NICHOLAS INSTITUTE REPORT

State of the Science on Coastal Blue Carbon

A Summary for Policy Makers

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Executive Summary

Coastal habitats store large amounts of carbon in their living vegetation and soils. When these habitats are converted to other uses, this stored carbon—increasingly known as coastal blue carbon—can be released in the form of greenhouse gases. For this reason, carbon storage should be considered in habitat management decisions. One tool for preserving this critical ecosystem service is payments to landowners and managers for coastal blue carbon—if protocols that allow these carbon stores to be traded on carbon markets can be developed.

The natural science of blue carbon is evolving rapidly, and many policy makers remain uncertain about the biophysical potential of these habitats as engines of carbon storage. To better manage the ecosystem services provided by coastal blue carbon, we need a good scientific understanding of

- how coastal habitats sequester and store carbon,
- where on the planet carbon is stored in these habitats,
- how rapidly the habitats are being modified with a risk of carbon release into the atmosphere or water column, and
- the mechanisms and rate of carbon emissions that follow habitat conversion.

This report examines the current science as it relates to these topics. In doing so, it aims to give policy makers a feel for what is known and unknown about coastal blue carbon. Because of the high intensity of work in this field and variations in research methodologies, additional findings may be available in the near future.

Briefly, what scientists know now is that blue carbon sequestration and storage involves three components. The first is the annual sequestration rate, which in a mature system is the yearly flux of organic material transferred into anaerobic soils, where it cannot undergo oxidation to carbon dioxide (CO_2) and be released to the atmosphere. The second component is the amount of carbon stored in biomass, both above- and belowground. The third and largest component is the total carbon stock stored in soils as a result of prior sequestration. The total carbon stock integrates the complete column of organic soil lying beneath coastal habitats. This stock is a function of the soil carbon density and the depth of the rich, organic soils beneath these ecosystems. Scientists know more about the former than the latter. Generally, total carbon storage estimates are available for at least the first meter of soil—the depth at which carbon is most susceptible to release.

Annual Carbon Sequestration Rates

- **Annual carbon sequestration rates have been calculated for 39 mangrove sites.** Values range from 0.126 to 23.98 megagrams[1] of carbon dioxide equivalent per hectare per year (Mg CO_2e/ha/yr). Most estimates fall below 7 Mg CO_2e/ha/yr.
- **Annual carbon sequestration data are available for 122 coastal marshes.** Values range from 0.01 to 62.81 Mg CO_2e/ha/yr. Most estimates fall below 8 Mg CO_2e/ha/yr.
- **Annual carbon sequestration data are available for 377 seagrass sites.** Values range from -77 to 85 Mg CO_2e/ha/yr. Most estimates fall below 7 Mg CO_2e/ha/yr. A large number of estimates show annual net losses of carbon.

Carbon Stored in Biomass

- **Biomass carbon content data are available for 32 mangrove sites.** Values range from 25 to 2,254 Mg CO_2e/ha. Most estimates fall between 300 and 1,000 Mg CO_2e/ha.
- **Biomass carbon content data are available for 6 salt marsh sites.** Values range from 5.1 to 18.3 Mg CO_2e/ha.
- **Biomass carbon content data are available for 160 seagrass sites.** Values range from 0 to 13 Mg CO_2e/ha.

Soil Carbon Stocks

- **Estimates of the soil carbon stock of the first meter of mangrove soils are available for 62 sites.** Values range from 570 to 4,712 Mg CO_2e/ha. Most estimates fall between 800 and 3,000 Mg CO_2e/ha.
- **Estimates of the soil carbon stock of the first meter of salt marsh soils are available for 126 coastal marshes.**

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[1] One megagram (Mg) = 1 tonne = 1 metric ton = 1,000 kg.

Values range from 174 to 6,967 Mg CO_2e/ha. Most estimates fall between 900 and 1,700 Mg CO_2e/ha.

- **Estimates of the total soil carbon stock of the first meter of seagrass soils are available for only 10 sites, all in the Mediterranean.** Values range from 880 to more than 6,000 Mg CO_2e/ha.

Geographic Representation

Scientific information about blue carbon habitats is not representative of these habitats worldwide. Understanding of the areal extent of blue carbon habitats and their rate of loss is also not uniform across the globe. In general, habitat extent in the developed world is well known, and habitat extent in Asia is less known. Comparatively little is known about the extent and rates of loss of African coastal habitats.

Mangroves. Understanding of carbon sequestration and storage is geographically uneven. In the United States, most studies are of Florida. Globally, most studies are of Asia and Oceania. The United Nations Food and Agricultural Organization (FAO) amasses mangrove habitat data from around the world. Those data suggest that mangrove habitat loss is highest in absolute terms in Asia, followed by the Americas and Africa.

Salt marshes. Scientific knowledge of carbon sequestration and storage is greatest for eastern North America. Little information is available for the rest of the world. Most is known about the areal extent of salt marsh in North America and Europe, but relatively little is known about the extent of coastal marsh in the rest of the world and very little about rates of salt marsh loss anywhere.

Seagrasses. Understanding of carbon sequestration and biomass storage is greatest for European and North American sites. Little is known about soil carbon associated with seagrasses. Relatively little is known about the extent of seagrass habitat worldwide and even less is known about the loss of that habitat.

Emissions after Conversion

Scientists have amassed little empirical data on the emission of gaseous CO_2 from blue carbon habitats following habitat conversion. Only estimates of actual carbon emissions due to salt marsh conversion are available. To date, all estimates of potential carbon emissions have been estimates bounded by the potential carbon content of soils and biomasses.

1. Some Basics of Blue Carbon Science

Annual carbon sequestration

The annual sequestration rate is the quantity of CO_2 removed from the atmosphere and trapped in natural habitats on an annual basis. By trapping carbon in living tissue, biomass, and soils, these habitats remove carbon from the atmosphere. They can produce greenhouse gases through respiration and through the production of methane in soils (but methane production tends to be low or nonexistent in most marine habitats). They may also export carbon if detritus is removed (e.g., leaves are blown or washed away) or may trap carbon if detritus is captured and incorporated into soils.

Carbon stored in soils

The largest store of carbon in coastal habitats is within soils. To understand the total amount of carbon stored in these soils, scientists must know the carbon density of the soil and the depth of the organic-rich soil layer. The value of the former is typically presented in gC/cm^3. Sometimes soil organic carbon is expressed as a percentage of the total soil present. This value can be converted if the bulk density of the soil (g $soil/cm^3$) is known. The depth of the organic-rich soil layer of coastal habitats varies. In some cases, it can be several meters deep, the result of hundreds to thousands of years of growth and accumulation. In this review, we provide data where available on carbon density, soil depth, and when possible, estimates of the total carbon stored in the top meter of a typical hectare of soils.

Carbon stored in biomass

Carbon is stored in aboveground and belowground biomass. Aboveground biomass includes leaves, flowers, stems, branches, and (in the case of mangroves) trunks. Belowground biomass consists mainly of roots and associated flora and fauna. Carbon in biomass is calculated in various ways, as described below.

Areal extent of habitat and habitat conversion

The location, areal extent, and conversion locales and rates of coastal habitats is knowledge critical to identification of opportunities to prevent the emission of trapped carbon from these habitats into the atmosphere. To the extent possible, we document what scientists know about the areal extent of coastal blue-carbon habitats and rates of habitat conversion (often referred to as loss).

Carbon emissions from habitat conversion

Ultimately, the “blue carbon” aspect of coastal habitat hinges on the assumption that large amounts of carbon would be released into the atmosphere if these habitats are disturbed or converted to other uses. Carbon trapped in salt marsh and mangrove habitats is thought to be released directly into the atmosphere through a process of oxidation whereby soil carbon is turned directly into CO_2 when exposed to oxygen. When blue carbon remains under water, the process by which carbon is emitted is less clear. It may be that carbon is mineralized or oxidized in the water column when living biomass dies or when carbon in previously anaerobic soils is exposed to aerobic water. Carbon emitted into the water column could then be released into the atmosphere. Empirical studies that attempt to directly measure the release of carbon into the atmosphere following conversion of blue carbon habitats do not appear to exist.

2. Mangroves

Mangroves are a type of wetland forest with anaerobic sediments. Because the presence of water diminishes oxygen availability, the organic carbon stored in mangrove soils doesn’t decompose to atmospheric CO_2. Once these organic-rich soils are exposed to air, decomposition and production of CO_2 begins. Each gram of organic carbon, stored either as biomass or soil, represents 3.67 CO_2 equivalents.[2] Many mangrove forests have thousands of years’ worth of carbon sequestered beneath them [1]. The depth of these carbon-rich soils varies according to the local geomorphology. For example, mangroves in estuaries tend to have greater depths of organic soils than oceanic mangroves, which have a hard sandy or rocky substrate [2].

Annual sequestration rates of mangrove forests

Two major reviews of carbon sequestration in mangrove habitats have been published. The first, Cebrian (2002) [3], presents data from 8 published studies at 10 sites. It calculates the annual accumulation of carbon or sequestration rate

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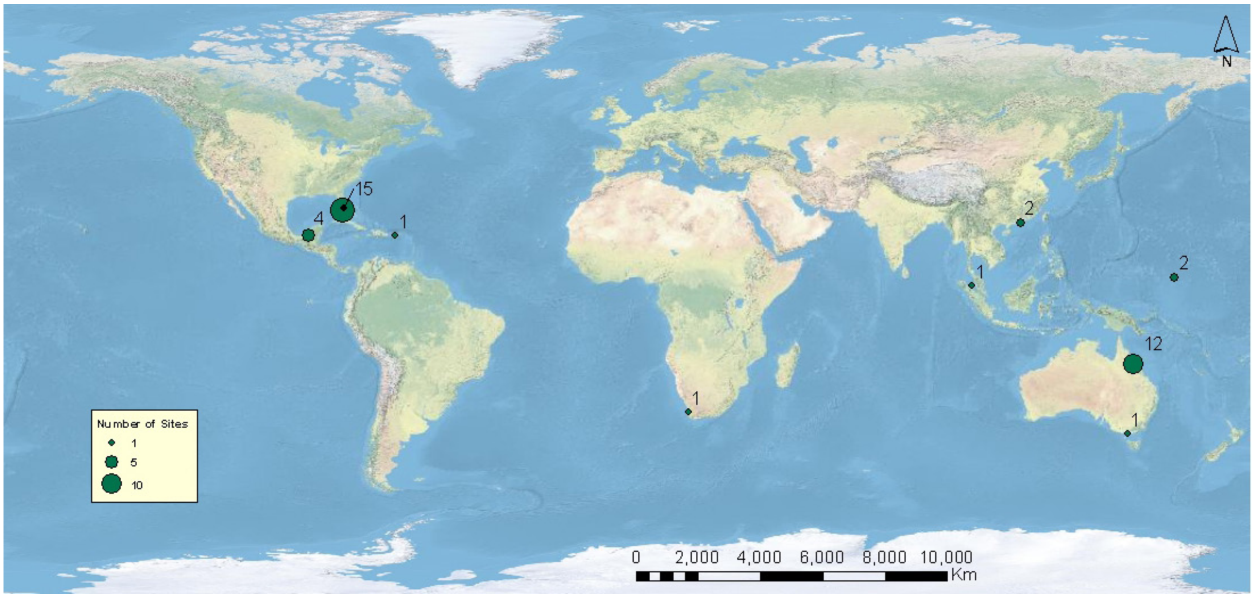
[2] The atomic mass of carbon is 12g/mol. The atomic mass of CO_2 is 44g/mol. Every 12g of organic carbon is equal to 44g of CO_2 equivalents.

using available measurements of community production and respiration. The second important review, by Chmura and colleagues [4], presents data from 5 published studies as well as some unpublished data at 27 sites. It examines organic carbon density within salt marsh and mangrove soils. Combining these density values with annual sediment accretion rates, Chmura and colleagues [4] calculate annual carbon sequestration rates.

