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Carbon Footprints

Technical Note

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How to quantify blue carbon sequestration rates in seagrass meadow sediment: geochemical method and troubleshooting

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Abstract

Seagrasses take up carbon dioxide and transform it into organic carbon, some of which is buried in meadow sediments. Very high carbon burial rates have been claimed for seagrass meadows globally, and international protocols have been developed with a view to awarding carbon offset credits. However, recent geochemical work has shown that a misunderstanding of how marine sediment buries and processes organic carbon has led to overestimates of at least an order of magnitude. Common blue carbon methodology does not adequately account for bioturbation or remineralization in surface sediment, and there is often a conflation of standing stock with ongoing burial. To determine accurate seagrass carbon burial rates requires the following steps: (1) Determine the sediment accumulation rate below the surface mixed layer, using ^{210}Pb and porosity; (2) Determine the burial concentration of organic carbon; (3) Multiply the sediment accumulation rate by the buried % organic carbon; (4) If excluding allochthonous carbon burial, use biomarkers to determine the proportion of seagrass-derived organic carbon; and (5) Account for the offset due to the burial of carbonate formed inside the meadow. Seagrass meadows provide valuable habitat and protect coastlines from erosion. They can also play a role in short-term carbon sequestration. However, if carbon credits are awarded based on inflated estimates and used to offset emissions elsewhere, the net effect could be an increase in carbon dioxide emissions to the atmosphere.

Keywords: Sediment, blue carbon, seagrass, sequestration, burial, methodology, remineralization, bioturbation

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INTRODUCTION

Seagrasses take up carbon dioxide and transform it into organic carbon, burying a portion of it in the meadow sediment. Very high carbon sequestration rates have been claimed for seagrass meadows globally (27-44 TgC yr^{-1}[1], representing 10%-18% of the ocean's carbon sequestration in just 0.1% of the area[1]). This has led to interest in developing a market for carbon offset credits for their expansion or protection[2]. Because seagrass meadows are undeniably important as critical habitat and for coastline protection, local food security, and ecotourism[3], protecting them seems like a no-regrets activity. However, marine geochemical work has shown that common methodology systematically biases local sequestration rates high, leading to an overestimate of at least an order of magnitude on a global scale[4,5]. If carbon credits are awarded on the basis of overstated sequestration estimates and used to offset increased emissions elsewhere, there could be a net increase in the flux of carbon dioxide to the atmosphere.

Carbon burial in vegetated ecosystems, such as seagrass meadows, cannot truly offset emissions of ancient fossil fuels, because of the orders of magnitude difference in timescale (seasons to hundreds of years for meadow sediment *vs*. hundreds of millions of years for fossil fuels)[6,7]. However, increased burial in these ecosystems could provide a short-term sink to buy time to consider other options for climate change mitigation.

Standing stock and burial flux give different information about carbon stored in the sediment. Stock is the inventory of organic carbon over a defined depth of sediment, often the top 1 m, e.g.,[8]. It is a measure of the carbon that has already been fixed and stored, and which no longer draws down additional carbon dioxide. Burial flux is a measure of the ongoing rate of capture and burial of carbon.

It is useful to measure stock to quantify and map the vulnerable carbon as a liability assessment of potential future release due to physical disturbance or climate change[9,10], which would add to a country's total carbon emissions. However, only carbon burial flux represents the potential for ongoing, additional carbon storage. The remainder of this paper will discuss how to calculate carbon burial flux and some important considerations.

Field methods for the collection of sediment cores in seagrass meadows have been described elsewhere, including the importance of site selection[11,12] and reducing and quantifying compaction[13]. The purpose of this Technical Note is to present a specific, step-by-step method for interpreting sediment core profiles in seagrass meadow sediment, building on the author's previously published, broad critique of common blue carbon methodology[4].

Geochemical oceanographers devised a methodology for determining accurate sedimentation and organic carbon burial rates in marine sediment in the 1970s-1990s, e.g.,[14-18]. This paper presents that methodology, modified for use in seagrass meadow sediment. The first part of the paper discusses the effects of bioturbation, remineralization, allochthonous (non-seagrass-derived) organic carbon, and the formation and burial of inorganic carbon within the meadow. The second part presents a step-by-step method and includes example profiles of ^{210}Pb and organic carbon to help with interpretation in non-ideal sedimentary settings.

