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TOPICAL REVIEW

Geoengineering with seagrasses: is credit due where credit is given?

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Abstract

Blue carbon, the carbon fixed by vegetated coastal ecosystems including seagrasses, is reported to have a large potential to sequester atmospheric carbon dioxide. Planting, expanding or protecting seagrass meadows has, accordingly, been proposed as a form of geoengineering. Seagrasses are reported to account for up to 18% of the carbon burial in the world's oceans, which is on the same order of magnitude as other proposed geoengineering techniques, including iron fertilization. International protocols have been developed to quantify carbon sequestration in seagrass meadows, with a view to awarding carbon credits under the Verified Carbon Standard. Unfortunately, because these protocols do not adequately account for post-depositional processes in marine sediment, they significantly overestimate carbon capture by seagrass beds and give an incorrect view of its distribution. Specifically, neglecting biomixing and remineralization of carbon in surface sediments biases burial rates high, while using sediment carbon inventory (soil carbon stock) over the top 1 m as a proxy for burial rate incorrectly identifies areas of high carbon burial. Seagrass beds likely provide a limited setting for geoengineering, because they generally comprise slowly-accumulating, fine to medium sand, which captures organic carbon less efficiently than fine-grained sediments or rapidly-accumulating delta deposits. While there is no question that seagrass meadows provide valuable habitat, nor that they are disappearing rapidly, their contribution to the global burial of carbon has not yet been established. The danger of geoengineering with seagrasses before reliable assessment methods have been established is that overestimated carbon offsets could lead to a net increase in emissions of carbon dioxide to the atmosphere.

1. Introduction

Carbon dioxide added to the atmosphere by anthropogenic burning of fossil carbon is changing the world's climate and acidifying the oceans, threatening marine ecosystems. In addition to the direct solution of reducing greenhouse gas emissions, a number of geoengineering solutions have been proposed. These solutions include technologies to reduce energy flux to the Earth's surface (e.g., installing mirrors in space to reflect sunlight, injecting reflective particles into the atmosphere), to intercept CO_2 heading for the atmosphere (carbon capture), to reduce reliance on fossil fuels (bioenergy) or to sequester CO_2 out of the atmosphere (iron fertilization of the ocean). Over the last decade interest has developed in the sequestration of carbon in vegetated coastal ecosystems, such as seagrass meadows (known as 'blue carbon').

The blue carbon sink is reported to be huge. The global rate of sequestration in seagrass meadows has been estimated at $(48–112) \times 10^9$ kg C yr^{-1} (Kennedy *et al* 2010), which is about 20%–50% of the rate estimated for iron fertilization ($(250–750) \times 10^9$ kg C yr^{-1}, Williamson *et al* 2012), and as much as 18% of the carbon sequestered in the sediment of the whole ocean (Kennedy *et al* 2010). (For comparison $(48–112) \times 10^9$ kg C yr^{-1} represents about 0.4%–0.8% of the global, annual anthropogenic carbon emissions of 49×10^{12} kg CO_2 equiv. yr^{-1} for 2010 (IPCC 2014b). Furthermore, seagrass meadows have been shrinking worldwide, thus reducing an important natural pathway to sequester CO_2 while, at the same time, releasing an estimated 100×10^9 kg yr^{-1} of carbon back to the atmosphere (Duarte *et al* 2010, Fourqurean *et al* 2012, Pendleton *et al* 2012).

Bioengineering proposals are designed to mitigate one or more of the consequences of loading CO_2 into the atmosphere, but they also bring a degree of risk (Nibleus and Lundin 2010, Williamson *et al* 2012). Injection of sulfate aerosols, for example, could change global precipitation patterns, further reducing rainfall in areas that are already dry (Moore *et al* 2010), and would not mitigate ocean acidification. Iron fertilization could widely alter ocean ecosystems, reduce the concentration of oxygen in subsurface seawater, and starve unfertilized areas of nutrients (Williamson *et al* 2012). In contrast, replanting seagrasses appears to be relatively safe and even beneficial, as seagrass meadows provide essential habitat for a wide range of marine animals (Green and Short 2003).

Consequently, scientific interest in this field has expanded rapidly. International protocols have been developed recently (Murray and Vegh 2012, CEC 2014, Emmer *et al* 2014, Howard *et al* 2014, IPCC 2014a, Emmer *et al* 2015), that prescribe how to calculate the amount of carbon sequestered by a vegetated ecosystem, with a view to awarding carbon credits under the Verified Carbon Standard.

Unfortunately, the application of these protocols to seagrasses is based on a misunderstanding of how marine sediments receive, process and store organic carbon. As we will show, the current methods systematically overestimate carbon sequestration by seagrass meadows, as well as resulting in an incorrect delineation of the spatial distribution of carbon burial. The danger of geoengineering with seagrasses, then, is not one of unanticipated side effects, as with most other types of geoengineering, but rather, that illusory gains in carbon storage will be used to offset emissions elsewhere, permitting an overall increase in carbon dioxide emissions to the atmosphere.

Here we outline the roles of sedimentation, sediment mixing, microbial remineralization and energy of the environment in the net sequestration of organic carbon in marine sediments, and present some fundamental problems with the current methodology. We present a method to calculate the rate of carbon burial directly and discuss implications for estimates of global carbon sequestration in seagrass meadows.

2. Methods

We performed a literature review of the field of carbon sequestration in seagrass meadows. We began with international method protocols, and gathered and read the references cited in those documents. Following that review, we performed three literature searches using Google Scholar, with the search terms 'blue carbon,' 'seagrass, carbon,' and 'seagrass, sediment, carbon,' which, although the latter two overlapped in part, did not all produce exactly the same set of results. We evaluated the top 300 results of each search, selecting papers for review based initially on article title, and in cases where the title was unclear, on article abstract.

