degradation or destruction of naturally occurring terrestrial biological carbon reservoirs. To are publicy acceptable. Bloogical reservoirs of carbon
are, however, finite in capacity, making it likely that a
combination of biological and artificial mechanisms of
carbon sequestration will be required.
Currently appr

has not been accounted for in assessments of the cost of degradation and loss of coastal marine habitats. This very significant global impact of the coastal habitat loss is demonstrated by calculating the areas of terrestrial forest with equivalent sediment carbon sequestration capacity (see Table 2). For example, the total annual loss of mangroves and seagrasses has the longterm carbon sequestration capacity of a tropical forest area similar to the annual deforestation rate in the Amazon. The total carbon sequestration capacity lost through mangrove and seagrass clearing is equivalent to the sediment sequestration capacity of a tropical forest area greater than the Amazon forest. Since reducing carbon emissions will be a global concern for centuries, longterm carbon sequestration capacity must now also be accounted for in the benefits associated with coastal marine habitat restoration and protection.

Mul ple Bene ts of Coastal Habitat Protec on and Restora on

In addition to providing extensive longterm carbon sequestration benefits, coastal habitats are the source of numerous valuable ecosystem services. Mangroves are extensively used traditionally and commercially worldwide, particularly in developing countries, and have been valued at 200,000-900,000 USD ha-1 (UNEP-WCMC, 2006). Seagrasses provide important ecosystem services including nutrient cycling, enhancement of coral reef fish productivity, and habitat for fish, mammal, bird and invertebrate species. In addition, seagrasses support subsistence and commercial fisheries worth as much as \$3500 ha-1 yr-1 (Waycott et al. 2009). Tidal salt marshes are important for their nutrient cycling and sediment stabilization of near coastal areas.

Corals and kelp habitats are essential components of the coastal environment, providing their own extensive range of ecosystem services (Moberg & Folke 1999, Steneck et al. 2002). These habitats are also critical to the longterm survival of mangroves and seagrasses by

providing habitat and food sources for species common to numerous coastal ecosystems. All coastal habitats are therefore critical either directly or indirectly for the high rates of carbon sequestration in coastal areas.

Increasing emphasis is now also being placed on the role of coastal habitats in climate change adaptation, both for human communities and marine species. Increased coastal protection and stability will be needed in response to sea level rise and the changing storm conditions expected as a result of climate change. Under appropriate conditions, tidal salt marshes, mangroves and coral reefs provide protection from waves, storm events, can reduce shoreline erosion and provide sediment stabilization along many coasts. The food resources provided by coastal marine ecosystems will essential to maintaining human adaptive capacity to changing resource availability.

Protecting and restoring coastal marine ecosystems therefore has significant multiple benefits that are global (longterm carbon sequestration) to local (community ti catal protecti

Next steps for the Management of Coastal Carbon Sinks

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This report provides a strong new evidence base on the role of selected coastal marine habitats as carbon sinks. There is now an urgent need to take the next step - to turn such knowledge into action - by ensuring that such coastal marine sinks are included in National Inventory Submissions.

Those countries who have signed the United Nations Framework Convention on Climate Change (UNFCCC) have to make annual National Inventory Submissions (NIS) which records their Green House Gas (GHG) emissions from energy use, industrial processes, agriculture, land use and waste as well as any sequestration from land use and forestry. These national inventories have to be submitted annually to the UNFCCC and be based on guidance from the Intergovernmental Panel on Climate Change (IPCC). They are used to assess compliance with international treaties to reduce emissions (ie Kyoto, EU) and for any national commitments (ie Climate Change Act for UK). Land Use, Land Use Change & Forestry (LULUCF) is the section in the national inventories that accounts for emissions and sequestration from the management of *terrestrial* carbon sinks. The types of activities covered by LULUCF include afforestation, reforestation & deforestation, changes to soil carbon stocks from land use and land use change, peatland extraction and drainage, liming of soils, etc.

For the LULUCF section of NIS, only GHG emissions and sequestration that occur *as a direct result of human* ac vity can be counted. Any natural sequestration (or emissions) from unmanaged/pristine habitats cannot count towards a countries' GHG commitments. Carbon credits cannot be earned for sequestration from unmanaged habitats. GHG emissions and sequest ration that occur as a result of the management of coastal and marine habitats are currently *not accounted for by LULUCF* and for that reason are *not included in interna onal climate change mechanisms* (ie UNFCCC, Kyoto, CDM, etc) and are *not included, for example, in the UK's carbon budgets.*

To get coastal/marine habitats included in LULUCF would require the IPCC to update their guidance and possibly even need the agreement of the UNFCCC. The IPCC would need to be convinced that there is enough of a robust evidence base to demonstrate that the degradation of coastal and marine habitats due to direct human activity results in GHG emissions. They would also need to be confident that restoration (or creation) of coastal habitats will reduce those emissions and deliver sequestration.

An essential step to including coastal marine sinks in NISs will be to build on the evidence base provided in this report. In particular we need to know that coastal marine habitats are not just important as global carbon sinks but what happens (from a GHG perspective) when any of these habitats are damaged, developed or lost? The logical conclusion is that anthropogenic activities cause the carbon to be lost back to the atmosphere, but do they lose their stored carbon and if so where to? Does it result in other GHG emissions and if so what type and on what scale?

Processes are slightly ahead when considering some of the terrestrial sinks. For example, with peatlands it is known that they are an important carbon store and that they sequester carbon when in a pristine state. There is fairly good evidence that drainage, cultivation and over-grazing/burning results in carbon losses and that restoration stops those losses (although may increase methane) and, possibly, re-starts sequestration. Unfortunately the UK LULUCF inventory does not fully record these carbon losses and so does not recognise the carbon savings delivered by restoration. There is therefore now common cause across existing terrestrial

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