# Climate Regulation: Salt Marshes and Blue Carbon

# 165

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## Contents

## Abstract

Carbon sequestered and stored in, or released from, salt marshes, mangroves, and seagrass ecosystems is often referred to as coastal "blue carbon." The term was first used in 2009 as a means of highlighting the significance of carbon

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sequestration and storage in these highly productive coastal ecosystems, largely to the policy and carbon finance communities.

**Keywords**
Carbon sequestration · Carbon storage · Saltmarshes

## Introduction

Carbon sequestered and stored in, or released from salt marshes, mangroves, and seagrass ecosystems, is often referred to as coastal "blue carbon." The term was first used in a 2009 United Nations Environment Programme (UNEP) report "Blue Carbon" (Nellemann et al. 2009), as a means of highlighting the significance of carbon sequestration and storage in these highly productive coastal ecosystems, largely to the policy and carbon finance communities.

The sustainable management, conservation, and enhancement of sinks and reservoirs of all greenhouse gases (GHG) in natural environments, "including biomass, forests and oceans as well as other terrestrial, coastal and marine ecosystems" (UNFCCC Art. 4.1(d)) has been enshrined into the United Nations Framework Convention on Climate Change (UNFCCC) since its adoption in 1992. Its accompanying Kyoto Protocol also clearly allows for specific accounting of reducing emissions by sources and removals by sinks in specific natural systems – mainly related to terrestrial land-use changes and forestry activities.

Terrestrial forested ecosystems have, therefore, received most attention for their role in the drawdown and sequestration of $CO_2$ and climate change mitigation and for years have featured prominently in UNFCCC processes. In contrast, coastal carbon ecosystems have been, until recently, largely ignored in international and national carbon accounting.

It was not until the development of, and growing international interest in, the Reducing Emissions from Deforestation and Forest Degradation Plus (REDD+) program as a financing scheme for forest restoration, conservation, and overall management that the marine community started looking into the "important missing sinks" (Pidgeon 2009) in the climate mitigation debate.

While scientific research has been conducted on carbon dynamics in coastal ecosystems for some time, it was not until 2009 with the publication of IUCN's report *The Management of Natural Coastal Carbon Sinks* (Laffoley and Grimsditch 2009) and the UNEP report *Blue Carbon* (Nellemann et al. 2009) that this topic received greater attention. Since then there has been an increase in scientific research as well as improved development of management and policy responses for coastal "blue carbon" ecosystems (Herr et al. 2012; Sutton-Grier and Moore 2016).

Coastal blue carbon ecosystems are among the most productive in the world (Mitsch and Gosselink 2000; McLeod et al. 2011). The average global carbon burial rates are an order of magnitude greater than those of upland forests (Fig. 1); thus $CO_2$ drawdown and carbon storage potential in blue carbon ecosystems is extraordinary.

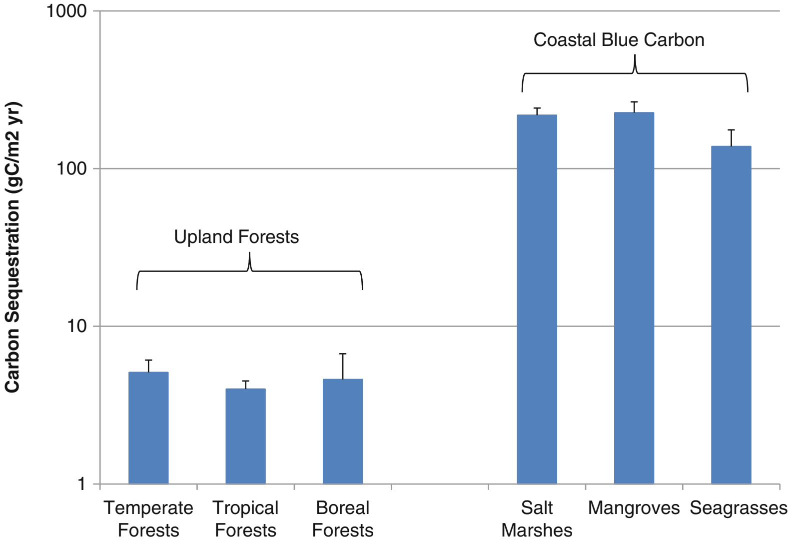

**Fig. 1** Average global carbon burial rates (error bar equal to one standard deviation) for upland forests and coastal blue carbon ecosystems (Modified after McLeod et al. 2011)

In addition to carbon storage, salt marshes provide a variety of other benefits – ecosystem services – to humans. They provide nutrients and habitat for many estuarine and marine organisms, buffer against storm surges reduce coastal erosion, and filter out nutrients and pollutants. These ecosystem services are important for improving local livelihoods, tourism and culture, as well as for climate change mitigation and adaptation.