We included in the review all six published international protocols that we discovered, all the papers that described methods for calculating carbon sequestration in the sediments of seagrasses, and all the papers that reported regional or global estimates of sequestration by seagrasses. From these papers and reports, we extracted the local and global carbon sequestration estimates and the methods used to make the estimates. We also included papers and a book that described the biology of seagrasses, where we judged that they would provide useful context for the carbon storage measurements. From a later search on the same terms, we selected a few papers that described the economics of coastal zone management and the application of carbon credits. In addition to the review of the Blue Carbon field, we also selected some papers from the more extensive geochemical literature to illustrate the points that we wished to make regarding the Blue Carbon protocols. We selected the geochemical papers based in part on our own experience in this field, as well as on Google Scholar searches on the terms 'sediment mixing,' 'bioturbation,' 'sediment mixed layer' and 'sediment carbon oxidation.'

3. Results

The objectives of our review were (1) to illustrate why the international protocols for calculating organic carbon sequestration in seagrass sediments were not valid, and (2) to inform the development of proper protocols. Listing incorrect literature and pointing out errors in individual papers would not be productive, given the widespread nature of the problem. Instead we have concentrated on the methods presented in the international protocol documents, referring to the primary literature where necessary to illustrate a point.

Blue Carbon sequestration is a young field, but interest in this field has expanded rapidly. According to the Thompson Reuters ISI Web of Science online citation index (accessed September 28, 2016), the number of papers per year with 'blue carbon' as a topic has increased from one in 2001 to 37 for the first nine months of 2016. The number of citations per year to those papers has increased from 0 to 363 over that period (figure 1). In addition to the primary literature, six international protocols have been developed (Murray and Vegh 2012, CEC 2014, Emmer *et al* 2014, Howard *et al* 2014, IPCC 2014a, Emmer *et al* 2015) that prescribe how to calculate the amount of carbon sequestered by vegetated ecosystems, including seagrass meadows, with a view to awarding carbon credits under the Verified Carbon Standard.

Although the literature on this topic is expanding, it is still relatively limited. Most of the papers that present global-scale estimates rely on a small number of original studies, particularly those by Duarte *et al* (2005) and

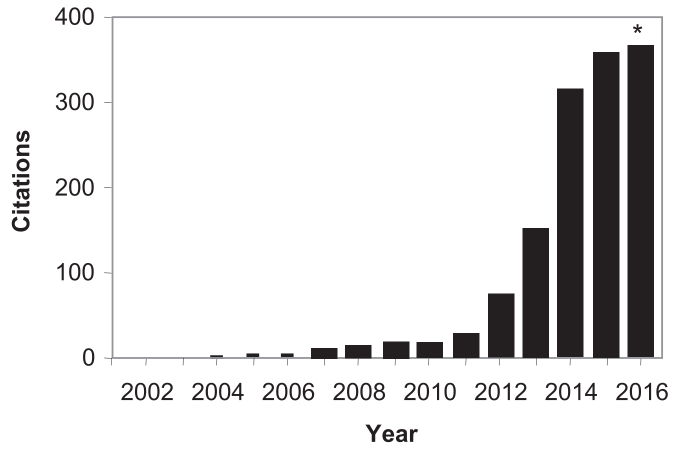

Figure 1. Number of citations per year to papers with 'blue carbon' as a topic, based on Thomson Reuters ISI Web of Science search, September 28, 2016. *The bar for 2016 includes only the first nine months of the year.

Kennedy *et al* (2010), rather than presenting their own independent estimates. We anticipate that the number of independent sequestration estimates will increase, given the increasingly high profile of carbon sequestration in seagrass meadows and other coastal wetlands (e.g. January 2016 Nature Editorial: http://nature.com/news/blue-future-1.19191).

International blue carbon protocols (Murray Vegh 2012, CEC 2014, Emmer *et al* 2014, Howard *et al* 2014, IPCC 2014a, Emmer *et al* 2015) have proposed three approaches for calculating carbon sequestration in seagrass meadows: (1) measure carbon storage in sediments, estimating either the sediment organic carbon inventory (soil carbon stock) or the rate of organic carbon burial; (2) measure gas fluxes (CO_2, O_2, N_2) and calculate sequestration by difference; (3) model or budget the gain or loss of sequestration potential through known or projected human activities and climate change. Since most of the literature relies principally on some measure of carbon storage in sediments, we concentrate here on this first approach, touching only briefly on the other two approaches.

From the protocols and primary literature, we have identified 6 methodological problems with carbon storage calculations that have arisen from a misunderstanding of how sediments receive, process and bury carbon: (1) confusing inventory with flux; (2) extrapolating global rates based on measurements from beds of the *Posidonia* genus, which forms unusually large root mattes; (3) neglecting bioturbation and other sediment mixing; (4) neglecting remineralization of organic carbon in surface sediments; (5) neglecting the effect of the energy of the local environment; and (6) assuming that captured allochthonous carbon represents additional burial that would not have occurred in the absence of the seagrass meadow. The first error results in an incorrect determination of the spatial distribution of carbon burial, while the others all bias the calculated sequestration rates high. Of the 20 papers that provided independent carbon storage or burial estimates, eight based their calculations on *Posidonia* alone or with *Posidonia* weighted disproportionately; six relied on cores or grabs ⩽10 cm long; nine (and all the international protocols) quantified inventory only, rather than flux; one used a budget based on community production; and one did not explain the method clearly enough for us to assess it. Of all the papers that we assessed, only one (Marbà *et al* 2015) applied ^{210}Pb correctly to calculate a sedimentation rate, and none accounted for the remineralization of organic carbon in surface sediments.

4. Sources of error in current methods

4.1. Inventory is not a proxy for flux

A number of studies and protocols propose that a measure of the sediment carbon inventory (soil carbon stock) at multiple locations may be used to compare carbon storage among sites and to identify hotspots of carbon storage for special protection. The difficulty of measuring carbon over the total sediment depth at most sites has led to a proposed practicable standard of measuring carbon inventory in the uppermost 1 m (Howard *et al* 2014, Emmer *et al* 2015). This approach neglects differences in sediment accumulation rate among sites and, as demonstrated below, cannot be used to assess the rate of sequestration (e.g., see Macreadie *et al* 2014).