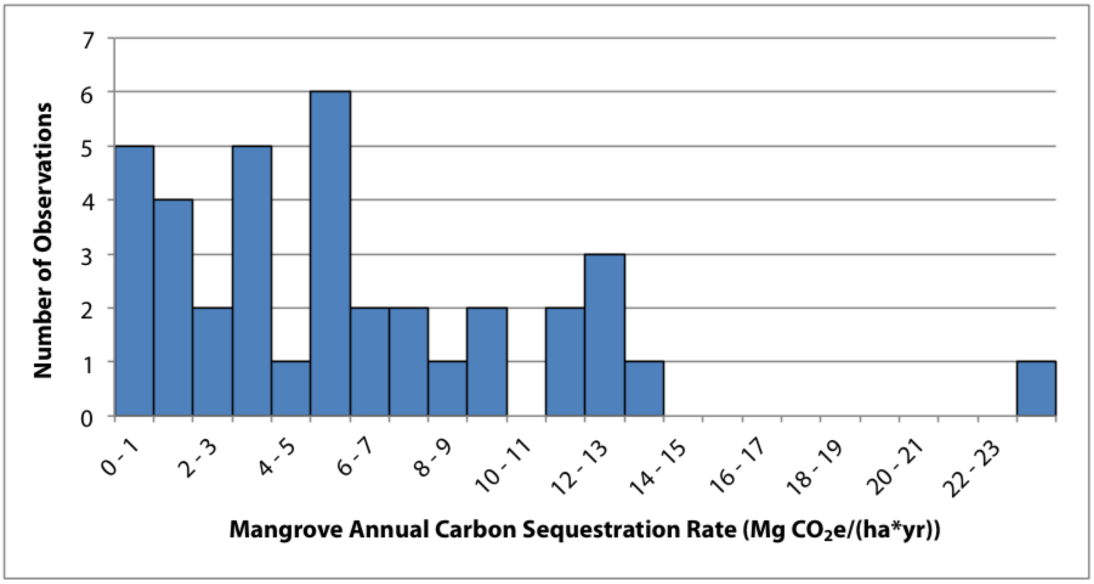
This report includes one additional study, by Fujimoto and colleagues [5], that was not included in either of these reviews. Although additional reviews of carbon sequestration in mangrove habitats exist [6-11], they report only summarized data, not individual measurements. Figure 1 displays the geographic representation of the available data. Table A-1 in Appendix A provides a comprehensive summary of the data by geographic location.

Figure 1. Location of data on the annual carbon sequestration rate for mangrove forests.



The range of estimates for carbon sequestration at 39 sites is 0.126 to 23.98 Mg CO_2e/ha/yr (1 Mg CO_2e/ha/yr = 1 megagram of CO_2 equivalents per hectare per year). Figure 2 displays the distribution of the rounded annual sequestration rates. The variability it shows may partly be a function of the two methodologies used. The mean of the values from Cebrian (2002) is 2.87 ($n = 9$), and the mean of the values from Chmura is 6.96 ($n = 28$), with a $p < 0.05$, a two-sample t-test assuming unequal variances. The difference between the means is still significant at the $p < 0.05$ level, even when the large outlier value of 23.98 is removed from the calculations. How geography, geology, and methodology influence the estimates of sequestration is unclear.

Figure 2. Number of observations for sequestration rates available in the scientific literature.



Soil carbon stocks of mangrove forests

As Figure 3 shows, the organic-rich soils underlying mangrove forests can range in depth from less than a meter [2, 12] to over 10 meters [1]. This report presents 30 observations from four published studies [1, 2, 5, 12]; 25 of the observations are derived from Donato and colleagues [2].

Figure 3. Number of observations for depth data for the organic soil layer beneath mangroves.

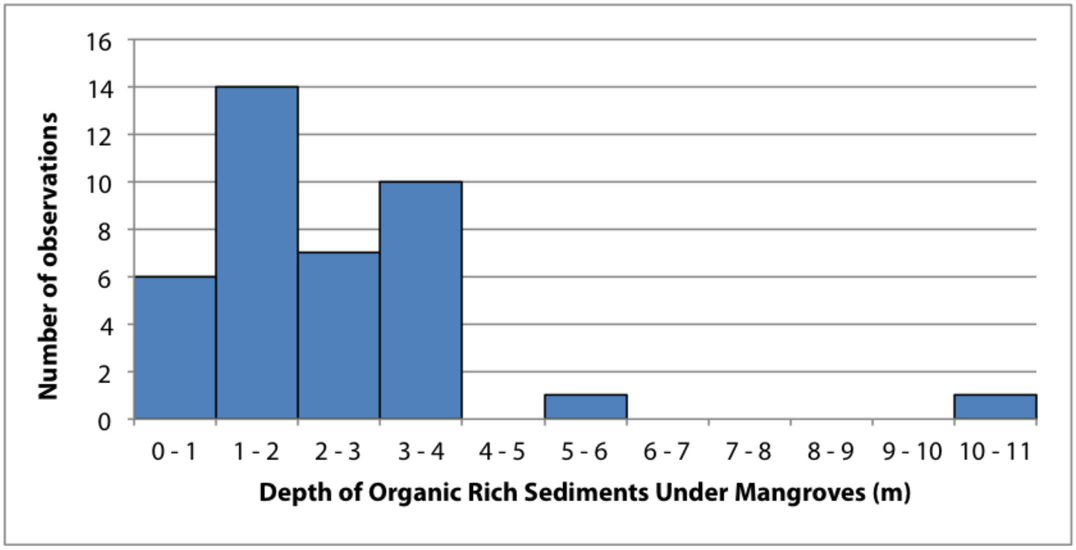
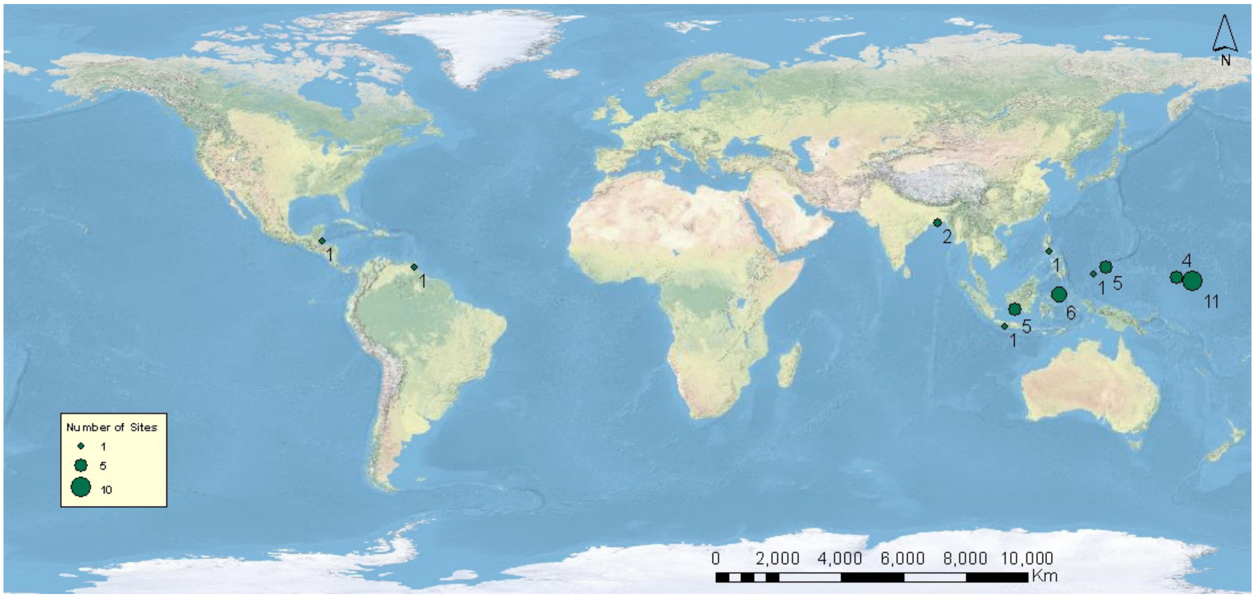


Figure 4 presents the geographic representation of the available data on the depth of organic soils beneath mangrove forests.

Figure 4. Location of available mangrove soil depth data.



In assessing estimates of the soil carbon stocks of mangrove forests, there are two key papers to consider. The first is the review by Chmura and colleagues [4], which presents the carbon density of soils. Its data are derived from six published studies and one unpublished source, and it covers 33 locations. The other major article of interest is Donato and colleagues [2], which examines the carbon content of the soil column of 25 mangrove sites in the Indo-Pacific. The Donato paper [2] reports % organic carbon and bulk density data (g/cm^3). We use simple multiplication to calculate the carbon density for each of the 25 sites and include data from Fujimoto and colleagues [5] and Vegas-Vilarrubia and colleagues [12], which are not included by Chmura and colleagues [4]. The Fujimoto paper [5] reports organic carbon (gC/kg) and bulk density (kg/m^3) at multiple depth intervals; we use these values to calculate a weighted average of carbon density for the entire soil column. Vegas-Vilarrubia and colleagues [12] present organic carbon (g/kg) and bulk density (g/cm^3), which we use to calculate carbon density. Other reports contain summaries of review data [13]. However, they were not included here as they presented no new data.

The soil carbon density data, available from 62 sites, ranges from 0.015 to 0.115 gC/cm^3. Figure 5 presents the geographic representation of the data. Figure 6 shows the distribution of the available mangrove soil carbon density data. Carbon stocks for the first meter of soil depth were calculated from the available carbon density data using the following conversion:

$$\frac{gC}{cm^3} * \frac{10^6 cm^3}{1m^3} * \frac{10^4 m^2}{1ha} * \frac{44gCO_2e}{12gC} * \frac{1Mg}{10^6 g} = \frac{MgCo_2e}{ha*m}$$

Most mangrove habitats have at least one meter of carbon-rich soil; this top meter is at risk if mangroves are converted. On the basis of data from the literature, we find that estimates of carbon stocks in the first meter of mangrove soils range from 570 to 4,217 Mg CO$_2$e/ha. Figure 7 presents the distribution of these estimates. Table A-2 in Appendix A presents a geographic summary of these data.

Figure 5. Location of data availability on carbon density in soils beneath mangrove forests.