IMPORTANT CONSIDERATIONS: BIOTURBATION, REMINERALIZATION, ALLOCHTHONOUS CARBON, AND EFFECT OF CARBONATE

Effects of bioturbation on sediment core profiles

In most parts of the ocean, surface sediment is mixed (bioturbated) by the activities of animals that live in or on the sediment[19]. In the intertidal or shallow subtidal zone, sediment can also be mixed by waves. Bioturbation and wave-mixing result in a surface mixed layer (SML) in most marine sediment. The average depth of the SML globally is 9.8 ± 4.5 cm[19]. Published estimates of SML depth in seagrass meadow sediment are rare, but range from 2-3 cm[20] to 15 cm[21].

Bioturbation or wave mixing affects the profiles of transient tracers in sediment [Figure 1]. It smears multiple years of sedimentation together[22]. For example, in sediment that accumulates at 0.1 cm yr^{-1}, with a 2-3 cm SML[20], 20-30 years of sediment are mixed together. Consequently, it is incorrect to assign a discrete year to a particular depth in a mixed core[23].

An introduced tracer, such as a layer of feldspar, e.g.[24], would be mixed to a greater depth than it would have reached without mixing. Similarly, ^{137}Cs, which entered the environment in 1954, will be found in most marine sediment at a greater depth than it would have reached in the absence of mixing[23]. Using a tracer without accounting for mixing always overestimates the sedimentation rate[23]. The Appleby[25] Constant Rate of Supply methodology cannot be used to determine a variable sedimentation rate in a mixed core; it is designed only for undisturbed cores, such as those collected in anoxic basins.

Bioturbated cores can be interpreted, but mixing must be taken into account, as described in below.

Carbon remineralization in surface sediment

Bioturbating animals consume some of the organic carbon, remineralizing it to CO_2 and reducing the amount available to be buried [Figure 2][26,27]. Remineralization continues below the surface mixed layer (SML) due to the microbial degradation of organic matter. (Microbial remineralization occurs even in the absence of bioturbation). Mixing moves oxygen deeper into the core, which increases the rate of microbial degradation[18].

Eventually, the organic carbon is buried to a depth where it only degrades very slowly. This is the effective carbon burial depth[4]. The % organic carbon at the burial depth represents the buried % organic carbon. As illustrated in Figure 2, measuring organic carbon in the top 10 cm, as is commonly the case in blue carbon studies, e.g.,[1,28], would overestimate the amount of carbon buried.

Whether to include allochthonous carbon

The total organic carbon measured in seagrass meadow sediment represents a combination of seagrass carbon and carbon from other sources (allochthonous carbon + phytoplankton). These other sources of carbon include terrigenous material from land runoff, marine-derived material, such as phytoplankton, and organic matter transferred from other nearby blue carbon ecosystems, such as mangroves. There has been some disagreement over whether to include or exclude the allochthonous carbon in the sequestration rate calculated for the seagrass meadow, e.g.,[29] *vs.*[30].

For the calculation of carbon offset credits, the Voluntary Carbon Standard protocol, VM0033[31], specifies that allochthonous carbon is to be excluded. That can be done using biomarkers, as discussed in Section "Separate seagrass carbon from total organic carbon using biomarkers" below.