The rate of vertical accretion of sediments, or sedimentation velocity (cm yr^{-1}), can vary over more than an order of magnitude in a single coastal basin (e.g., Johannessen *et al* 2003). Sedimentation velocity depends partly on the proximity of the site to sediment sources (e.g., rivers, coastal erosion) and partly on the trapping efficiency of the site. Comparing 1 m inventories at two sites with different sedimentation velocities gives a misleading impression of the relative carbon sequestration at the two sites. For example, if a

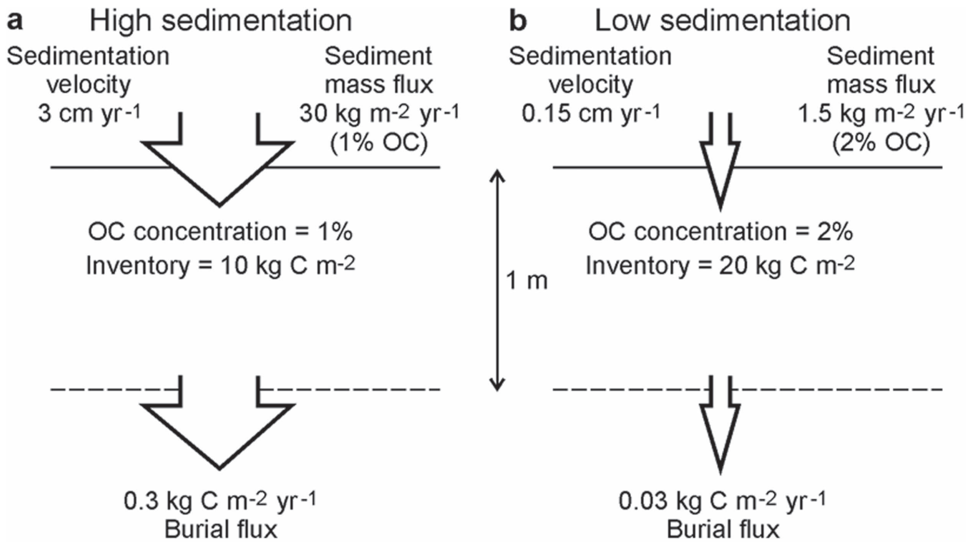

Figure 2. The effect of sedimentation rate on the 1 m inventory of organic carbon and on its burial rate. (a) A site with a high sedimentation rate (3 cm yr^{-1}) and low organic carbon concentration (1%). (b) A site with a low sedimentation rate (0.15 cm yr^{-1}) and high organic carbon concentration (2%). The 1 m inventory is twice as high at site B as at site A, while the actual burial rate of organic carbon is 10 times higher at site A. (Fluxes and concentrations are based on actual values measured in sediment cores on the west coast of Canada. For simplicity the effect of remineralization of organic carbon in surface sediment is neglected.)

location has a high sedimentation velocity (e.g., 3 cm yr^{-1}, figure 2(a)) it can sustain a high carbon burial rate (0.3 kg m^{-2} yr^{-1}) even with sediments containing a low carbon concentration (1%). The top meter of this sediment contains only a small inventory of carbon (10 kg m^{-2}), due to the large accompanying inorganic flux. (In these calculations we neglect the effects of mixing and remineralization, which are discussed below.) In contrast, a site with a lower sedimentation velocity (e.g., 0.15 cm yr^{-1} figure 2(b)) cannot sustain a large carbon burial flux, even with a higher carbon concentration (2%). In the example shown in figure 2, the 1 m inventory implies that twice as much carbon is being sequestered at site B as at site A, while, in fact, the burial rate at site A is ten times as high. Relying on a 1 m inventory to compare rates of carbon storage among locations will give an incorrect view of the spatial distribution of the rate of carbon burial. In this example, the relative importance of site B would be overestimated by a factor of 20.

Although inventory alone is not representative of flux either into or out of the sediment, the change in carbon inventory (carbon stock change) in the uppermost 1m of sediment is sometimes used to quantify carbon burial, with an increase in the inventory being used to indicate flux into the sediment. Even if a complete inventory were established, measuring a change would be difficult, if not impossible. The absolute change in sediment height over time is slow (on the order of 0.1 cm yr^{-1} in nearshore marine sediments away from river mouths), while the seafloor is hummocky, often varying by 2–5 cm in height within a few tens of cm. Where sediment is accumulating at 0.1 cm yr^{-1}, it would take 20–50 years of accumulation to be sure that the height had changed. Horizontal advection of sediment or changing locations of stream or river discharge could further confound the measurement. In addition, because the surface layer of sediment is often much less compacted than deeper layers, the increase in height at the surface will not necessarily correspond to the actual sedimentation velocity. Further, inserting a marker layer as a datum for the change in sediment height does not work in marine sediments undergoing surface mixing, as described in section 4.3.

4.2. Seagrasses are not all equal

Posidonia spp. forms enormous root mattes several meters deep, which after a time essentially become the substrate (Romero *et al* 1994, Lo Iacono *et al* 2008), and *Posidonia* meadows appear to be important locations for carbon burial (e.g., Duarte *et al* 2005). Using ^{210}Pb-dated sediment cores, Marbà *et al* (2015) showed clearly that carbon burial increased in a *Posidonia australis* meadow when the seagrass colonized the site, and decreased when seagrass was lost. In other types of seagrass meadows, where most of the OC storage is in the sediment, not in a root matte, change in OC storage can be more subtle. Carbon burial rates in *Posidonia* meadows are not representative of those in other types of meadows (Lavery *et al* 2013). While seagrasses are distributed globally, *Posidonia* only occurs in the Mediterranean Sea and along the south coast of Australia (Short *et al* 2007). Using rates determined for the anomalous *Posidonia* genus overestimates the global sequestration of carbon by seagrasses, as does including *Posidonia* meadows in an unweighted average of storage rates in different locations and extrapolating to the whole area of occupied by seagrasses.