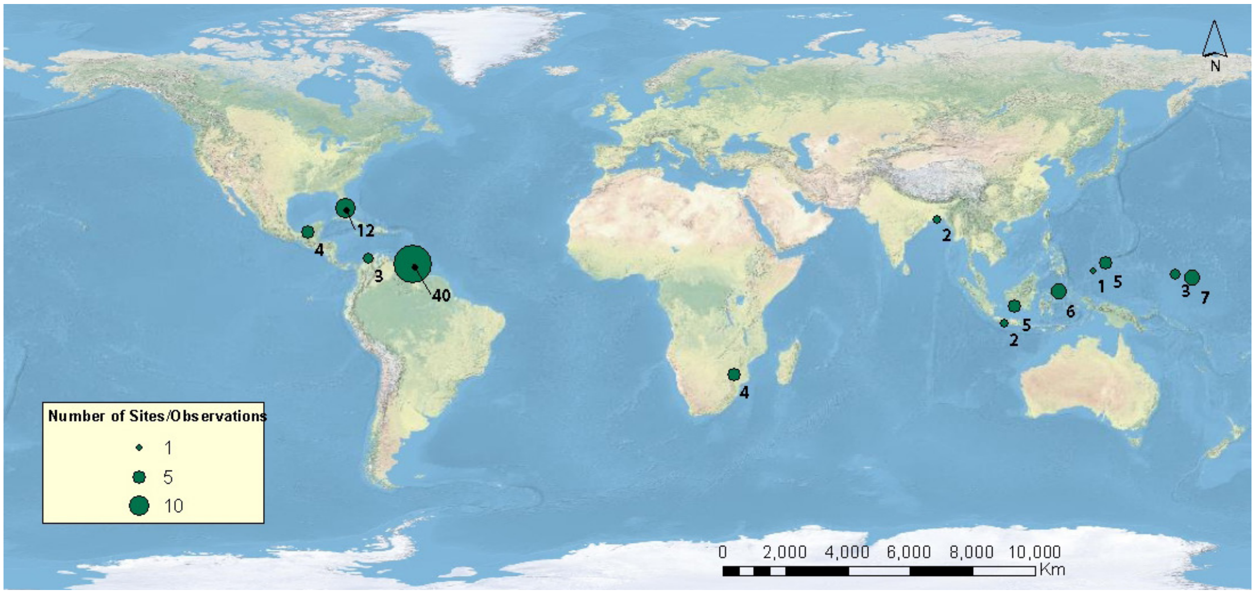


Figure 6. Number of observations for mangrove soil carbon density data.

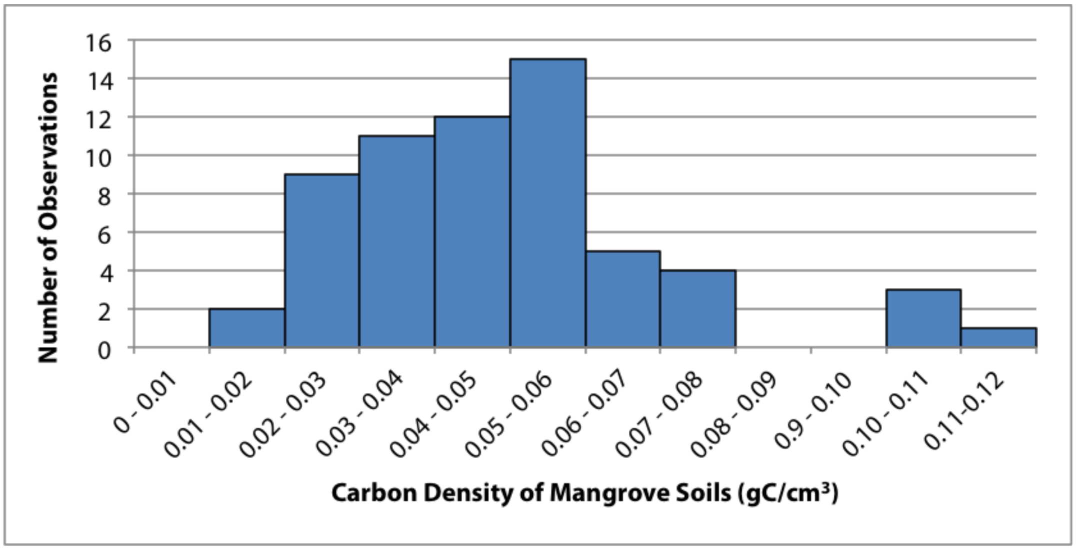
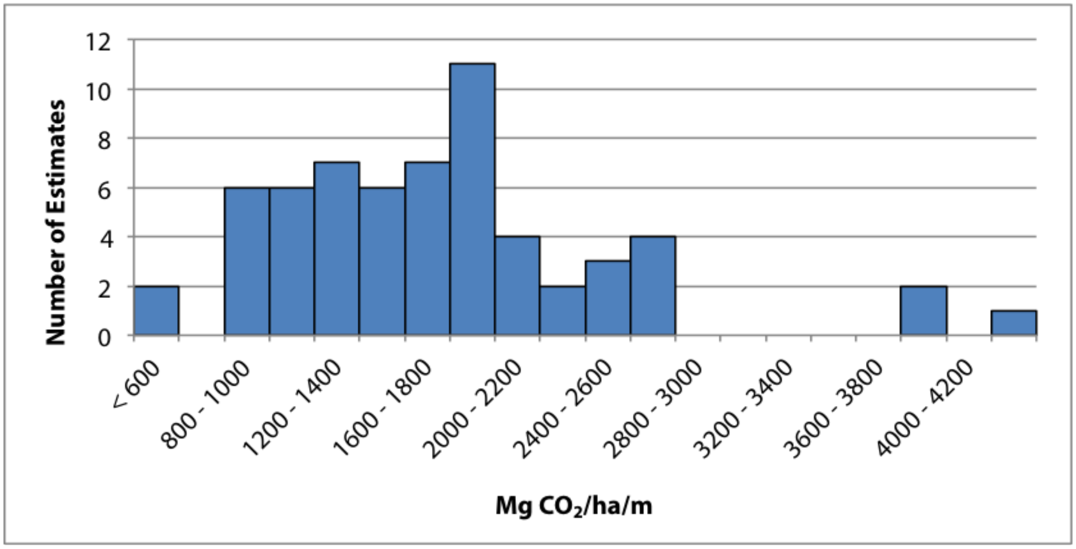


Figure 7. Number of estimates of carbon contained in the top meter of soil beneath mangrove forests.



Carbon content of mangrove biomass

Carbon is stored in the woody biomass of mangrove forests and is typically reported on a dry weight basis. Total biomass estimates can be converted to the carbon content of biomass by using a factor of 45% per dry mass [10]. Two significant papers present empirical data. The most recent is by Donato and colleagues [2] and provides data from 25 mangrove sites throughout the Indo-Pacific. The other is a review by Twilley [10] that provides data from seven published sources on nine sites. Other review papers exist [11, 14] but do not present original data on the topic and are therefore not included here.

A total of 34 observations for the carbon content of mangrove biomass are identified. They range from 26 to 2,554 Mg CO_2e/ha. Figure 8 presents the distribution of the available data for the carbon content of mangrove biomass. Figure 9 presents the geographic representation of these data. The high variability in the numbers is due to the high variability among mangrove species. The FAO recognizes 71 distinct species as true mangroves [15]. These species can range from the size of a small bush to that of a large tree.

Figure 8. Number of observations for data on the carbon content of mangrove biomass.

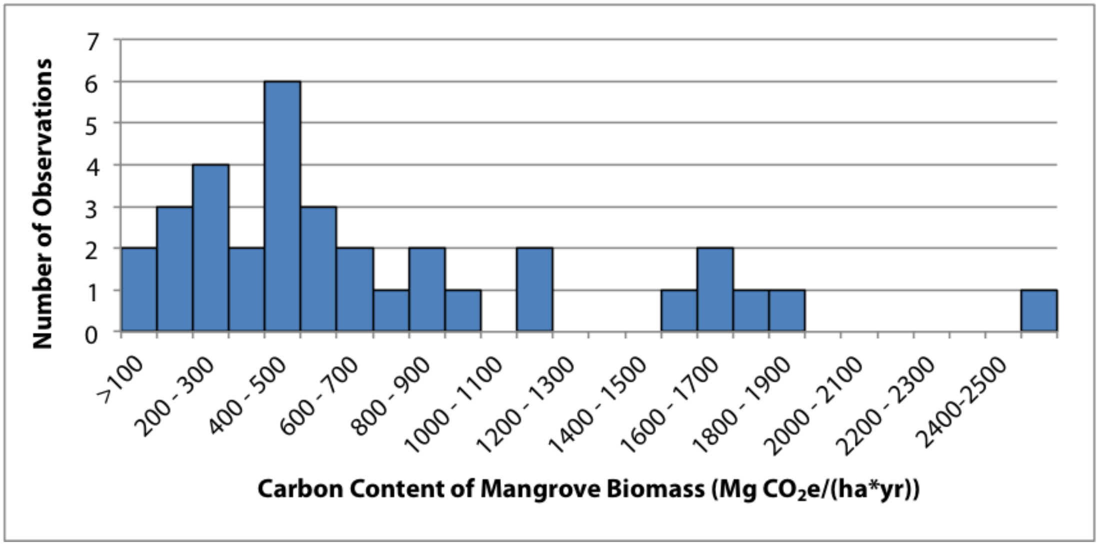
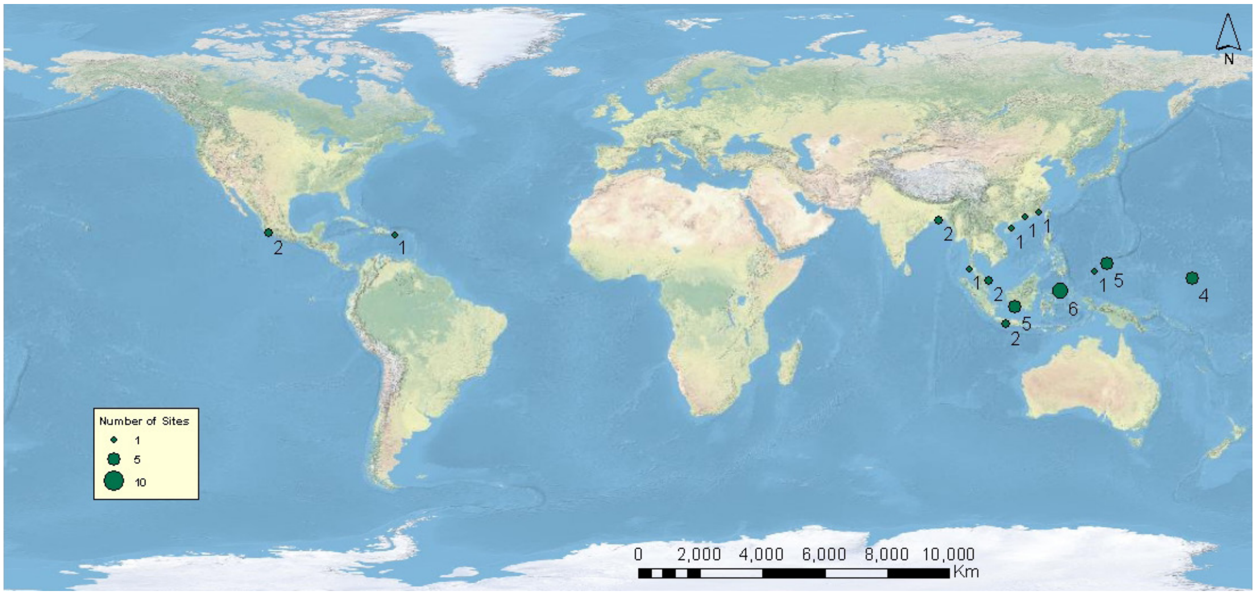


Figure 9. Location of carbon content of mangrove forest biomass data.



Mangrove habitat extent and loss rates

Mangroves seem to be disappearing at a relatively high rate [15]. The FAO [15] provides the most recent accurate data for mangrove extent. It documents mangrove areas in 124 countries from 1980 through 2005. The data provided in the FAO report build on the Tropical Forest Resources Assessment 1980 [16-18] and on information provided to the Global Forest Resources Assessment 2000 and FRA 2005 [19, 20]. The report combines an extensive review of the literature with a survey of mangrove countries and leading mangrove expert scientists.

Table 1. Regional mangrove loss rates [15].