In this article, we present a broad overview of the general science behind carbon accounting in blue carbon ecosystems, with a focus on salt marshes, and refer the reader to the appropriate references for making these measurements. We also include an update on the current policies and programs in place designed to utilize blue carbon ecosystems for climate mitigation. It is important to keep in mind that the nature of these fields (blue carbon science and policy) is evolving rapidly at the writing of this article. The reader is encouraged to use the information presented here as a starting point for exploring blue carbon as an opportunity for coastal management efforts.

## Salt Marshes and Climate Change Mitigation

Salt marshes and coastal blue carbon ecosystems mitigate climate change by reducing GHG concentrations in the atmosphere. To include coastal blue carbon ecosystems in a carbon accounting scheme, it is necessary to track the GHG fluxes in to

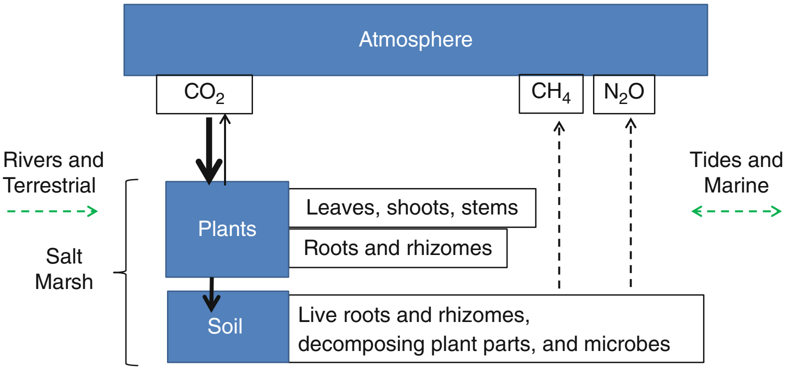

**Fig. 2** Concept map of carbon reservoirs and GHG fluxes in a salt marsh. *Boxes* = reservoirs of organic matter (box size is not proportional to reservoir size); *arrows* = fluxes of organic matter and/or GHG. *Black solid arrows* = dominant fluxes of carbon (photosynthesis, respiration, and burial); *black dashed arrows* = variable, and usually minor, fluxes of GHG; *green dashed arrows* = variable, and often unknown, inputs of organic matter from terrestrial and marine biomes

(and out of) the area in question, as well as the amount of carbon that is stored within its reservoirs. A step-by-step manual for making carbon stock and GHG flux measurements in coastal blue carbon ecosystems has been developed by the Blue Carbon Initiative and can be accessed online (Howard et al. 2014).

Figure 2 provides a simple concept map illustrating the major carbon reservoirs and GHG fluxes in salt marshes. These are further described below.

## Carbon Reservoirs

The major carbon reservoirs in a salt marsh are in soils and plants. Soils are composed of a combination of living below ground biomass, decomposing organic matter, and inorganic sediments and represent the largest reservoir of stored carbon (Murray et al. 2011). Salt marsh vegetation is primarily composed of a mix of herbaceous plants (grasses, sedges, rushes, forbs) and succulent and sometimes woody chenopods.

Very simply, $CO_2$ in the atmosphere is converted into organic matter via photosynthesis by plants. Some of the organic matter is used to synthesize leaves and shoots; most is transported to and stored within the roots and rhizomes (Elsey-Quirk et al. 2011; Pickoff 2013). Because salt marshes are inundated regularly by the tides, the underlying sediments are saturated and largely anoxic, and the organic matter stored within decomposes relatively slowly. Thus, the bulk of the organic matter in salt marsh (and all blue carbon) ecosystems is stored in the soils (Fig. 3).