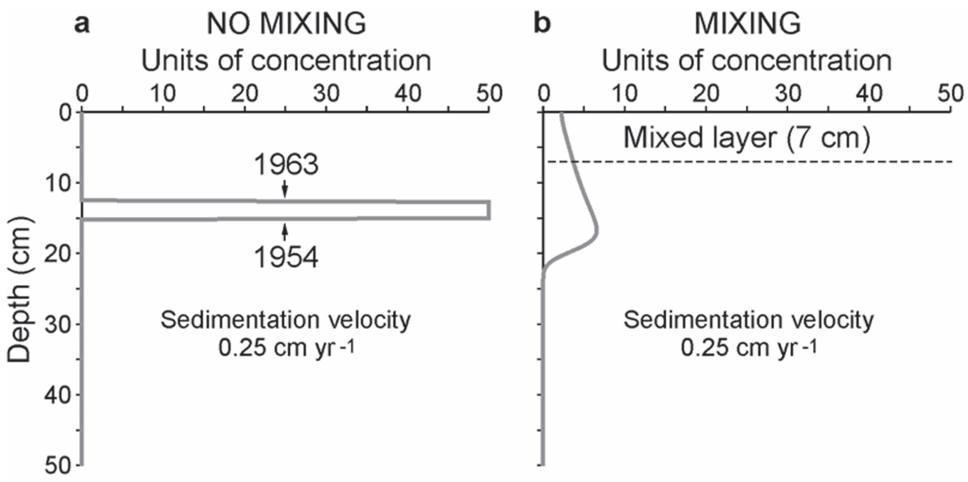

Figure 3. The effect of biomixing on the sediment depth profile observed in 2014 for a transient tracer added to accumulating sediment between 1954 and 1963. Modeled depth profiles show the difference between a sediment with a) no biomixing and b) slow biomixing (3 $cm^2\ yr^{-1}$) within a 7 cm surface mixed layer. Both cores have the same sedimentation velocity (0.25 cm yr^{-1}) and the same tracer input (50 units concentration over 1954–1963). If the initial date of entry (1954) were used to determine the sedimentation rate, the rate calculated in the mixed core would be 1.5 times too high. (Advective-diffusive model based on Guinasso and Schink 1975.)

4.3. Biomixing alters the depth distribution of carbon and tracers

Benthic animals mix the surface layer of marine sediment (Silverberg *et al* 1986, Boudreau 1994), except where the surface sediments are anoxic. In shallow waters, where seagrasses grow, wave energy can also contribute to mixing. Seagrasses tend to reduce the depth of sediment mixing as they become established (Duarte *et al* 2013), but surface sediment mixed layers of 2–3 cm have been reported even in a *Posidonia australis* bed (Marbà *et al* 2015). Mixed layers are likely deeper beneath seagrasses that do not form such dense root mattes. For example, in cores collected from a *Zostera marina* meadow (Greiner *et al* 2013), the ^{210}Pb profile can be interpreted as evidence of a 5–10 cm mixed layer, which is typical for marine sediments globally (Boudreau 1994). The number of years of sediment accumulation that are mixed together in the surface layer depends on the depth of the surface mixed layer and on the sedimentation velocity. For example, in a sediment with a 10 cm mixed layer and 1 cm yr^{-1} sedimentation velocity, 10 years of accumulation are at least partially mixed before the sediment becomes buried below the mixed layer, while, with the same mixed layer depth but a sedimentation velocity of only 0.1 cm yr^{-1}, 100 years of accumulation are mixed before burial.

Any substance introduced at the surface is mixed into the underlying sediment and penetrates to a greater depth than the time since deposition might suggest (figure 3). Consequently, a sedimentation velocity calculated without accounting for mixing will always be too high (Silverberg *et al* 1986). In the example shown in figure 3, the sedimentation rate calculated without considering surface mixing would be 1.5 times too high. Mixing complicates the use of tracers, such as ^{137}Cs, to determine sedimentation velocity using a known date of entry (Johannessen and Macdonald 2012). ^{137}Cs is further complicated by delayed inputs from drainage basins and potential post-deposition diffusion (Smith *et al* 1987, Crusius and Anderson 1995). Similarly, the use of an introduced reference plane (for example, a layer of feldspar, e.g., CEC 2014) will not directly yield a reliable sedimentation velocity, because it will be redistributed vertically by biomixing (unless the layer is thick enough to stop mixing, which would compromise the natural behavior of the seagrass bed under study).

Another implication of mixing is that if seagrass were to be introduced into a barren area with low sedimentation, a subsequent rapid change in organic carbon or ^{210}Pb in the sediment surface layer beneath the seagrass might indicate that the local sedimentation velocity has increased, but cannot be used to calculate that velocity, as the fresh material is rapidly mixed throughout the surface layer.

4.4. Microbes remineralize organic carbon in sediment, even below the surface mixed layer

In a global survey of 946 seagrass sites, Fourqurean *et al* (2012) noted that the concentration of organic carbon usually declined with depth in sediment. Organic carbon is consumed in the sediment by benthic animals and microbes and is remineralized to carbon dioxide, which may then be outgassed to the water. Microbial remineralization continues below the surface mixed layer of sediment, although more slowly than in the upper layer (Stolpovsky *et al* 2015) (figure 4). Carbon cannot be considered truly sequestered on the >100 year timescale required by international protocols (CEC 2014) until it has been buried below the remineralization depth. Therefore, a carbon

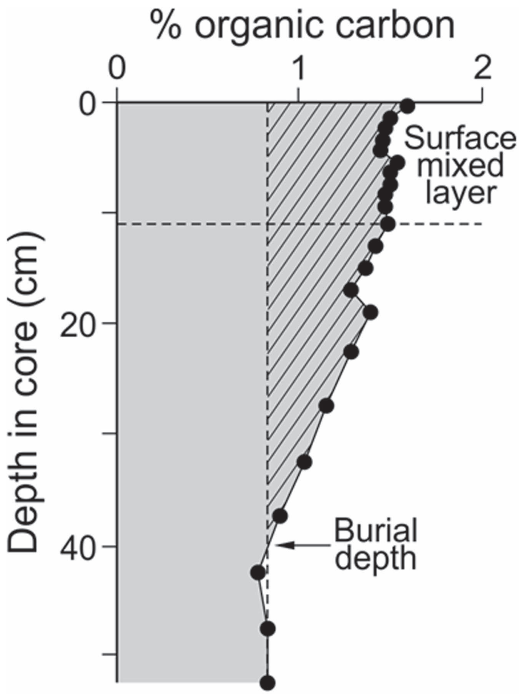

Figure 4. Typical organic carbon concentration profile in a coastal sediment core. Organic carbon continues to be remineralized below the surface mixed layer of the sediment. The concentration becomes approximately constant at the burial depth, below which it is only minimally remineralized. Carbon is not sequestered over the long term until it reaches the burial depth.

burial flux estimated from the surface concentration will usually be too high. In the example shown in figure 4, a carbon burial flux calculated from the surface concentration of organic carbon would be too high by a factor of two. The ratio of surface to buried organic C varies among locations.