Region	1980 Area (103 ha)	2005 Area (103 ha)	Annual Change 2000–2005 (103 ha)	Annual Change 2000–2005 (%)
Africa	3,670	3,160	-12	-0.36
Asia	7,769	5,858	-61	-1.01
North and Central America	2,951	2,263	-18	-0.77
Oceania	2,181	1,972	-8	-0.39
South America	2,222	1,978	-4	-0.18
WORLD	**18,794**	**15,231**	**-102**	**-0.66**

Table excerpted from FAO (2007) [15].

Emissions from mangrove conversion

No specific observational data are available on the amount of carbon released as CO_2 when mangrove forests are converted to other land uses. Donato and colleagues [2] present estimates based on expert opinion, as does a report from Duke University's Nicholas Institute for Environmental Policy Solutions [21], which estimates these releases on the basis of observed data on area loss and carbon storage, as described above. Other land uses, such as forest, also lack direct carbon emissions data at an aggregated scale and require imputation.

3. Salt Marsh

Salt marshes are intertidal ecosystems found on sheltered coastlines ranging geographically from the sub-arctic to the tropics and occurring most extensively in temperate zones. Salt marshes store carbon in anaerobic sediments where it is not oxidized to CO_2 and therefore is not released to the atmosphere. Intertidal ecosystems, such as salt marshes, are dependent on sediment accretion and rising elevation to compensate for sea level rise. As the anaerobic sediments beneath salt marshes accumulate, so too does the total amount of carbon stored in them. Freshwater wetlands tend to be sources of methane (CH_4) [11], a greenhouse gas 25 times more potent than CO_2. But the saline environment of salt marshes inhibits the natural creation of methane, making for much lower releases of methane in these habitats. The result is that salt marshes have a much greater capacity for carbon storage than freshwater wetlands.

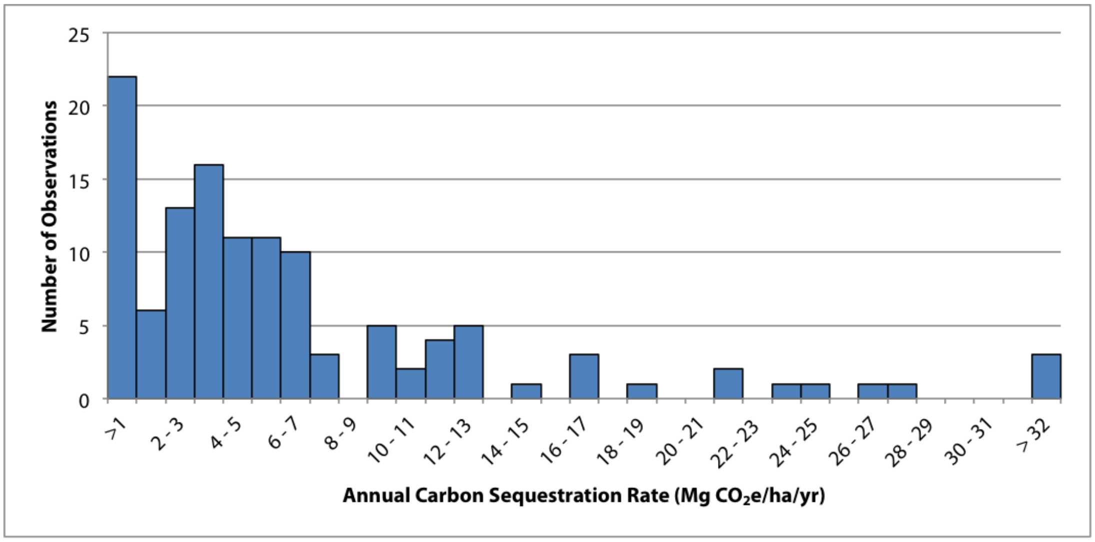
Annual sequestration rate of salt marshes

Two major articles examine carbon sequestration in salt marshes. The first, by Cebrian [3], presents data from 10 published studies at 19 sites. It calculates this annual accumulation using available measurements of community production and respiration. The second important article, by Chmura and colleagues [4], presents data from 19 published studies as well as some unpublished data at a total of 96 sites. It summarizes information about organic carbon density within salt marsh and mangrove soils. Combining these density values with annual sediment accretion rates, it calculates annual carbon sequestration rate.

This report includes data from these two articles as well as data from six additional studies [22-27]. Yet other studies exist [7, 11] but present only summarized data, not individual measurements.

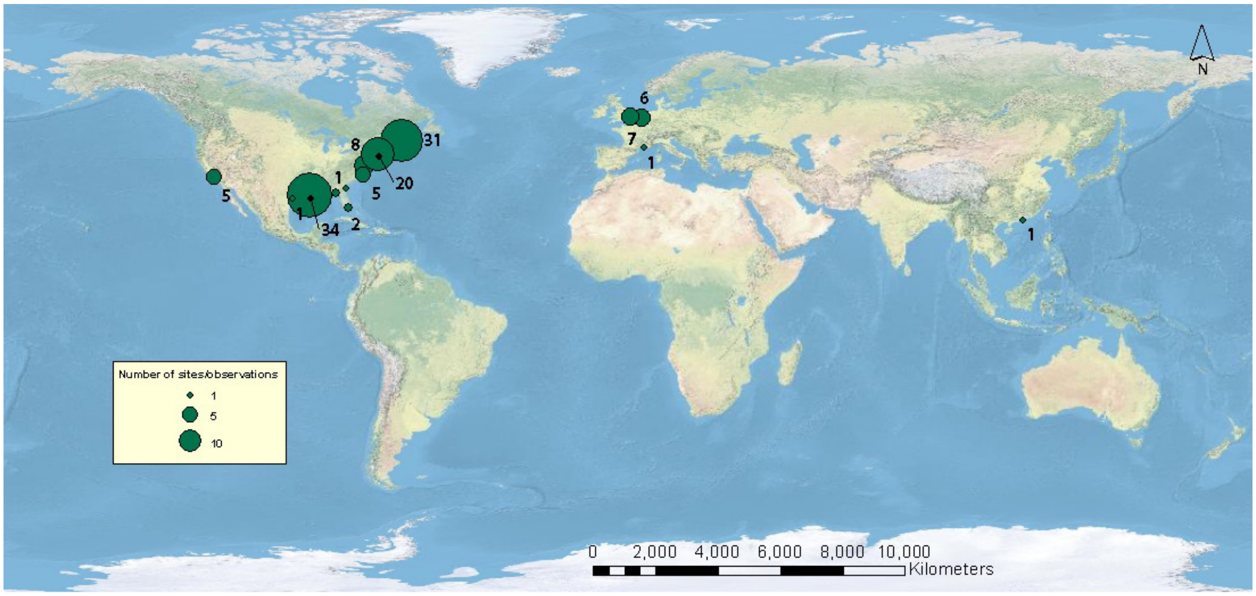
Estimates of annual carbon sequestration, from 122 observations, range from 0.01 to 62.81 Mg CO_2e/ha/yr. The distribution of the available data is shown in Figure 10. The distribution is wide, though clustered primarily in the range of 1 to 10 Mg CO_2e/ha/yr. Figure 11 displays the geographic representation of the available data. It shows that the studies largely draw from observations in the eastern North America and Western Europe. Table A-10 in Appendix A provides a comprehensive summary of the data by geographic location.

Figure 10. Number of observations for data on annual carbon sequestration by salt marshes.



The methodology presented by Cebrian [3], which is based on metabolic principles, yields lower estimates than the sediment accumulation methodology used by Chmura and colleagues [4], a two-sample t-test assuming unequal variance, $p = 0.05$. The average of the estimates from Cebrian (0.13 Mg CO_2e/ha/yr, n = 19) is lower than the average of the estimates by Chmura (8.42 Mg CO_2e/ha/yr, n = 96).

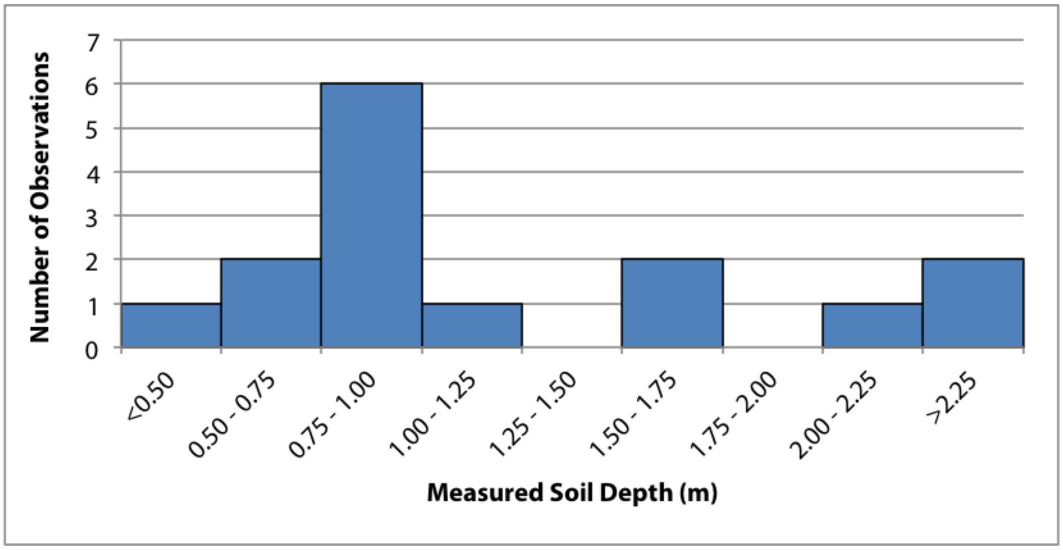
Figure 11. Location of original data on annual carbon sequestration rate in the soils beneath salt marshes.



Soil carbon stocks of salt marshes

The rich peaty organic soils underlying salt marshes can range in depth from less than a half a meter [23] to over 7 meters [26, 28], as shown in Figure 12. Brevik and Homburg (2004) [26] note depths of up to 17 meters. However, because their observations were from a coastal wetland system, including a lagoon, only the average depth of 4.57 meters is used here. Drexler and colleagues [28] report a depth of 7.7 meters of salt marsh peat on an island in the Sacramento in the San Joaquin Delta in California. A total of 16 observations are reported here. In some cases, the depths reported are merely the depths that were sampled. The values therefore do not indicate the full depths of the carbon-rich sediments.

Figure 12. Number of observations of data on the depth of organic soils beneath salt marshes.



The leading review article on the carbon density of salt marsh soils is from Chmura and colleagues [4]. The Chmura article presents carbon density data for 106 sites from 20 published papers and several unpublished sources. This report presents these data and data from several other primary sources. Hussein and colleagues [23] present data on soil organic carbon (g/kg) and bulk density (Mg/m^3) at various depth increments from nine sampling sites in Dorchester County, Maryland. This report determines the average carbon density for the soil column by calculating a weighted average of the different depth intervals. Choi and Wang [29] report carbon storage in the top 84 cm of soil beneath a vegetative marsh sequence in St. Marks National Wildlife Refuge in Florida. This report calculates the average carbon density from these available data using average bulk density and percentage soil organic carbon as reported by Johnson and colleagues [24]. Choi and Wang et al. (2004) [25] report a range of carbon density in mmolC/cm^3. This report calculates the average of the range and converts it to gC/cm^3. Brevik and Homburg [26] also report salt marsh soil carbon density. Craft and colleagues [30] report soil carbon density for two depth intervals at five sites in North Carolina. This report calculates a weighted average of the carbon density by depth at each site.