The global average carbon storage in the top meter of salt marsh soils is approximately 255 Mg C $ha^{-1}$ (with a range of 16–623 Mg C $ha^{-1}$) (IPCC 2013). But many salt marshes have carbon stored to depths of as much as 6 m below the surface, making the above estimates conservative. North American tidal marshes, for

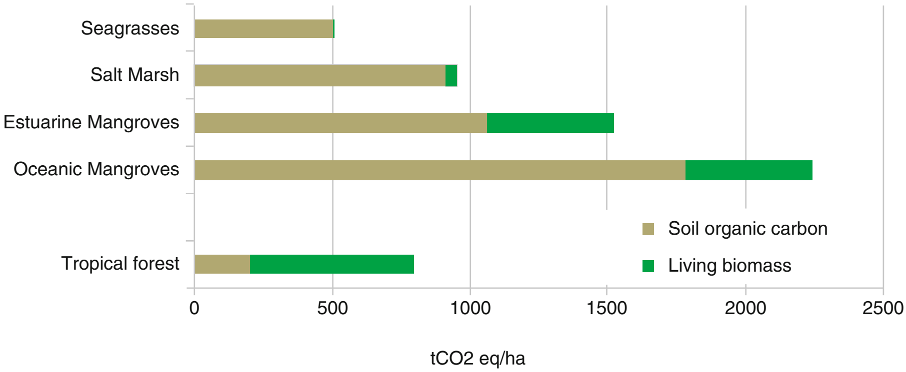

**Fig. 3** Average tons of $CO_2$ equivalents per hectare stored in the above ground/living biomass and the upper meter of soil organic carbon for coastal blue carbon ecosystems and tropical rainforests (From Murray et al. 2011; https://nicholasinstitute.duke.edu/environment/publications/naturalresources/blue-carbon-report)

**Fig. 4** North American tidal saltmarshes, such as this marsh in Phippsburg, Maine, store large amounts of carbon and many times more than forests. (Photo credit: Phyllis Graber Jensen © copyright remains with the author)

example, have been found to store up to 1700 Mg C ha−1, well above the global average (Fig. 4) in sediments up to 4000 years old.

Soil carbon in salt marshes is primarily autochthonous (i.e., generated in situ). Minor amounts of allochthonous organic matter (derived from terrestrial or marine sources) can also be incorporated into the soil carbon pool. It is possible to use stable isotopes and/or lipid biomarker analyses to identify the source of organic matter within the sediments (Chmura and Aharon 1995; Johnson et al. 2007). Distinguishing between autochthonous and allochthonous sedimentary carbon may be important, depending on the project.

Salt marshes have been subject to modification and conversion by humans for centuries to millennia (Adam 2002; Bromberg Gedan et al. 2009), with an estimated net loss of 35–50% (Murray et al. 2011). Recent global estimates of annual losses of salt marsh ecosystems ranges between 1 and 2% (Duarte et al. 2008). Marshes have been/are (1) used for grazing and haymaking; (2) converted to agricultural, aquacultural, and urban landscapes; and (3) altered for insect control *inter alia*. Salt marshes are currently vulnerable to sea level rise and coastal storms, sediment starvation, coastal squeeze, excess nutrients, invasive species, runaway consumer effects, and ill-informed management decisions (Bromberg Gedan et al. 2009; Kirwan and Megonigal 2013). The degree to which carbon dynamics are impacted by these and other types of alterations is a topic of study by many (e.g., Vincent et al. 2013; Macreadie et al. 2013; Gunn 2016; Martin and Moseman-Valtierra 2017; Kroeger et al. 2017).

## Greenhouse Gases

The three major GHG emitted from salt marshes include $CO_2$, methane ($CH_4$) and nitrous oxide ($N_2O$) (Mitsch and Gooselink 2000; Moseman-Valtierra 2013). Because $CH_4$ and $N_2O$ have global warming potentials that are 45 and 310 times greater than $CO_2$ over 100 years, respectively, it is necessary to consider the release of these gases for climate mitigation. Release of GHGs can be significant in marshes that experience reduced soil water salinities, changes in soil oxygen availability, and increases in anthropogenic nutrient loading (Moseman-Valtierra 2013; Adams et al. 2012; Emery and Fulweiler 2014).

## Carbon Dioxide ($CO_2$)

$CO_2$ is drawn out of the atmosphere via photosynthesis and released via respiration. Though there is some uncertainty in flux measurements due to a lack of data and variability among ecosystems, approximately 20% of the carbon fixed during photosynthesis is thought to be respired as $CO_2$, 70% exported into the surrounding estuary as organic carbon or inorganic carbon, and 10% buried in the soils (Bauer et al. 2013). Recent estimates of global carbon accumulation rates in salt marsh sediments have continued to increase as more and more data are generated and synthesized. Estimates of 150, 218 and 244.7 g C $m^{-2}$ $yr.^{-1}$ have been published in Duarte et al. (2005), McLeod et al. (2011), and Ouyang et al. (2014), respectively (Kroeger et al. 2017).