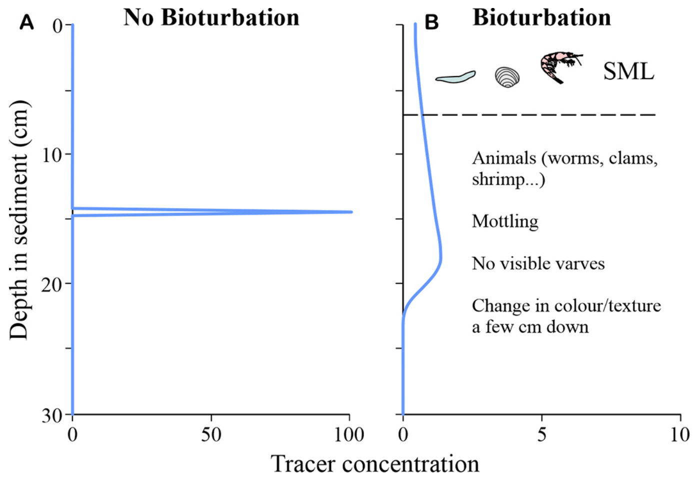

Figure 1. Effects of bioturbation on tracer profiles in sediment (modified from[4]). Modeled tracer concentration profile that would result after 60 years of sedimentation at 0.25 cm yr^{-1}, with the same initial tracer concentration in both panels: (A) with no bioturbation, and (B) with slow bioturbation (3 cm^2 yr^{-1}) within a 7 cm surface mixed layer. Note that the bottom of the tracer pulse reaches 14.5 cm in panel a and 24.5 cm in (B). If a sedimentation rate were calculated based on a known date of entry of the tracer in this mixed sediment, without accounting for mixing, the calculated rate would be 1.7 times too high.

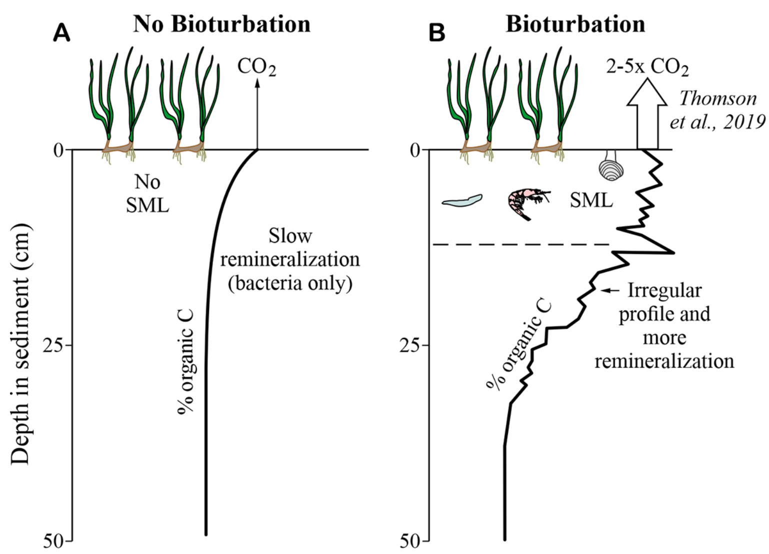

Figure 2. Effect of remineralization on organic carbon profiles in sediment (modified from[4]), with CO_2 efflux result from[26]. Organic carbon concentration declines with depth due to microbial remineralization, even in the absence of bioturbation (A). With bioturbation (B), remineralization is rapid and irregular and continues deeper into the core, resulting in a greater reduction in organic carbon burial. In both cases, using the concentration of organic carbon in the top 10 cm would overestimate the rate of carbon burial.

Effect of carbonate

Inorganic carbon (e.g., carbonate-rich parts of seagrasses or calcium carbonate shells from associated meiofauna) is often buried along with organic carbon in seagrass meadows[32]. When calcium carbonate is formed, it has the non-intuitive effect of releasing carbon dioxide[33]. At the current pH of seawater, approximately 0.6 moles of CO_2 are released for every mole of carbonate formed, and the ratio is expected to increase as seawater pH continues to decline[33]. The burial of inorganic carbon locks in this CO_2 release[32].

Consequently, the burial of inorganic carbon that was formed within the meadow offsets some of the organic carbon burial [Figure 3]. Note that if the inorganic carbon buried in the meadow comes from land and is just being moved from one reservoir to the other, there is no offset effect [Figure 3][34].

STEP-BY-STEP SEDIMENT CARBON BURIAL CALCULATION METHOD

The method is summarized in Table 1 and described below. Steps 1-3 describe a general method for calculating the rate of total organic carbon burial in marine sediment. Steps 4 and 5 present modifications specific to seagrass meadows: determining the proportion of organic carbon derived from the seagrass itself, and accounting for the offset due to the burial of inorganic carbon formed within the meadow.