Estimates of soil carbon stock, from 126 observations, range from 0.009 to 0.190 gC/cm^3, though most estimates are found in the lower end of that range. Figure 13 displays the distribution of the data, and Figure 14 displays the geographic representation of the data, again reflecting mostly eastern North America and western Europe.

Figure 13. Number of observations of salt marsh soil carbon density data.

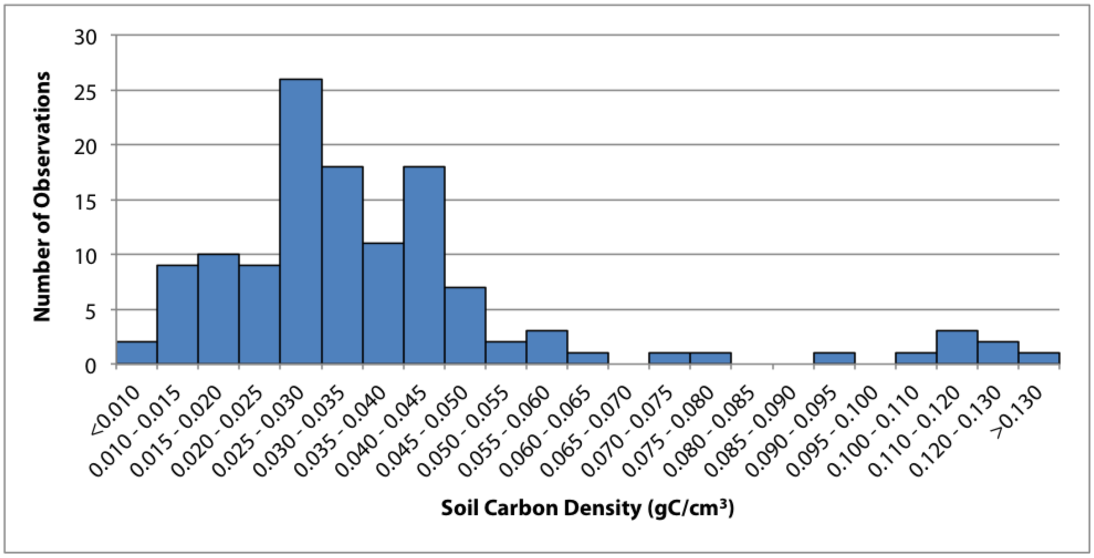
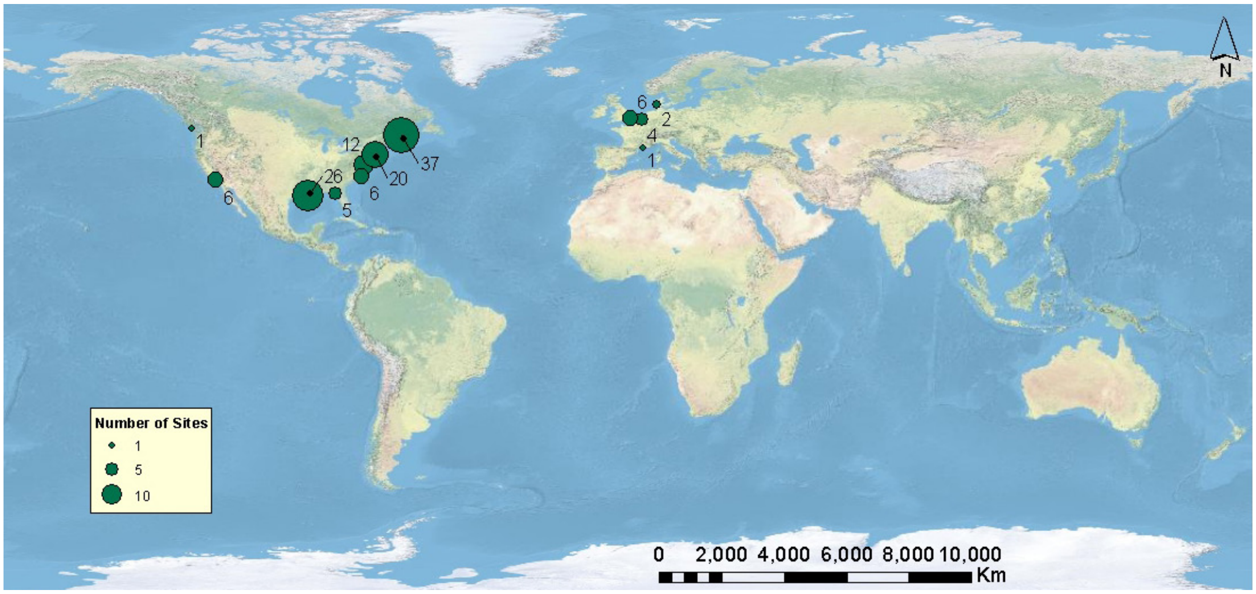


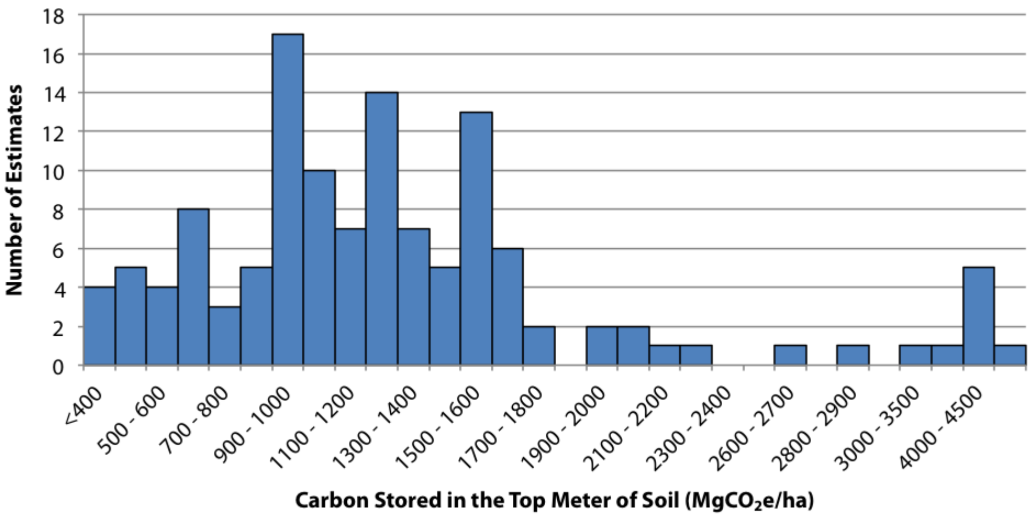
Figure 14. Location of original data on salt marsh soil carbon density.



Carbon stocks for the first meter of soil depth were calculated from the available carbon density data using the conversion presented in the mangrove section above. Carbon stocks in the first meter depth of salt marsh soils ranges from

174 to 6,967 Mg CO_2e/ha. Figure 15 presents the distribution of these estimates. The geographic summary of this data is provided in Table A-11 of Appendix A.

Figure 15. Number of observations of carbon stored in the top meter of salt marsh soil estimates.



Carbon content of salt marsh biomass

Numerous studies dating back to the 1970s measure both above- and belowground biomass of salt marshes. However, data on the carbon content of salt marsh biomass is scarce. One key study by Hemminga and colleagues [31] explores the carbon content of both above- and belowground biomass for salt marshes throughout the growing season. This study shows lower carbon content in salt marsh roots (below ground) than in shoots (above ground) in the beginning of the growing season. However, later in the season the carbon content of both roots and shoots equilibrated at 40% dry weight. We use this factor to convert some of the available peak-season dry-weight biomass data to carbon [32-35]. Biomass estimates vary even within a given species at a given site. For example, Teal and Howes [35] present data for both the tall and short forms of *Spartina alterniflora* at a marsh in Massachusetts. The mean biomass for the tall salt marsh is more than 1,000 g/m^2 whereas that of the short form is less than 500 g/m^2. Given the likelihood of variability in carbon content, we transformed only the data from five studies by the 40% carbon content factor in the Hemminga study [31]. We cannot estimate biomass for other salt marsh species because conversion factors, like that given by Hemminga and colleagues [31], are unavailable. Another key study is that of Craft et al. (1988), which specifically examined the carbon content of belowground biomass.

We provide six observations of aboveground biomass from five studies ranging from 5.1 to 18.3 Mg CO_2e/ha. We also present seven observations of belowground biomass from three studies ranging from 3.4 to 51.2 CO_2e/ha. Figure 16 presents the distribution of this data. Figure 17 presents the geographic representation of the data.

Figure 16. Number of observations of data on carbon content of salt marsh biomass.

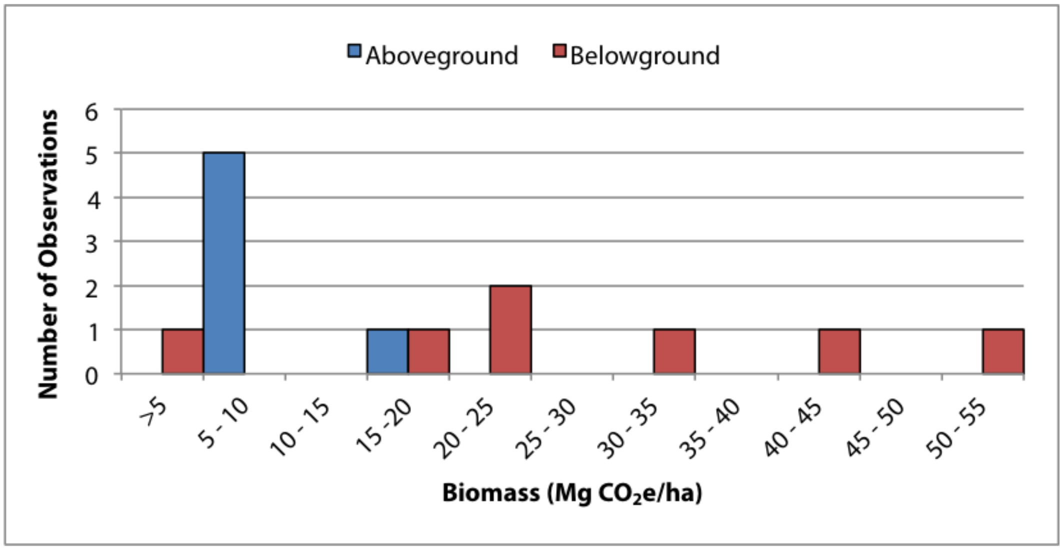
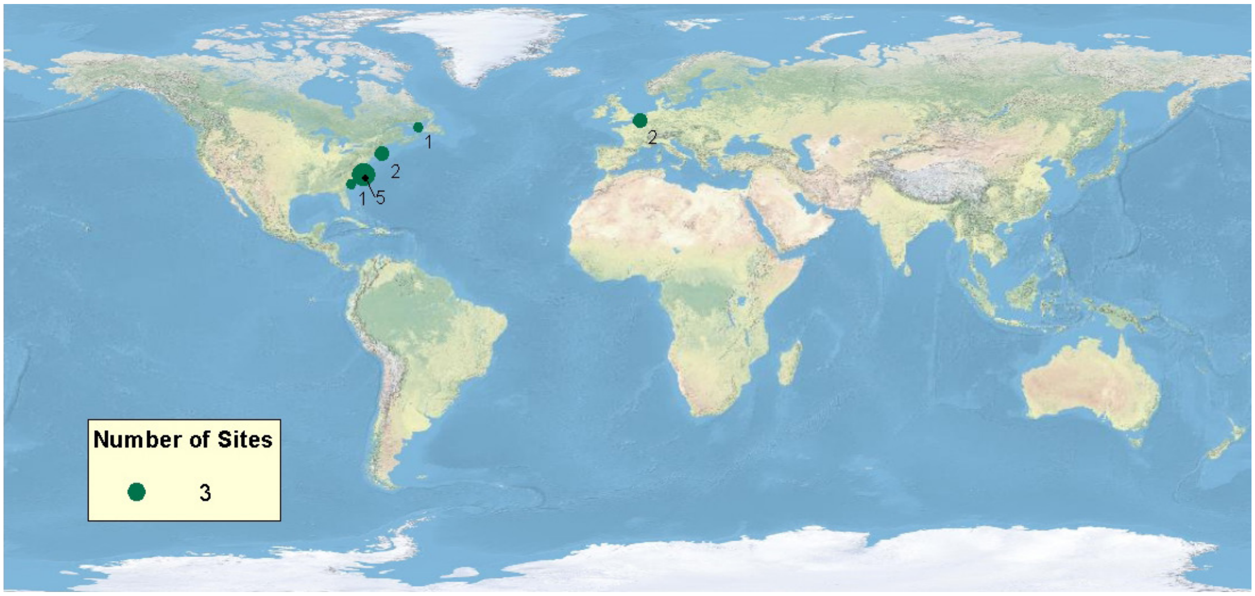


Figure 17. Location of data on carbon content of salt marsh biomass.