Drainage of wetlands, and lowering of the water table, results in a rapid emission of $CO_2$ through oxidation (Crooks et al. 2011; Lovelock et al. 2011; Pendleton et al. 2012). Restoring the hydrology to a drained wetland that is emitting $CO_2$, $CH_4$, or $N_2O$ can reduce emissions effectively (Kroeger et al. 2017).

### Methane ($CH_4$)

Highly variable in wetland systems, methane emissions are generally lower where water sulfate concentrations are high, because methanogens are outcompeted by sulfate-reducing bacteria (Bartlett et al. 1985). Using salinity as a proxy for sulfate concentrations (where both parameters are high in marine waters), Poffenbarger et al. (2011) have determined that methane emissions are minimal in tidal wetlands with salinity greater than 18 PSU (practical salinity unit).

Tidal restrictions and subsequent reduction of soil salinities below 18 PSU can result in $CH_4$ emissions (Gunn 2016). Restoring tidal flow to increase salinity may provide a reduction in methane emissions (Kroeger et al. 2017). Restoring a site below the salinity threshold could result in new methane emissions, and these should be quantified and weighed against the greenhouse gas benefits to accurately predict the overall climate mitigation benefits of such projects.

### Nitrous Oxide ($N_2O$)

$N_2O$ is a naturally occurring gas in wetland soils, with concentrations increased by anthropogenic nitrogen pollution. Creating or restoring a wetland where none exists may result in an increase in $N_2O$ emissions (Adams et al. 2012). Additionally, anthropogenic loading of nitrate can promote $N_2O$ emissions from salt marshes (Moseman-Valtierra 2013).

## Climate Finance and Policies for Better Management

Policies and finance mechanisms are now being developed and implemented for climate change mitigation. They present the possibility to mobilize additional funds and revenue schemes to combine best practices in coastal management with climate change mitigation goals and needs (Herr et al. 2012; Herr et al. 2015).

Conserving and restoring salt marshes can become a management activity as part of the other land-use activities aimed at reducing carbon emissions and enhancing carbon sequestration in natural systems. Such activities are also known as nature-based solutions to climate change mitigation. Projects and activities incentivizing such management responses are most advanced for terrestrial tropical forests policies and programs, such as the REDD+ program developed under the UNFCCC (Pendleton et al. 2012).

Salt marshes can also be part of Nationally Appropriate Mitigation Actions (NAMAs). Some technical elements need to be fully integrated into the implementation of such mechanisms. For example, in order to put a value on their full coastal carbon potential soil carbon needs to be accounted for, not the least because salt marshes do not have much plant biomass (in comparison to tropical forest) for which to account.

“Wetland drainage and rewetting” has been accepted as a new management effort that may (but not must) be included in national accounting of GHG from the Land-Use, Land-Use Change and Forestry (LULUCF) sector by developed countries under the Kyoto Protocol, as part of the UNFCCC. For example, emissions arising from the drainage of tidal marshes would be a qualified activity, so would subsidence reversal by gradually raising water levels and building soil surfaces to intertidal elevation.

On an implementation level, saltmarshes can be included in national GHG accounting and national reporting from all countries to the UNFCCC, now that the IPCC 2013 Supplement to the 2006 Guidelines for National Greenhouse Gas Inventories: Wetlands (Wetlands Supplement) has been issued (IPCC 2013).

Carbon markets are one of many options to incentivize and finance better management of coastal carbon ecosystems, alongside other types of climate finance and more “traditional” conservation approaches (Herr et al. 2015). While the regulated markets (including the Clean Development Mechanisms as part of the Kyoto Protocol) have limited scope or are not trading at all in land-use related credits, the voluntary carbon market has seen an increase in available carbon offset methodologies (Emmer and von Unger 2014; Herr et al. 2015). These are needed to develop, account for, and credit GHG removals or emissions. The Verified Carbon Standard (see: http://www.v-c-s.org) has one Methodology for Coastal Wetland Creation (VM0024) (limited to the Coastal United States) and one Methodology for Tidal Wetland and Seagrass Restoration (VM0033). It outlines procedures to quantify GHG emission reductions resulting from tidal wetland restoration projects. Such projects include creating or managing the conditions required for healthy, sustainable wetland ecosystems.