Determine sediment accumulation rate

Radioactive lead, ^{210}Pb, is produced in the atmosphere from the decay of ^{222}Rn. It sticks to particles, which sink through the water column and settle to the seafloor. ^{210}Pb decays with a half-life of 22.26 years[35]. As sediment accumulates, the older material is buried, leading to a decline in ^{210}Pb activity with depth, which can be used to determine the sedimentation velocity (cm yr^{-1})[35].

Radioactive decay of radium in the sediment continually produces new ^{210}Pb; this is the supported ^{210}Pb[35]. The supported ^{210}Pb is subtracted from the total ^{210}Pb activity to determine the excess ^{210}Pb, which is the part that, below the surface mixed layer, declines in proportion to the sedimentation velocity[35].

The bottom of the surface mixed layer is usually marked by a change in the slope of the depth profile of total or excess ^{210}Pb [Figure 4A and B][16]. After about five half-lives (~110 years), the excess ^{210}Pb is exhausted. The profile becomes approximately constant with depth, once only the supported ^{210}Pb remains [Figure 4A]. The sedimentation velocity, w_s (cm yr^{-1}), is calculated from the slope of the plot of ln(Excess ^{210}Pb) *vs*. depth (cm^{-1}), below the SML and above the depth where ^{210}Pb reaches background (Equation 1)[16].

$$w_s = -0.03114/\text{slope} \tag{1}$$

where -0.03114 yr^{-1} is the decay rate constant of ^{210}Pb. It is important to collect a core that is long enough to see the decay of ^{210}Pb with depth below the SML. In coastal sediment, a ~ 40 cm core is generally long enough. The uppermost section of the core should be sub-sectioned finely enough to identify the SML, e.g., 1-cm intervals for at least the top 10 cm. Deeper intervals can be sub-sectioned at the same or somewhat coarser (2-5 cm) resolution.

The sedimentation velocity is converted to a mass accumulation rate, r_s (g cm^{-2} yr^{-1}), using the porosity, ϕ and the sediment density, ρ_s (g cm^{-3}) (Equation 2)[16].

$$r_s = w_s(1-\phi)\rho_s \tag{2}$$

The porosity can be determined from the ratio of dry mass (g) to wet volume (cm^{-3}) in each subsection of the core (Equation 3). (The analytical lab can provide a correction for the mass of salt based on the salinity of the overlying seawater.)

$$\phi = 1 - (\text{dry mass}/\text{wet volume})\rho_s^{-1} \tag{3}$$

Table 1. Summary of steps to determine net, additional carbon burial due to seagrass

Step	Notes
1. Determine sediment accumulation rate	
Section sediment core	Minimize/quantify compaction; use high enough resolution to identify SML e.g. 1-cm resolution for ≥ top 10 cm; Coarser (2-5 cm) OK in deeper part of core
Analyze radioisotopes for dating	^{210}Pb in all sections to bottom of core (~40-50 cm); ^{226}Ra or ^{214}Pb in ≥ 3 segments to determine supported ^{210}Pb
Identify surface mixed layer	Layer above the inflection point in the total or excess ^{210}Pb profile
Determine sedimentation velocity (cm yr^{-1})	From ln(Excess ^{210}Pb) profile below SML and above background
Convert to sediment accumulation rate (g cm^{-2}yr^{-1})	Use porosity below SML
2. Determine carbon burial %	Plot % organic C *vs.* depth; find ~ constant value in deep section of core
3. Calculate total organic C burial rate	Multiply % buried organic C by sediment accumulation rate
4. Correct for % seagrass C buried, if excluding allochthonous organic C	Use biomarkers to i.d. proportion of seagrass carbon; determine % seagrass organic C buried and multiply by accumulation rate
5. Correct for carbonate formed and buried within the meadow	Subtract 0.6 moles of organic C for every 1 mole locally-formed inorganic C buried

SML: Surface mixed layer.