4.5. Trapping of organic carbon depends on energy of the environment

Organic particles, such as pieces sloughed off seagrasses, largely settle in calm waters with low turbulent energy, as do the fine particles with which organic matter is strongly associated (Keil *et al* 1994). Seagrasses can grow in substrates ranging from mud to coarse sand, but they thrive best in fine to medium sand (Koch 2001). Locally, the energy may be lower within seagrass beds, which would increase the efficiency of sediment capture (Koch 2001), but much of the organic carbon will be transported out of the relatively high-energy, shallow-water environment of the meadow to settle in the finer mud of nearby, quiescent deep basins, or may be washed up on shore and remineralized.

Kennedy *et al* (2010) reported that the average concentration of sediment organic carbon in seagrass patches globally was 1.8% (median 1.2%), including the exceptionally carbon-rich beds of *Posidonia*. In a subset of the studies reviewed by Kennedy *et al* (2010), where sites inside and outside seagrass patches were compared, the average organic carbon concentration within seagrass patches was 0.34%, while outside it was 0.17%. The inside–outside patch comparison illustrates that seagrasses may indeed increase the capture of organic carbon in sandy sediment. However, 0.34% is well below coastal basin, delta and fjord sediment averages of 0.7%–4% organic carbon (Bornhold 1978, Smith *et al* 2015). Even including the *Posidonia* meadows, the global concentration of organic carbon in seagrass beds is within the range of coastal sediments generally. Underscoring this point, near some seagrass meadows, the adjacent, barren sediment has been found to contain a higher concentration of OC (Orem *et al* 1999). Seagrass beds may not ultimately be particularly effective at capturing the carbon produced by seagrass. Instead, fine-grained coastal basin sediments or rapidly-accumulating sediment near the mouths of rivers may be the preferred sites of OC capture.

4.6. Allochthonous carbon capture does not necessarily represent additional burial

The capture of allochthonous carbon (carbon from outside the meadow), which is sometimes included in estimates of carbon sequestration by seagrasses, represents additional carbon storage only if such carbon would otherwise have been remineralized before burial. If the allochthonous carbon is terrigenous, it might well have been preserved in nearby basin sediments, if it had not been intercepted by the seagrass, since this form of carbon preserves preferentially to marine-derived organic carbon (Hedges and Keil 1995). Its capture by a seagrass meadow would not, in that case, represent additional carbon storage.

4.7. Other methods

4.7.1. Gas exchange

Measuring gas flux gives an instantaneous measure, which neglects short-term and seasonal variability, and results in a value that might be very different from the rate of carbon burial over the century timescale required to comply with the Verified Carbon Standard. In addition, this method does not satisfy the requirement that carbon be buried below the depth of remineralization before it is considered sequestered. A final problem is that carbon buried in seagrass beds may come from several outside sources, as well as from the seagrass beds themselves (figure 5). Accordingly, constructing a budget for carbon burial based on net gas fluxes balances the carbon fixation by seagrass alone against the remineralization of carbon from all three sources.

4.7.2. Modeling or budgeting gains and losses

Modeling gain or loss through known or projected local activities and climate change can be robust, but it requires measuring or estimating a large number of parameters. Often this approach requires the

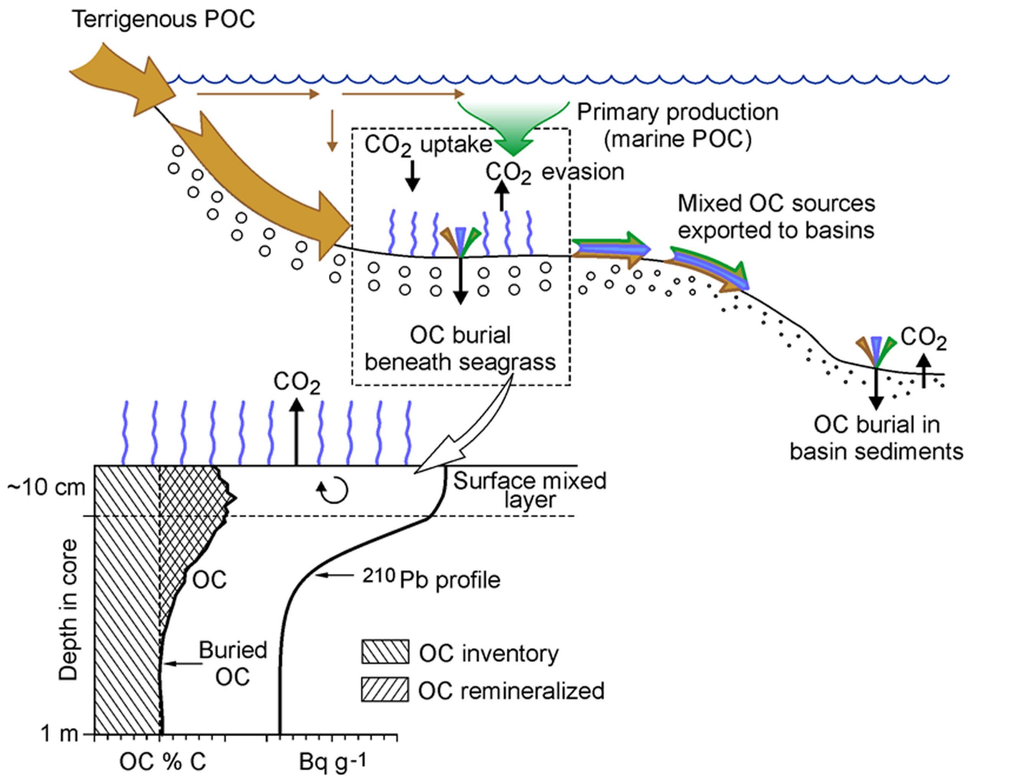

Figure 5. Carbon cycling and burial in coastal sediments with seagrass patches and an adjacent deep basin. Carbon fixed by seagrasses and phytoplankton sinks to the sediment along with terrigenous organic carbon that passes through the site. Some of the carbon is remineralized in the water column; some continues downslope to the quieter waters and finer sediment of the deep basin. Waves and benthic animals mix the sediment. A portion of the organic carbon that reaches the sediment is remineralized before burial by benthic animals and microbes. The remaining portion of organic carbon, whether in sediments of seagrass beds, barren regions or basins, is sequestered on a timescale greater than 100 years.