Salt marsh habitat extent and loss rate

Data on salt marsh area are readily available for North America and Europe and scarce elsewhere. Only one study, by Yang and Chen [36], calculates salt marsh area in China, and it reports a loss of 1.75 million ha of salt marsh between 1950 and 1995. Bridgham and colleagues [11] estimate a loss of 0.4 million ha of North American salt marsh area over the last 200 years. We found no data to estimate salt marsh area or loss rates in South America or Australia (see Table 2). Estimates of current global salt marsh loss rates are 1% to 2% per year [37, 38].

Table 2. Salt marsh area.

Region	Area (106 ha)	Reference
Unites States	1.926	[4]
Europe and Scandinavia	0.230	[4]
Canada	0.032	[4]
Tunisia	0.006	[4]
Morocco	0.003	[4]
South Africa	0.017	[4]
China	0.350	[36]
Global	140	[38]
North America	2.2	[11]

Emissions following salt marsh conversion

Empirical estimates of how much carbon is released to the atmosphere following salt marsh conversion are unavailable. Scientists have attempted to estimate possible carbon releases by examining the subsidence of salt marsh soils following drainage. For centuries, salt marshes subsided after being drained for agricultural purposes. Two types of subsidence occur in marshes. The first, primary subsidence, is a physical change in elevation caused by soil compaction. The mass of the drained soils compacts the soil particles and therefore lowers the elevation. Secondary subsidence is a chemical process whereby exposure of the organic soils of drained marshes to the atmosphere results in oxidation of the soils' organic carbon to CO_2. Much of the published work examining secondary subsidence is focused on freshwater marshes [39, 40]. Data on salt marsh secondary subsidence comes from several sources. Armentano and Menges [40] review available studies of wetland subsidence and soil carbon density from around the world. However, the majority of these studies cover bogs and other fresh water peatlands. The data from the southeastern United States in Armentano and Menges are derived from studies of salt marsh areas. These data are discussed here. Armentano and Menges report a regional mean carbon release rate of 35.64 Mg CO_2e/ha/yr for southeastern U.S. wetlands converted to cropland beginning in 1800.

Drexler and colleagues [28] examine peat loss in the Sacramento in California's San Joaquin Delta. Six of the eight drained wetland agriculture sites they considered were freshwater sites. The Drexler paper reports a total loss of carbon from drained wetlands ranging from 10,633 to 20,900 Mg CO_2e/ha over a period of 125 years. We convert this loss to an annual loss rate ranging from 85 to 167 Mg CO_2e/ha/yr.

Ewing and Vepraskas [41] present data on secondary subsidence of a salt marsh converted to agriculture. Their paper examines areas of North Carolina's Juniper Bay that were converted to agriculture. We use the bulk density and percentage carbon data to calculate soil carbon density. We then multiply this density by the secondary subsidence rates to calculate an organic carbon loss rate ranging from 31 to 59 Mg CO_2e/ha/yr.

4. Seagrass

Seagrass meadows are communities of underwater-flowering plants found in coastal waters of all continents except Antarctica. Seagrass meadows store relatively small amounts of carbon in aboveground biomass. However, belowground biomass, in the form of large long-lived root structures, stores the majority of carbon below ground. These root structures accumulate large stores of carbon through the formation of "mattes" beneath seagrass meadows. Theses mattes accrete vertically over time, raising the seagrass meadow toward the surface of the water.

Annual carbon sequestration rates of seagrasses

There are two ways to calculate annual carbon sequestration for seagrasses. The first is through the metabolic pathway, which compares annual primary production and community respiration. This method is used in the two review papers discussed below [3, 42]. The second method examines the sedimentary record using radiocarbon dating. Dating the various depths of accumulated sediments allows for calculation of an average annual sequestration rate [43, 44].

Duarte and colleagues [42] use estimates of net production in their review of seagrass sequestration rates and present 358 data points from 34 published studies and at least five unpublished sources.[3] Another review, by Cebrian [3],

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[3] Duarte presents net community production in units of mmol O_2 $m^{-2}d^{-1}$. We convert these values to Mg CO_2e/ha/yr using the following calculation:

$$\frac{mmolO_2}{m^2d}*\frac{mmolCO_2}{mmolO_2}*\frac{10^4m^2}{1ha}*\frac{365.25d}{1yr}*\frac{1molCO_2}{10^3mmolCO_2}*\frac{44g}{1molCO_2}*\frac{1Mg}{10^6g}=\frac{MgCO_2}{ha*yr}$$

calculates this annual accumulation or sequestration rate using available measurements of community production and respiration. Cebrian [3] reports a total of 10 estimates of carbon sequestration in seagrasses from six published studies.

The final two papers of interest on this topic are the studies conducted by Mateo and colleagues [43] and Romero and colleagues [44]. The Mateo paper [43] examined seven seagrass sites in the Mediterranean. The Romero paper [44] examined two of those same sites and used a shipwreck site to date the sediments. Mateo and colleagues [43] used radiocarbon methods to date the sedimentary record. Sediment cores were taken from the mattes under these seagrass sites and dated. These dates were then used to calculate an average annual carbon sequestration rate.

We report a total of 377 estimates ranging from -76.70 to 85.44 Mg CO_2e/ha/yr. Figure 18 shows the distribution of the data. All the negative values, indicating greater respiration than production, were derived from the Duarte et al. (2010). A one-way ANOVA and Tukey's test was run using Minitab 15 to compare the data sets from the three methodologies (i.e., those of Duarte, Cebrian, and Mateo). No statistically significant (α = 0.05) difference was detected among the means of the three data sets. Figure 19 shows the geographic distribution of sites from which the data are collected. A comprehensive summary of the data is presented in Table A-12 of Appendix A.

Figure 18. Number of observations of data on annual carbon sequestration rates of seagrass beds.

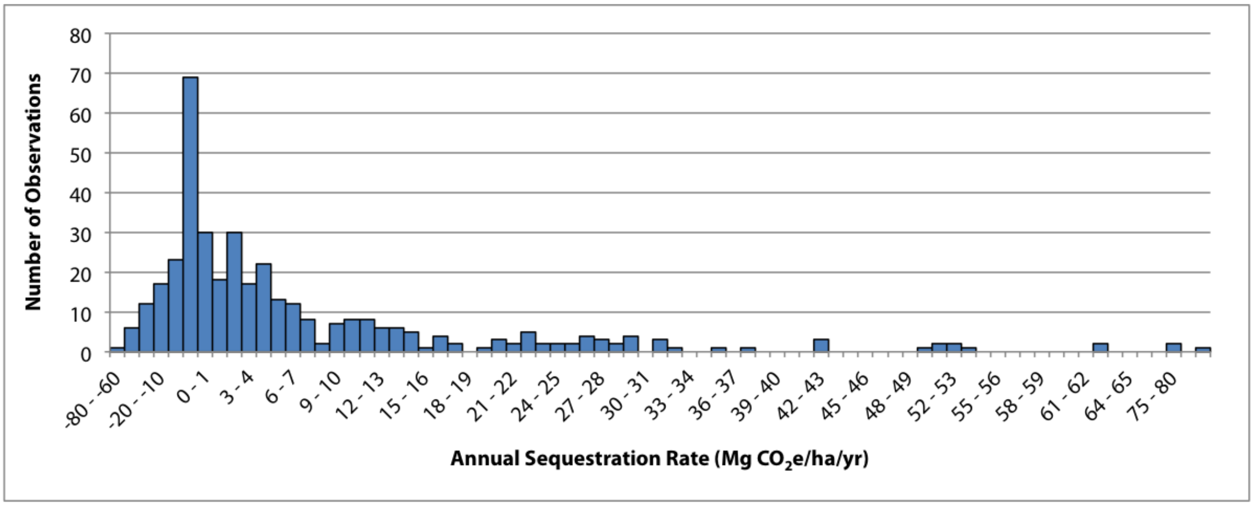
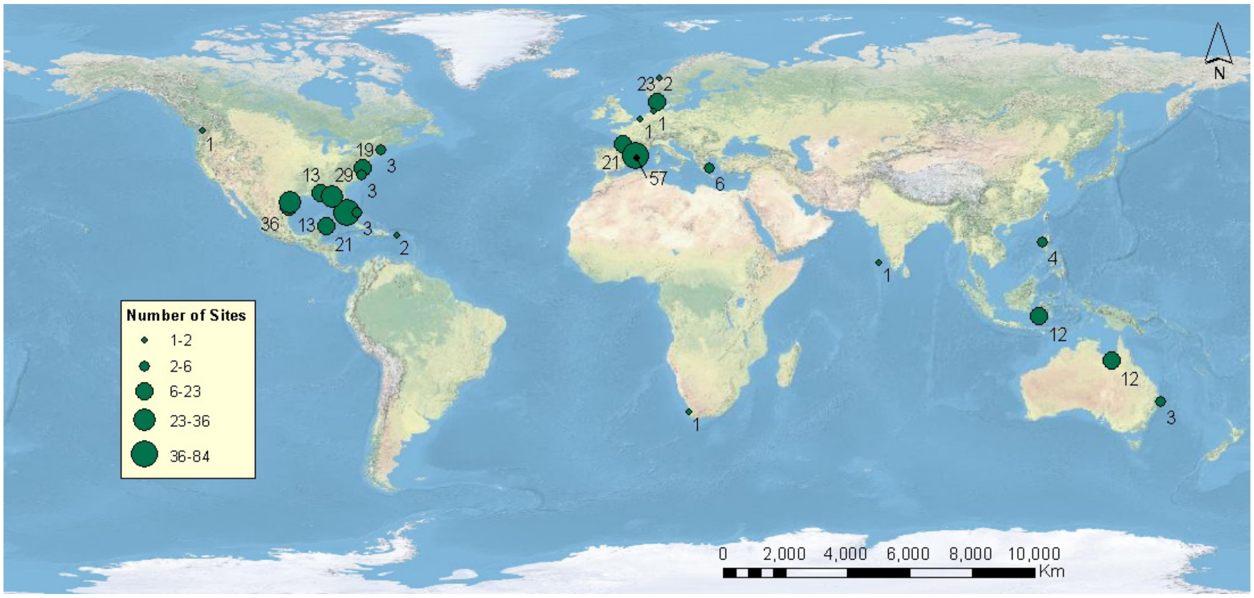


Figure 19. Location of estimates of annual carbon sequestration rates for seagrass beds.