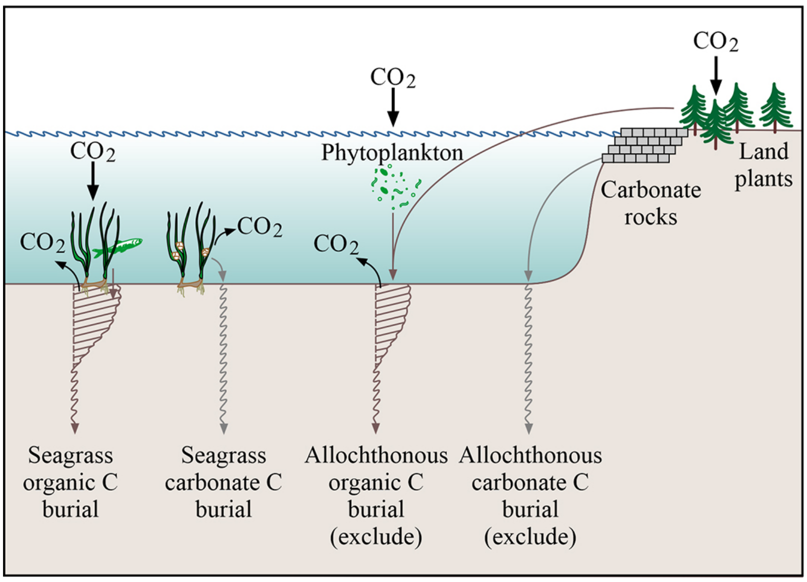

Figure 3. Cartoon representing deposition of seagrass-related and allochthonous organic and inorganic carbon, showing remineralization of organic carbon in surface sediment. Organic C in the deep part of the left-hand profile represents sequestered seagrass organic carbon, which is offset by the burial of inorganic C formed inside the meadow. Allochthonous organic and allochthonous inorganic C are both excluded from the calculation, because neither results from the presence of the seagrass meadow.

This requires the measurement or assumption of a sediment density. In sediment that is primarily inorganic, with only a few percent organic C, that can be approximated by the density of quartz sand or clay minerals (2.65 g cm^{-3}); Lavelle *et al.* (1986) used a measured density of 2.6 g cm^{-3} in Puget Sound, USA[16]. If the sediment is very organic-rich at a particular site, it would be advisable to measure the density of sediment there.

Troubleshooting ^{210}Pb profiles

^{210}Pb profiles are not always as ideal as those illustrated in Figures 4A and B, particularly in seagrass meadow sediment, which is frequently disturbed by waves and benthic animals. Figure 4 illustrates ^{210}Pb profiles that