calculation of a small difference between much larger values, resulting in large uncertainties in the estimate. Similarly, constructing a complete system budget (e.g., Macreadie *et al* 2014) can be useful but requires the measurement of a large number of parameters, and could be subject to aliasing, because the time scale of gas flux is much less than that of burial.

5. A direct method to determine the rate of carbon sequestration in seagrass sediments

The rate of carbon burial can be calculated from a representative set of sediment cores in four steps. For each core: (1) determine the sedimentation velocity (cm yr^{-1}); (2) convert sedimentation velocity to sediment accumulation rate (g cm^{-2} yr^{-1}); (3) determine the burial concentration of organic carbon; (4) multiply the sediment accumulation rate by the carbon burial concentration (Johannessen *et al* 2003). We will not exhaustively review the methodology for calculating sediment accumulation rate here, since it has been widely reported in the marine geochemical literature (e.g., Muhammad *et al* 2008).

Briefly, the sedimentation velocity can be determined from sediment cores, using the decay of ^{210}Pb with depth below the surface mixed layer (Lavelle *et al* 1986; ^{210}Pb decay constant 0.03114 yr^{-1}; half-life 22.3 years), assuming a constant rate of supply of ^{210}Pb (Robbins 1978). Unlike ^{137}Cs dating, the ^{210}Pb method can be applied to mixed sediments, because the sedimentation velocity (cm yr^{-1}) is calculated from the rate of decay of ^{210}Pb with depth, rather than from the concentration or activity at one specific depth. The sediment accumulation rate (g cm^{-2} yr^{-1}) is calculated from the sedimentation velocity and the average porosity of sediment below the mixed layer (Lavelle *et al* 1986).

The concentration of organic carbon, which can be measured in the same core subsections as the ^{210}Pb, usually declines with depth. At some depth, generally about 25–40 cm, the concentration of organic carbon becomes approximately constant with depth (figure 4)—this provides an estimate of the burial concentration, although this concentration might still be too high by virtue of any residual OC metabolism occurring deeper within the core. The carbon burial or sequestration rate is the product of the sediment accumulation rate and the burial concentration of organic carbon.

An estimated 29% of the area of vegetated coastal ecosystems was lost between 1879 and the early 2000s, due to human activities along the coast (Orth *et al* 2006, Waycott *et al* 2009). The total global area of

Table 1. Global estimate of carbon sequestration potential of seagrass meadows.

	Min	Max	Reference/notes
Global area of seagrass (km^2)	1.77×10^5	6.00×10^5	Pendleton *et al* 2012 (17.7–60 Mha)
% additional organic C due to seagrasses	0.085	0.17	Max: Kennedy *et al* 2010 (inside patch 0.34% minus outside patch 0.17%). Min: half of max, for surface/buried organic C ratio
Sediment accumulation rate (g cm^{-2} yr^{-1})	0.003	1.1	Unknown. Global coastal range,[a] including 0.04 g cm^{-2} yr^{-1} in Posidonia australis meadow (Marbà *et al* 2015)
Global C sequestration by seagrasses	1.5×10^7	1.0×10^{10}	Calculated from values above
Previous global estimates	4.8×10^{10}	1.12×10^{11}	e.g. Kennedy *et al* (2010)
Overestimate factor	11	3100	Ratio of previous to this estimate, max:max, min:min

[a] Global range from Boudreau (1994) and references therein, as well as from Zuo *et al* (1991), Alvisi (2009), Kuzyk *et al* (2013), Junttila *et al* (2014), Marbà *et al* (2015), and Emeis *et al* (2000), representing the eastern and western margins of the Pacific Ocean, the western Atlantic, the Baltic Sea, the southern Indian and Arctic Oceans and the Mediterranean Sea.

seagrass meadows is estimated at 1.77×10^5–6.00×10^5 km^2 (17.7–60 Mha; Pendleton *et al* 2012). With respect to changes in the global carbon cycle, it is important to determine how much the ocean's ongoing carbon sequestration capacity has declined with loss of biomass in these ecosystems, or how much capacity could be regained by restoring biomass. The loss or gain of inventory is an important consideration, but, unlike burial flux, inventory changes do not provide a sustained mechanism to sequester carbon. For climate change mitigation, it is the change in long-term sequestration *rate* that ultimately matters. The potential change in carbon sequestration rate can be determined by comparing carbon burial rates at vegetated and non-vegetated sites within areas having similar physical conditions (grain size, proximity to river, etc).

6. Global estimates of carbon sequestration by seagrasses

Global estimates of carbon sequestration by seagrasses are biased high. Most estimates have been based on the concentration or inventory of carbon in the uppermost 5–10 cm of underlying sediments (Kennedy *et al* 2010), which neglects the effect of remineralization of organic carbon in sediment. Even values determined over a greater sediment depth range overestimate sequestration, if they include the surface values. Habitat and species matter to carbon capture efficiency (Lavery *et al* 2013): *Posidonia spp*, on which many estimates are largely based, is not representative of seagrass beds in general, because it forms unusually large root mattes that persist over hundreds of years. Neglecting the effects of surface sediment mixing also overestimates the sediment accumulation rate and consequently the rate of carbon sequestration, as does including the capture of terrigenous carbon which would otherwise have been buried in nearby basin sediments. Confounding flux with concentration or inventory gives an incorrect impression of how effective various seagrass meadows are at sequestering carbon, and which areas are the most important to protect.