Carbon storage under seagrass beds

The largest store of carbon in seagrass systems is contained within the soil. To understand the total amount of carbon stored in the sediments beneath seagrasses, scientists must know the depth of the organic-rich soil layer and the carbon density of the soil, a value typically presented in gC/cm^3 but sometimes expressed as a percentage of the total soil present. This value can be converted if the bulk density of the soil (g soil/cm^3) is known.

The depth of the "mattes" underneath seagrass meadows is documented only in the Mediterranean. Measured depths range from 1 to 6.5 m. See Table 3.

Table 3. Depth of seagrass mattes.

Location	Number of Observations	Range (m)	Study
Spain/Italy	7	1 – 3.2	[43]
Spain/Italy	2	3.0 – 3.1	[44]
Spain	1	6.5	[45]

Few data on the total carbon stored in seagrass soils are available. We are aware of only three original studies that estimate carbon stored in seagrass soils, and all of them were conducted in the Mediterranean [43-45]. Table 4 presents data on total carbon stored beneath seagrass meadows that integrates both depth and carbon density. Few data on the carbon density of seagrass sediments are available. However, several large data sets on the carbon content of soils as percentage mass of total soil are available [42, 46, 47]. These data sets are not suitable for summary purposes because they do not include the bulk density of seagrass soils, the second component needed to calculate carbon density.

Table 4. Total Carbon stored under seagrass meadows.

Location	Number of Observations	Range (Mg CO_2e/ha)	Study
Spain/Italy	7	1,467 – 5,867	[43]
Spain/Italy	2	880 – 1,760	[44]
Spain	1	6,600	[45]

Carbon content of seagrass biomass

Seagrass meadows sequester carbon in both aboveground and belowground biomass. Duarte and Chiscano (1999) [48] show that aboveground biomass and belowground biomass are roughly equivalent. They use the conversion factor of 0.35gC/100g dry weight to calculate biomass carbon from dry-weight biomass data. Two review articles compile large data sets of aboveground biomass data [42, 46]. Duarte and colleagues [42] and Kennedy and colleagues [46] present large data sets with 282 unique observations of the carbon content of aboveground seagrass biomass. These data range from 0.01 to 22.75 Mg CO_2e/ha.

Duarte and Chiscano (1999) present aboveground biomass data on 27 species of seagrasses and belowground biomass for 21 species. Although they list the number of observations for each species, they do not identify the locations of the data collections. Therefore, these points are not included in the geographic representation presented in Figure 20 and Table A-13 in Appendix A. These points are included in Figure 21.

The analysis presented by Duarte and Chiscano (1999) reveals that carbon stores in aboveground and belowground biomass are very similar. Therefore, the aboveground biomass numbers presented here may represent only half of the biomass carbon pool.

Figure 20. Location of seagrass biomass data.

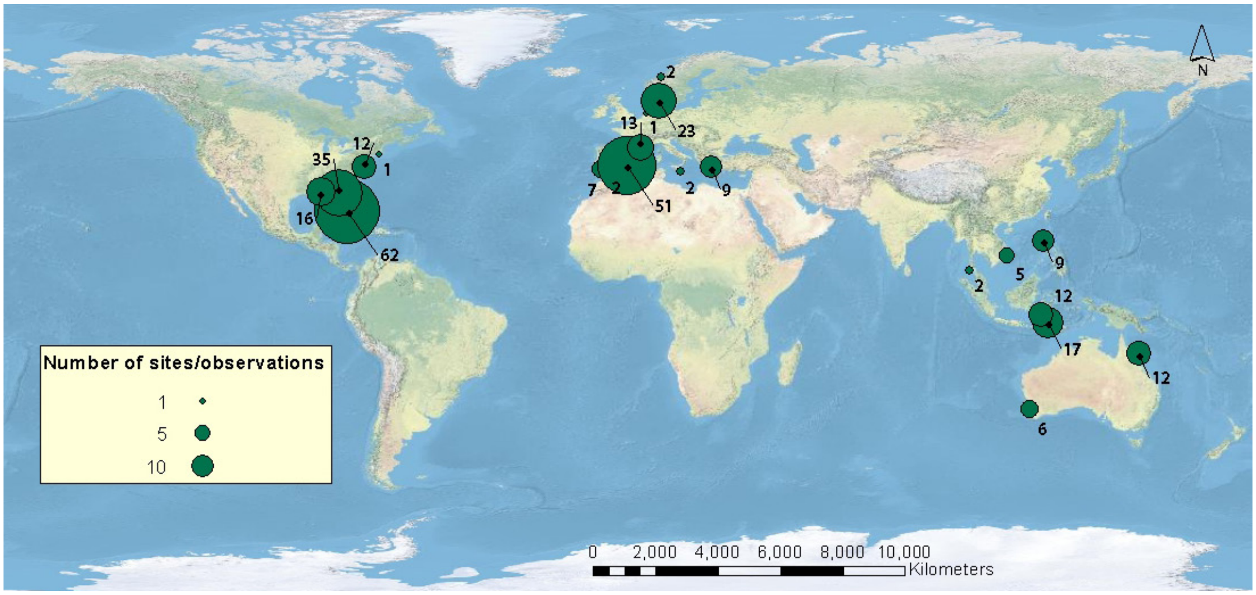
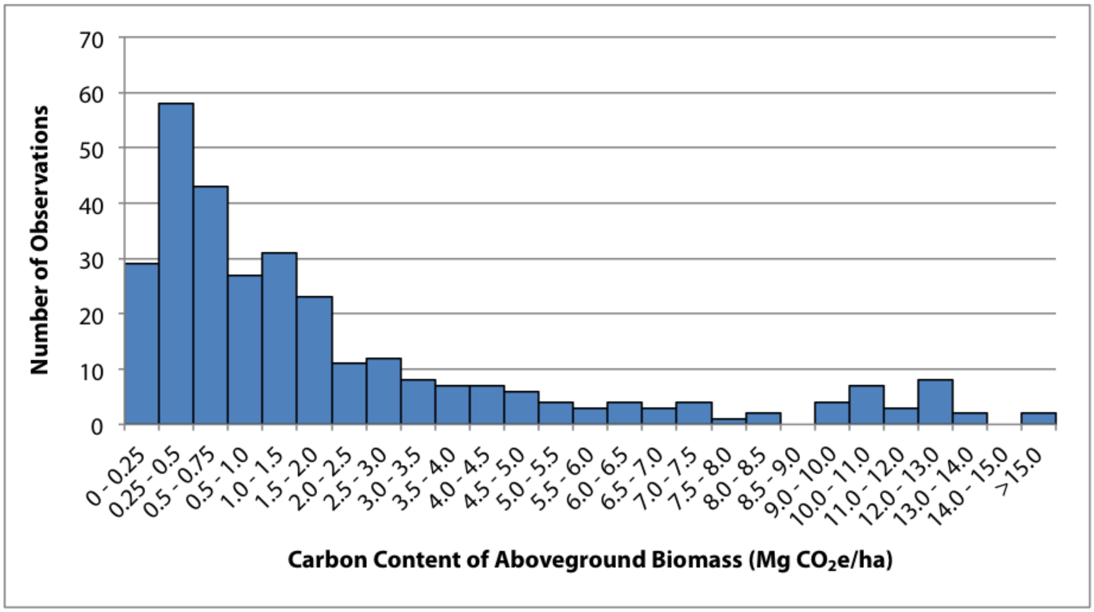


Figure 21. Number of observations of data on the carbon content of aboveground seagrass biomass.



Seagrass habitat extent and loss

Little is known about the areal extent of seagrasses. Table 5 presents the available data on current seagrass area. Waycott and colleagues [49] estimate an annual loss in seagrass habitat of 11,000 ha globally since 1980 and a total loss of 7.2 million ha in the last 100 years.

Table 5. Available data on seagrass areal extent.

Region	Area (Million ha)	Reference
Mediterranean	2.5 (min)	[50]
Mediterranean	5.0 (max)	[50]
Global	30	[7]
Global	60	[51]
Global	17.7 (min)	[49]
Global	430 (max)	[49]

Appendix A: Summary of Available Data

Table A-1. Available data on annual carbon sequestration rate of mangrove forests.

Location	Number of sites/ observations	Range Mg CO_2e/ha	Average Mg CO_2e/ha	Original references
Florida Keys, USA	15	0.12 – 13.97	5.35	[3, 4, 52-55]
Queensland, Australia	12	0.95 – 12.32	5.76	[3, 4, 56-58]
Estero Pargo, Mexico	4	5.35 – 23.98	11.94	[4, 54]
Hong Kong, China	2	3.75 – 7.8	5.77	[3, 59, 60]
Pohnpei Island, Micronesia	2	1.94 – 3.41	2.68	[5]
Victoria, Australia	1		0.19	[3, 61]
Malaysia	1		5.51	[3, 62]
Puerto Rico	1		1.60	[3, 63]
South Africa	1		4.73	[3, 64]

Table A-2. Available data on total carbon sequestered in the top meter of soils underlying mangrove forests.

Location	Number of sites/ observations	Range Mg CO_2e/ha	Average Mg CO_2e/ha	Original references
Orinoco Delta, Venezuela	40*		825	[4, 12]
Florida, USA	12	880 – 2,457	1,588	[4, 53, 54, 65, 66]
Kosrae	7	843 – 2,643	2,085	[2, 4]
Sulawesi	6	2,123 – 2,777	2,487	[2]
Borneo	5	858 – 1,255	1,077	[2]
Yap	5	1,524 – 1,909	1,737	[2]
Boca Chica, Mexico	4	1,723 – 2,127	1,907	[4, 54]
Umengi estuary, South Africa	4	3,850 – 4,217	3,997	[4, 67]
Pohnpei Island, Micronesia	3	1,280 – 2,383	1,814	[5]
Colombia	3	2,126 – 2,603	2,322	[4, 68]
Sundarbans, Bangladesh	2	570 – 587	578	[2]
Java	2	894-1,153	1,024	[2]
Palau	1		1,687	[2]

*This value was calculated reflects the fact that of 227 sites, 49 (22%) represented mangrove habitat, a number decreased to 40 to incorporate a conservative margin of error.

Table A-3. Available data on the depth of organic sediments beneath mangrove forests.

Location	Number of sites/ observations	Range (m)	Average (m)	Original references
Kosrae	11	0.7 – 5.1	2.09	[2, 5, 69]
Sulawesi	6	0.48 – 3	1.22	[2]
Borneo	5	3	3	[2]
Yap	5	1.24 – 2.23	1.62	[2]
Pohnpei Island, Micronesia	4	1.1 – 3.65	2.67	[5, 70]
Sundarbans, Bangladesh	2	3	3	[2]
Java	2	1.42 – 2.81	2.16	[2]
Orinoco Delta, Venezuela	1		0.64	[12]
Pagbilau	1		1.7	[70]
Palau	1		1.17	[2]
Tobacco Range, Belize	1		10	[1]

Table A-4. Available data on the carbon content of mangrove biomass.

Location	Number of sites/ observations	Range Mg CO_2e/ha	Average Mg CO_2e/ha	Original references
Sulawesi	6	287 – 634	469	[2]
Borneo	5	368 – 946	685	[2]
Yap	5	807 – 2,254	1,550	[2]
Kosrae	4	1,136 – 1,819	1,564	[2]
Sundarbans, Bangladesh	2	338 – 590	464	[2]
Java	2	25.6 – 85	55.3	[2]
Malaysia	2	424 – 473	449	[10]
Mexico	2	198 – 223	210	[10, 71]
Fujijian, China	1		154	[10, 72]
Hainan, China	1		410	[10, 73]
Hong Kong, China	1		213	[10, 74]
Palau	1		681	[2]
Puerto Rico	1		103	[10, 63]
Phuket, Thailand	1		262	[10, 75]

Table A-5. Mangrove loss rates in Africa [15].