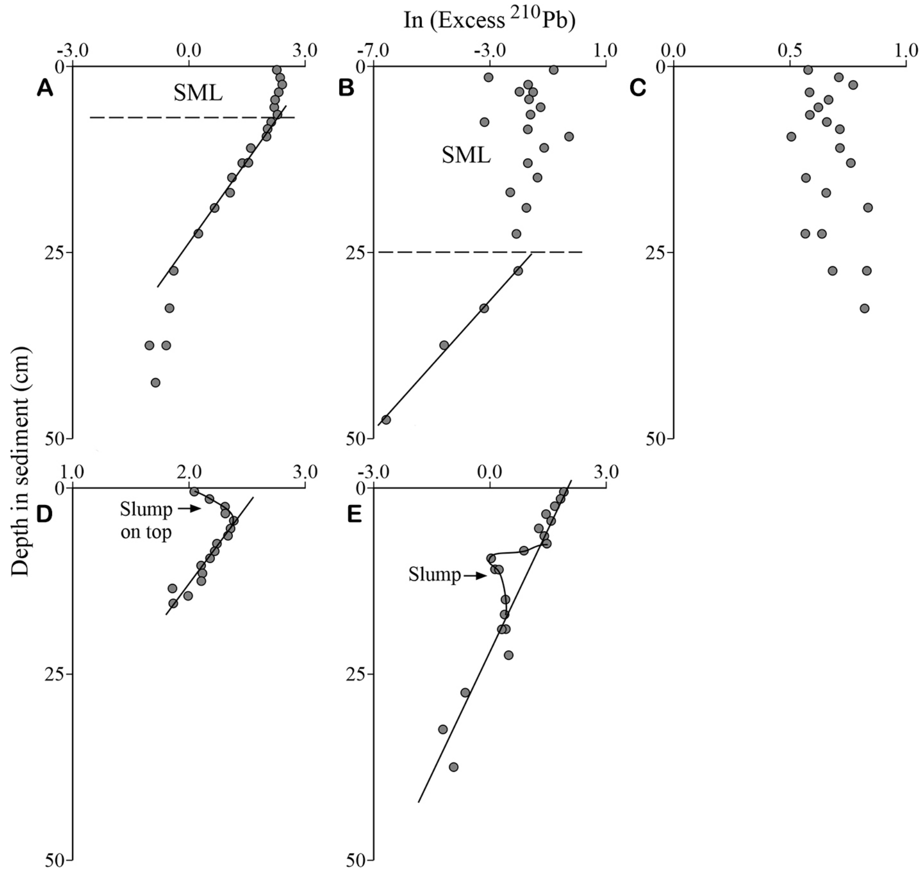

Figure 4. Example ^{210}Pb profiles. Horizontal dashed lines represent the bottom of the surface mixed layer (SML). Solid lines show the section of each profile to be used for the calculation of the sedimentation velocity. (A) A profile from a deep, coastal basin sediment. (B) A profile from a *Zostera marina* meadow, showing a deeper, more disturbed SML but clear decay with depth below the SML. (C) A profile where the core is too short or the sediment too disturbed to reach the decay depth, so no sedimentation velocity can be determined. (D) Inverted ^{210}Pb profile near-surface shows that older material has landed on top of newer; a sedimentation velocity can be determined below the slump, but the absolute age of the deep section is unclear. (E) A core with a slump of older material at mid-depth, above which regular accumulation seems to have resumed; SML may or may not be present; this rate would be uncertain relative to those in (A and B).

can result from several non-ideal situations, including when the core is either too short or too disturbed to show the decay with depth [Figure 4C], and where there has been a slump of older material on top of younger, either at the top [Figure 4D] or in the middle [Figure 4E] of a core. Additional, idealized examples are illustrated by Arias-Ortiz *et al.* (2018)[9].

If there is no detectable Excess ^{210}Pb above background, this indicates that the area is non-depositional or even erosional, and no burial is taking place. In such a situation, there might still be elevated organic carbon in the surface sediment below a seagrass meadow, because bioturbation can mix carbon or other substances down into the sediment, e.g.,[36]. However, if there is no sediment accumulation, then carbon is not actively buried at that site.

It is crucial to exercise caution when calculating sediment accumulation rate, because the rest of the interpretation depends on it.

Determine burial concentration of organic C

The burial % organic carbon can be determined from a depth profile of % organic carbon, based on the value reached in the deeper part of the core, once the organic carbon has stopped declining with depth [Figure 5A].

Troubleshooting organic carbon profiles

If the % organic C does not decline at all with depth (in a ~40 cm core), then either the sedimentation rate is so high that there is no time for the carbon to be remineralized before it is buried, or else all the labile carbon has been remineralized before it reached the sediment, and only refractory carbon remains. In either case, the burial % organic C is the constant value [Figure 5B].

If the organic carbon profile shows any shape other than a decline with depth or a constant value, then the sediment has been disturbed in some way, or there has been a change in the depositional environment. For example, a higher % organic C at the bottom [Figure 5C] might indicate a former seagrass meadow that has died, or an old log boom site, e.g.,[37].

Determine burial rate of total organic C

Multiply the sediment accumulation rate determined in Step 1 by the burial % organic carbon determined in Step 2. Do not calculate a different carbon burial rate at each depth in a single core; multiple years are mixed together, often unevenly, and organic carbon is remineralized with depth, even in the absence of mixing. See Section "Carbon remineralization in surface sediment" above.

This is the burial rate of total organic carbon, not of seagrass carbon specifically.

Separate seagrass carbon from total organic carbon using biomarkers

Biomarkers can be used to determine the proportion of the organic carbon that is derived from seagrass. See the discussion of allochthonous carbon above.