Table 1 shows a revised global estimate of the carbon burial potential of seagrass meadows, using published sediment accumulation rates for coastal areas not immediately adjacent to large rivers and using a value for the buried concentration of organic carbon in excess of that which would have been in the sediment in the absence of seagrass. The estimate is highly uncertain (ranging over three orders of magnitude), because the data required to make this calculation have generally not been collected or reported during blue carbon studies. This estimate suggests that the previously-published global values for carbon burial by seagrasses are too high by 10–3000 times. However, the calculation needs to be refined with accurate sedimentation rates and buried concentrations of organic carbon measured in seagrass meadows around the world.

Beyond these problems in estimating flux at a given site is the question of whether planting new seagrasses in an area increases the overall storage of carbon. If the water is replete with nutrients, as many coastal zones are, then organic carbon sequestration might be increased by adding more seagrass, but in areas of nutrient limitation, the seagrass might expand only at the expense of other primary producers. In the latter case, the critical question is whether seagrass carbon is more efficiently preserved than is the phytoplankton carbon or other fixed carbon that it is replacing. This might well be the case, given that seagrass (C3–4 plants, Touchette and Burkholder 2000) produces structural compounds like lignins, which are relatively biologically refractory. This effect has not been demonstrated, but it is worth investigation.

There is no question that seagrass beds are important ecologically, nor is there any doubt that they have been shrinking rapidly. But whether replanting or restoring seagrass beds will add to the total capture of atmospheric carbon dioxide has not yet been established. A reliable estimate of the magnitude of carbon

burial by seagrasses requires sediment accumulation rates that explicitly account for the effects of bioturbation, as well as organic carbon profiles that extend to at least 40 cm depth. Without such data, geoengineering with seagrasses remains unproven, and basing carbon credits on overblown estimates of its effectiveness might actually sanction overall increases in carbon dioxide emissions.

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References

Alvisi F 2009 A simplified approach to evaluate sedimentary organic matter fluxes and accumulation on the NW Adriatic Shelf (Italy) *Chem. Ecol.* **25** 119–34

Bornhold B D 1978 Carbon/nitrogen (C/N) ratios in surficial marine sediments of British Columbia. *Sci. Tech. Notes Curr. Res.* C **78** 108–12

Boudreau B P 1994 Is burial velocity a master parameter for bioturbation? *Geochim. Cosmochim. Acta* **58** 1243–9

CEC 2014 *Greenhouse Gas Offset Methodology Criteria for Tidal Wetland Conservation* Commission for Environmental Cooperation, Montreal, p 36

Crusius J and Anderson R F 1995 Evaluating the mobility of ^{137}Cs, ^{239,240}Pu, and ^{210}Pb from their distributions in laminated lake sediments *J. Paleolimnol.* **13** 119–41

Duarte C M, Kennedy H, Marbà N and Hendriks I 2013 Assessing the capacity of seagrass meadows for carbon burial: current limitations and future strategies *Ocean Coast. Manage.* **83** 32–8

Duarte C M, Marbà N, Gacia E, Fourqurean J W, Beggins J, Barrón C and Apostolaki E T 2010 Seagrass community metabolism: assessing the carbon sink capacity of seagrass meadows *Glob. Biogeochem. Cycles* **24** GB4032

Duarte C M, Middelburg J J and Caraco N 2005 Major role of marine vegetation on the oceanic carbon cycle *Biogeosciences* **2** 1–8

Emeis K-C, Struck U, Leipe T, Pollehne F, Kunzendorf H and Christiansen C 2000 Changes in the C, N, P burial rates in some Baltic Sea sediments over the last 150 years —relevance to P regeneration rates and the phosphorus cycle *Mar. Geol.* **167** 43–59

Emmer I, Emmett-Mattox S and Crooks S 2014 Methodology for tidal wetland and seagrass restoration (Silvestrum: University of Maryland) Restore America's Estuaries, Smithsonian Environmental Research Center, Chesapeake Bay Foundation, University of Virginia, (Arlington, Virginia), 85 pp

Emmer I, von Unger M, Needelman B, Crooks S and Emmett-Mattox S 2015 *Coastal Blue Carbon in Practice: Manual for Using the VCS Methodology for Tidal Wetland and Seagrass Restoration* VM0033 Restore America's Estuaries, Silvestrum, Arlington p 82

Fourqurean J W *et al* 2012 Seagrass ecosystems as a globally significant carbon stock *Nat. Geosci.* **5** 505–9

Green E P and Short F T 2003 *World Atlas of Seagrasses* (Berkeley: UNEP World Conservation Monitoring Centre, University of California Press)

Greiner J T, McGlathery K J, Gunnell J and McKee B A 2013 Seagrass restoration enhances 'blue carbon' sequestration in coastal waters *PLoS One* **8** e72469

Guinasso N L and Schink D R 1975 Quantitative estimates of biological mixing rates in abyssal sediments *J. Geophys. Res.* **80** 3032–43

Hedges J I and Keil R G 1995 Sedimentary organic matter preservation: an assessment and speculative synthesis *Mar. Chem.* **49** 81–115

Howard J, Hoyt S, Isensee K, Pidgeon E and Telszewski M E 2014 Coastal blue carbon: methods for assessing carbon stocks and emissions factors in mangroves, tidal salt marshes, and seagrass meadows *Conservation Int., Intergovernmental Oceanographic Commission of UNESCO, Int. Union for Conservation of Nature (Arlington, VA)* p 181

IPCC 2014a *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* ed T Hiraish *et al* (Cambridge: Cambridge University Press) p. vi + 55 pp

IPCC 2014b Summary for policymakers *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* ed O Edenhofer *et al* (Cambridge: Cambridge University Press)

Johannessen S C and Macdonald R W 2012 There is no 1954 in that core! Interpreting sedimentation rates and contaminant trends in marine sediment cores *Mar. Pollut. Bull.* **64** 675–8

Johannessen S C, Macdonald R W and Paton D W 2003 A sediment and organic carbon budget for the greater Strait of Georgia *Estuarine, Coast. Shelf Sci.* **56** 845–60