Country	Annual change 2000–2005 (ha)	Annual change 2000–2005 (%)
Madagascar	-3,000	-1
Senegal	-2,400	-2
Guinea-Bissau	-2,200	-1
Sierra Leone	-1,060	-1
Gabon	-588	-0.4
Liberia	-500	-6.1
United Rep. of Tanzania	-440	-0.4
Mozambique	-320	-0.1
Cameroon	-300	-0.1
Ghana	-280	-2.1
Angola	-120	-0.4
Somalia	-100	-1.3
Congo	-70	-0.9
Equatorial Guinea	-60	-0.2
Benin	-40	-3.2
Guinea	-40	n.s.
Dem. Rep. of the Congo	-20	-0.1
Gambia	-20	n.s.
South Africa	-10	-0.3
Côte d’Ivoire	-8	-0.1
Djibouti	0	0
Egypt	0	0
Eritrea	0	0
Kenya	0	0
Mauritania	0	0
Mayotte	0	0
Nigeria	0	0
Seychelles	0	0
Sudan	0	0
Togo	0	0
Mauritius	6	5.9
Comoros	n.s.	-0.3

Table A-6. Mangrove loss rates in Asia [15].

Country	Annual change 2000–2005 (ha)	Annual change 2000–2005 (%)
Indonesia	-50,000	-1.6
Malaysia	-4,900	-0.8
Philippines	-2,000	-0.8
Myanmar	-1,940	-0.4
Cambodia	-880	-1.2
Thailand	-820	-0.3
Pakistan	-200	-0.1
Viet Nam	-100	-0.1
China	-95	-0.4
India	-40	n.s.
Sri Lanka	-40	-0.4
Iran, Islamic Republic of	-20	-0.1
Bahrain	0	0
Bangladesh	0	0
Brunei Darussalam	0	0
Japan	0	0
Oman	0	0
Qatar	0	0
Saudi Arabia	0	0
Singapore	0	0
Timor-Leste	0	0
Yemen	0	0
United Arab Emirates	20	0.5

Table A-7. Mangrove loss rates in North and Central America [15].

Country	Annual change 2000–2005 (ha)	Annual change 2000–2005 (%)
Mexico	-13,000	-1.5
Honduras	-2,300	-3.1
United States	-1,000	-0.5
Panama	-880	-0.5
Dominican Republic	-520	-2.8
Costa Rica	-160	-0.4
Haiti	-120	-0.8
Belize	-100	-0.1
El Salvador	-100	-0.3
Antigua and Barbuda	-30	-3.8
Cayman Islands	-20	-0.3
Jamaica	-20	-0.2
U.S. Virgin Islands	-10	-5.6
British Virgin Islands	-4	-0.7
Grenada	-3	-1.3
Guadeloupe	-2	-0.1
Barbados	-1	-10.6
Saint Kitts and Nevis	-1	-1.4
Anguilla	0	0
Aruba	0	0
Bahamas	0	0
Bermuda	0	0
Guatemala	0	0
Martinique	0	0

Country	Annual change 2000–2005 (ha)	Annual change 2000–2005 (%)
Montserrat	0	0
Netherlands Antilles	0	0
Nicaragua	0	0
Saint Lucia	0	0
Saint Vincent and the Grenadines	0	0
Trinidad and Tobago	0	0
Turks and Caicos Islands	0	0
Puerto Rico	20	0.2
Cuba	400	0.1
Dominica	n.s.	-2.1

Table A-8. Mangrove loss rates in Oceania [15].

Country	Annual change 2000–2005 (ha)	Annual change 2000–2005 (%)
Papua New Guinea	-6,000	-1.5
Solomon Islands	-760	-1.7
Fiji	-420	-1.1
Australia	-400	n.s.
New Caledonia	-280	-1.6
Samoa	-4	-1.1
American Samoa	-2	-3
Guam	-1	-1.7
Kiribati	0	0
Micronesia (Fed. States of)	0	0
Nauru	0	0
New Zealand	0	0
Niue	0	0
Palau	0	0
Tonga	0	0
Tuvalu	0	0
Vanuatu	0	0
Wallis and Futuna Islands	0	0
Northern Mariana Islands	n.s.	-0.3

Table A-9. Mangrove loss rates in South America [15].

Country	Annual change 2000–2005 (ha)	Annual change 2000–2005 (%)
Colombia	-2,060	-0.6
Venezuela (Bolivarian Rep. of)	-1,500	-0.7
Suriname	-40	n.s.
Brazil	0	0
French Guiana	0	0
Guyana	0	0
Peru	0	0
Ecuador	60	n.s.

Table A-10. Available data on annual carbon sequestration rate of salt marshes.

Location	Number of observations	Range Mg CO_2e/ha/yr	Average Mg CO_2e/ha/yr	References
Louisiana	34	0.66 – 30.1	10.18	[3, 4, 53, 76-83]
Northeast Canada	31	2.2 – 34.03	8.65	[4, 78, 84, 85]
New England (Connecticut, Massachusetts, and Maine)	20	1.5 –7.5	4.50	[3, 4, 24, 86-90]
Chesapeake Bay, USA	8	1.9 – 12.5	7.12	[3, 4, 23, 91-93]
Europe	7	5.1 – 68.6	31.50	[3, 4, 94-96]
United Kingdom	6	2.8 – 6.8	5.12	[4, 94, 97]
California	5	1.4 – 14.1	6.33	[4, 26, 98, 99]
North Carolina	5	0.8 – 5.3	2.96	[4, 100]
Saint Mark's Wildlife Refuge, Florida	2	1.6 – 6.7	1.88	[4, 25]
Everglades, Florida	2	3.5 – 6.7	5.15	[22]
Rhone Delta, France	1		5.90	[4, 101]
Georgia	1		1.47	[3, 102]
Hong Kong, China	1		6.53	[3, 59]

Table A-11. Estimates of carbon stored in the top meter beneath salt marshes using available soil carbon density data.

Location	Number of observations	Range Mg CO_2e/ha	Average Mg CO_2e/ha	References
Northeast Canada	37	660 – 2,680	1,266	[4, 78, 84, 85]
Gulf of Mexico (Louisiana, Texas, and Mississippi)	26	367 – 6,967	1,902	[4, 53, 76-80]
New England (Connecticut, Massachusetts, and Maine)	20	733 – 2,200	1,342	[4, 24, 86-89]
Chesapeake Bay, Maryland	12	902 – 1,613	1,191	[4, 23, 91]
California	6	330 – 1,588	863	[4, 26, 98, 99]
North Carolina	6	174 – 2,038	1,159	[4, 30]
United Kingdom	6	990 – 1,503	1,332	[4, 94, 97]
Florida	5	567 – 1,694	1,020	[4, 25, 29]
Netherlands	4	733 – 1,503	1,201	[4, 94, 95]
Denmark	2	770 – 990	880	[4, 103]
Rhone Delta, France	1		2,677	[4, 101]
British Colombia, Canada	1		623	[4]

Table A-12. Annual carbon sequestration rate data for seagrass meadows worldwide.

Location	Number of sites	Range Mg CO_2e/(ha*y)	Average Mg CO_2e/(ha*y)	Original references
Florida Keys	84	-9.4 - 50.22	2.83	[3, 42, 104-108]
Spain	57	-11.48 – 21.99	2.87	[3, 42-44, 109-112]
Redfish Bay, Texas, USA	36	-46.96 – 26.62	-6.77	[42, 113]
Northwest Florida	29	-9.97 – 16.97	1.94	[42, 114-116]
Denmark	23	-18.13 – 29.79	0.11	[42, 117]
France	21	-33.63 – 85.44	10.43	[42, 43, 118-121]
Mexico	21	-76.7 – 42.01	8.54	[42, 122]
Chesapeake Bay, USA	19	-12.33 – 62.13	13.81	[42, 104, 123, 124]
Alabama	13	-1.39 – 53.54	25.8	[42, 125]
Laguna Madre, Texas	13	-11.05 – 62.78	10.61	[42, 126, 127]
Gulf of Carpentaria, Australia	12	-2.68 – 22.77	9.37	[42, 128]
Indonesia	12	-52.54 – 2.83	-21.19	[42, 129]
Greece	6	4.35 – 10.26	6.33	[42, 130]
Philippines	4	-1.25 – 22.53	7.81	[42, 131]
East Coast of Australia	3	-14.55 – -5.2	-9.31	[42, 132]
Beaufort North Carolina	3	0.38 – 2.4	1.24	[3, 108]
New England (NH, MA) USA	3	-1 – 1.51	0	[42, 124]
The Bahamas	3	26.79 – 35.62	30.62	[42, 133]
Norway	2	-0.02 – 1.6	0.79	[42, 134]

Location	Number of sites	Range Mg CO_2e/(ha*y)	Average Mg CO_2e/(ha*y)	Original references
Puerto Rico	2	25.11 – 75.33	50.22	[42, 135]
India	1		77.81	[42, 136]
South Africa	1		13.4	[3, 137]
Wadden Sea, Germany	1		1.21	[42, 138]
The Netherlands	1		1.87495	[3, 139]
Padilla Bay, Washington, USA	1		-2.01	[42, 124]

Table A-13. Distribution of seagrass biomass sites/observations.

Location	Number of sites	Range Mg CO_2e/ha	Average Mg CO_2e/ha	Original references
Florida Keys	62	0.21 – 3.67	0.62	[42, 46, 105, 115, 140-143]
Spain	36	1.87 – 15.58	7.91	[42, 46, 110, 111, 144]
Gulf Coast of Florida	35	0.01 – 5.00	1.04	[42, 114-116, 145]
Denmark	23	0.06 – 5.90	1.89	[42, 117, 146]
Flores Sea, Indonesia	17	0.26 – 4.91	2.28	[42, 147]
Gulf of Mexico (AL, MI)	15	0.06 – 2.12	0.41	[42, 125, 148, 149]
France	13	0.14 – 2.19	0.84	[42, 106, 118, 119]
Southwest Australia	12	0.06 – 3.32	1.22	[42, 128]
Spermonde Archipelago, Indonesia	12	0.21 – 3.05	1.26	[42, 129]
Ebro Delta, Spain	12	0.02 – 3.18	1.52	[42, 46, 109]
Chesapeake Bay (VA and MD)	11	0.29 – 1.42	0.83	[42, 123]
Greece	9	1.1 – 8.42	3.47	[42, 46, 130, 150]
Philippines	9	0.08 – 3.00	1.44	[42, 46, 131, 151]
Portugal	7	8.0 – 13.20	11.10	[42, 138]
Northeast Australia	6	0.20 – 22.75	7.18	[46]
Alicante, Spain	3	6.34 – 10.75	8.78	[46, 150]
Italy	2	0.62 – 3.68	2.15	[42, 46, 130, 150]
Norway	2	1.75 – 1.84	1.79	[42, 134]
Bay of Cadiz, Spain	2	0.65 – 1.21	0.93	[46]
Thailand	2	0.52 – 0.61	0.56	[46, 152]
Wadden Sea, Germany	1		10.67	[42, 138]
North Carolina, USA	1		1.30	[42, 153]
Rhode Island, USA	1		0.82	[42, 154]

Appendix B: Bibliography by Species

Mangrove References

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