The American Carbon Registry issued a methodology on Restoration of Degraded Deltaic Wetlands of the Mississippi Delta (see: http://americancarbonregistry.org/carbon-accounting/standards-methodologies/restoration-of-degraded-deltaic-wetlands-of-the-mississippi-delta) that details requirements for GHG emission reduction accounting from wetland restoration activities implemented on degraded wetlands of the Delta. The methodology quantifies increased carbon sequestration in above ground biomass, below ground biomass, and soil organic carbon over and above the baseline scenario. A methodology on California Deltaic and Coastal Wetland Restoration is currently in development.

The new Paris Agreement to the UNFCCC, a result from its 2015 Conference of the Parties (COP 21), sets the framework of how to deal with GHG emissions mitigation, adaptation, and finance starting in the year 2020. It makes several references to all sinks and reservoirs/ emissions by sources and removals by sinks of GHG, also quoting Art 4.1(d) of the Convention itself, which specifically lists the conservation of coastal and marine ecosystems. This provides the right signals to increase post-2020 climate activities and continue the work being undertaken to implement various mitigation-related efforts in coastal areas – national GHG accounting, REDD+, NAMAs, and the voluntary carbon market.

The cost of conserving saltmarshes as a means to reduce GHG emissions relative to other emissions reduction approaches (such as energy efficiency or alternative energy generation) is less clear. As nations struggle to reduce GHG emissions, it has become apparent that targets and commitments cannot be met through increased regulation of any single source of GHGs. Avoided emissions through salt marsh and other coastal and marine ecosystem conservation is likely one of the many options that should be included in a portfolio of cost-effective mechanisms for GHG reductions. An expansion of the implementation of programs and projects, using the above mentioned mechanisms and means, all around the world is still needed to stop the ongoing loss of these systems and the resulting emissions.

## Carbon Management Responses

In order to determine net climate mitigation benefits of a salt marsh restoration or conservation project, the changes in GHG reductions and emissions as a result of the project activities have to be calculated against the GHG reductions and emissions which would have occurred in the absence of the project (called the “baseline”) (Emmett-Mattox and Crooks 2014).

### Conservation of Intact Wetlands

Large emissions of $CO_2$ emissions can be prevented if intact salt marshes are not drained or changed to other land-uses such as agriculture or aquaculture. Although large-scale conversions are being regulated and limited in the USA, European Union, and Australia, wetland conversions with high impacts are still very common globally. Projects conserving carbon stocks within at-risk wetlands through regulation and/or land owner agreements are eligible for carbon credits and national carbon accounting.

### Rewetting of Drained Organic Soils

$CO_2$ is continuously emitted from organic soils that have been drained until either the water table rises to near the surface of the soil or the stock of carbon is depleted. Management of water tables to reduce $CO_2$ from drained organic soils is an eligible climate change mitigation activity.

## Restoration and Creation of Vegetated Wetlands

Restoration and creation activities such as lowering of water levels on impounded former wetlands, removing tidal barriers, raising soil surfaces with dredged material, or restoring salinity conditions restore or create new habitats. Activities that restore the combination of native plants, hydrology, and sediment will lead to a self-sustaining productive wetland, creating net GHG benefits. The success of mitigation projects also depends on site-specific examinations of habitat restoration and management potentials, as the response from salt marshes differ on a regional and watershed level.

## Future Challenges: Filling Knowledge Gaps

The global extent of coastal marsh and rates of loss are currently associated with relatively large uncertainties, and further work is needed in this area. Additional mapping of converted and degraded salt marshes and the quantification of emissions from exposed organic soils is needed to enable inclusion in relevant databases (e.g., the IPCC Emission Factor Database).

Emission rates associated with specific human activities over time for a range of drivers of ecosystem degradation or loss (e.g., drainage, burning, harvesting, or clearing of vegetation at different intensity levels) are also limited at the moment.

A significant amount of the eroded coastal carbon is thought to be dissolved in the ocean water where it enters the ocean-atmosphere system, and the remaining eroded carbon is deposited in offshore sediments and sequestered. The fate of carbon eroded from salt marshes and carried offshore by ocean waves and currents is an ongoing topic of scientific research.

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