Junttila J J, Carroll K, Husum and Dijkstra N 2014 Sediment transport and deposition in the Ingøydjupet trough, SW Barents Sea *Cont. Shelf Res.* **76** 53–63

Keil R G, Montluçon D B, Prahl F G and Hedges J I 1994 Sorptive preservation of labile organic matter in marine sediments *Nature* **370** 549–52

Kennedy H, Beggins J, Duarte C M, Fourqurean J W, Holmer M, Marbà N and Middelburg J J 2010 Seagrass sediments as a global carbon sink: isotopic constraints *Glob. Biogeochem. Cycles* **24** GB4026

Koch E W 2001 Beyond light: physical, geological, and geochemical parameters as possible submersed aquatic vegetation habitat requirements *Estuaries* **24** 1–17

Kuzyk Z Z A, Gobeil C and Macdonald R W 2013 ^{210}Pb and ^{137}Cs in margin sediments of the Arctic Ocean: controls on boundary scavenging *Glob. Biogeochem. Cycles* **27** 422–39

Lavelle J W, Massoth G J and Crecelius E A 1986 Accumulation rates of recent sediments in Puget Sound, Washington *Mar. Geol.* **72** 59–70

Lavery P S, Mateo M A, Serrano O and Rozaimi M 2013 Variability in the carbon storage of seagrass habitats and its implications for global estimates of blue carbon ecosystem service *PLoS One* **8** e73748

Lo Iacono C, Mateo M A, Gràcia E, Guasch L, Carbonell R, Serrano L, Serrano O and Dañobeitia J 2008 Very high resolution seismo-acoustic imaging of seagrass meadows (Mediterranean Sea): implications for carbon sink estimates *Geophys. Res. Lett.* **35** L18601

Macreadie P I, Baird M E, Trevathan-Tackett S M, Larkum A W D and Ralph P J 2014 Quantifying and modelling the carbon sequestration capacity of seagrass meadows—a critical assessment *Mar. Pollut. Bull.* **83** 430–9

Marbà N, Arias-Ortiz A, Masqué P, Kendrick G A, Mazarrasa I, Bastyan G R, Garcia-Orellana J and Duarte C M 2015 Impact of seagrass loss and subsequent revegetation on carbon sequestration and stocks *J. Ecol.* **103** 296–302

Moore J C, Jevrejeva S and Grinsted A 2010 Efficacy of geoengineering to limit 21st century sea-level rise *Proc. Natl Acad. Sci.* **107** 15699–703

Muhammad Z, Bentley S J, Febo L A, Droxler A W, Dickens G R, Peterson L C and Opdyke B 2008 Excess ^{210}Pb inventories and fluxes along the continental slope and basins of the Gulf of Papua *J. Geophys. Res.: Earth Surf.* **113** F01S17
Murray B C and Vegh T 2012 *Incorporating Blue Carbon as a Mitigation Action Under the United Nations Framework Convention on Climate Change: Technical Issues to Address* Nicholas Institute for Environmental Policy Solutions, Duke University, Durham, North Carolina, p 20
Nibleus K and Lundin R 2010 Climate change and mitigation *AMBIO* **39** 11–7
Orem W H, Holmes C W, Kendall C, Harry E L, Ann L B, Steven R S, Anne B, Margo C, Marot M and Cheryl H 1999 Geochemistry of Florida bay sediments: nutrient history at five sites in eastern and central Florida Bay *J. Coast. Res.* **15** 1055–71
Orth R J *et al* 2006 A global crisis for seagrass ecosystems *BioScience* **56** 987–96
Pendleton L *et al* 2012 Estimating global 'blue carbon' emissions from conversion and degradation of vegetated coastal ecosystems *PLoS One* **7** e43542
Robbins J A 1978 Geochemical and geophysical applications of radioactive lead *The Biogeochemistry of Lead in the Environment* ed Nriagu (Amsterdam: Elsevier, North-Holland) pp 285–393
Romero J, Pérez M, Mateo M A and Sala E 1994 The belowground organs of the Mediterranean seagrass Posidonia oceanica as a biogeochemical sink *Aquatic Bot.* **47** 13–9
Short F T, Carruthers T J B, Dennison W C and Waycott M 2007 Global seagrass distribution and diversity: a bioregional model *J. Exp. Mar. Biol. Ecol.* **350** 3–20
Silverberg N, Nguyen H V, Delibrias G, Koide M, Sundby B, Yokoyama Y and Chesselet R 1986 Radionuclide profiles, sedimentation rates, and bioturbation in modern sediments of the Laurentian Trough, Gulf of St. Lawrence *Oceanol. Acta* **9** 285–90
Smith J N, Ellis K M and Nelson D M 1987 Time-dependent modeling of fallout radionuclide transport in a drainage basin: Significance of 'slow' erosional and 'fast' hydrological components *Chem. Geol.* **63** 157–80
Smith R W, Bianchi T S, Allison M, Savage C and Galy V 2015 High rates of organic carbon burial in fjord sediments globally *Nat. Geosci.* **8** 450–3
Stolpovsky K, Dale A W and Wallmann K 2015 Towards a parameterization of global-scale organic carbon mineralization kinetics in surface marine sediments *Glob. Biogeochem. Cycles* **29** 812–29
Touchette B W and Burkholder J M 2000 Overview of the physiological ecology of carbon metabolism in seagrasses *J. Exp. Mar. Biol. Ecol.* **250** 169–205
Waycott M *et al* 2009 Accelerating loss of seagrasses across the globe threatens coastal ecosystems *Proc. Natl Acad. Sci.* **106** 12377–81
Williamson P, Wallace D, Law C S, Boyd P W, Collos Y, Croot P, Denman K, Riebesell U, Takeda S and Vivian C 2012 Ocean fertilization for geoengineering: a review of effectiveness, environmental impacts and emerging governance *Process Saf. Environ. Prot.* **90** 475–88
Zuo Z Z, Eisma D and Berger G W 1991 Determination of sediment accumulation and mixing rates in the Gulf of Lions, Mediterranean Sea *Oceanol. Acta* **14** 253–62