Stable isotopes of carbon and nitrogen ($\delta^{13}C$, $\delta^{15}N$) can provide a simple separation of marine-derived and terrigenous organic matter[38]. However, it can be difficult to discriminate among multiple vegetative end-members, such as phytoplankton, seagrass, seaweed, mangrove litter, *etc*., using only two tracers[38]. Multiple tracers can be more effective[38]. Potential additional tracers include fatty acids, lipids, lignin, eDNA, and stable isotopes of hydrogen[38,39].

Even if step 4 is not practical for cost or other reasons, just following steps 1-3 would result in better estimates of carbon burial rates than those commonly used in blue carbon studies. It would be important in that case to recognize that the rate included the allochthonous carbon as well as the seagrass carbon.

Correct for the offset due to carbonate formation and burial

The reduction in net carbon burial due to the burial of calcium carbonate that was formed in the water column within the meadow varies widely (5%-300%), depending on the environment, e.g.,[34,40]. Unfortunately, the blue carbon community has not settled on a methodology for determining the provenance of buried carbonate[41], so the overall effect of carbonate burial is still an open question. Some authors have determined the balance of carbonate formation, dissolution and burial within a meadow using a mass balance approach[34], and others have made short-term measurements of CO_2 exchange above the meadow[40]. However, these methods are not simple to use. If it is not possible to determine the provenance of the inorganic carbon at a particular site, a conservative approach would be to subtract 0.6 moles of carbon for every mole of inorganic carbon buried. This would likely reduce the net burial more than

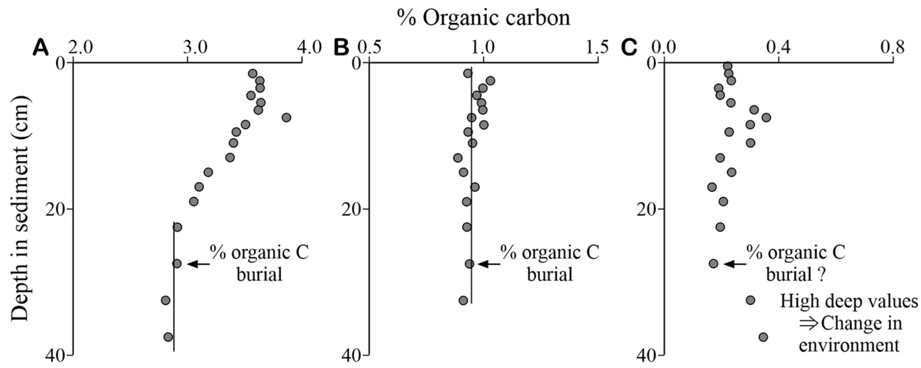

Figure 5. Example organic carbon profiles. Vertical lines mark the burial % organic C. (A) remineralization in upper section overlies buried % C; (B) constant % organic C indicates either a very high sediment accumulation rate or only refractory C at this site; (C) decline from surface to mid-point, with higher values below, indicates a change in the environment - it is unclear whether the % organic C reaches its burial value.

necessary, which would not make a very big difference in sediment with a high organic:inorganic carbon ratio (e.g., ~ 10:1 in a temperate sediment), but could change the calculated net burial into a net release in sediment with a low organic: inorganic ratio (e.g., 1:10 in a tropical meadow).

CONCLUSION

Although carbon burial in seagrass meadows cannot truly offset fossil fuel emissions, expanded organic carbon burial in seagrass meadows could draw down some atmospheric carbon dioxide in the short term (years to hundreds of years). Since there are real regional variations in seagrass species, sedimentary environment, and water properties, the magnitude of this carbon sink varies widely and needs to be assessed separately for each area. The methodology presented here avoids the systematic, high bias of commonly used methods.

It would be useful for future research to use the methodology presented here to determine carbon burial rates in a wide variety of environments with different seagrass species. Those results could then be used to develop appropriate average burial rates for different situations that could be applied on a regional scale.

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Authors' contributions

The author contributed solely to this article.

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Conflicts of interest
The author declared that there are no conflicts of interest.

Ethical approval and consent to participate
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