Environmental Research Letters

REPLY • OPEN ACCESS

Reply to Macreadie *et al* Comment on 'Geoengineering with seagrasses: is credit due where credit is given?'

To cite this article: Sophia C Johannessen and Robie W Macdonald 2018 *Environ. Res. Lett.* **13** 028001

Environmental Research Letters

OPEN ACCESS

RECEIVED
29 March 2017

REVISED
15 December 2017

ACCEPTED FOR PUBLICATION
15 January 2018

PUBLISHED
6 February 2018

REPLY

Reply to Macreadie *et al* Comment on 'Geoengineering with seagrasses: is credit due where credit is given?'

Sophia C Johannessen[1,2] and **Robie W Macdonald**[1]

[1] Fisheries and Oceans Canada, Institute of Ocean Sciences, 9860 W. Saanich Rd., PO Box 6000, Sidney, BC, V8L 4B2, Canada
[2] Author to whom any correspondence should be addressed.

E-mail: sophia.johannessen@dfo-mpo.gc.ca

Keywords: blue carbon, sediment, organic carbon, global burial rate, seagrass meadows

Abstract

Macreadie *et al* (this issue; M2017 *Environ. Res. Lett.*) challenged the conclusion presented by Johannessen and Macdonald (2016 *Environ. Res. Lett.*) that global estimates of carbon sequestration by seagrass meadows were too high. Here we clarify our global calculation, respond to M2017's criticisms and explain how the persistent misunderstandings about sediment dynamics within the Blue Carbon community continue to lead to overestimates of carbon sequestration in seagrass meadows. We point out that, although seagrasses appear to have a local effect on carbon sequestration compared with nearby barren sediments, their preferred substrate (slowly-accumulating, coarse sediment) makes them among the least effective coastal environments for burying carbon. We conclude with a proposal for the development of robust international protocols to quantify carbon burial in seagrass meadows that account for sediment accumulation, sediment mixing and carbon remineralization.

1. Introduction

We thank Macreadie *et al* (this issue; hereafter M2017) for providing this commentary on our paper (Johannessen and Macdonald 2016, hereafter J&M2016), with the aim of 'promoting discussion within the scientific community about evidence for carbon sequestration by seagrasses with a view to awarding carbon credits.' The ultimate aim of carbon credits—to produce a net reduction in CO_2 emission to the atmosphere—cannot be achieved without a common protocol that provides valid and accurate accounting of carbon sequestration. Although carbon may be sequestered and released on short time scales, we wrote J&M2016 in response to the claim by Blue Carbon researchers that seagrass meadows buried large amounts of carbon on long enough time scales to qualify for carbon credits (>100 years). In J&M2016 we argued that the methods currently in use within the Blue Carbon community and recommended by the international protocols systematically overestimated carbon burial by seagrasses. M2017 questioned our calculations and assumptions and asserted that current global estimates were correct.

Here we address the points raised by M2017, further clarify the incorrect assumptions and misunderstandings of sedimentary processes that persist within the field of Blue Carbon research, and suggest an approach for developing robust international protocols for quantifying the sequestration of organic carbon in seagrass meadow sediments.

2. Point-by-point response

Macreadie *et al* challenged J&M2016 on three main points: (1) the presentation of the global carbon burial rate calculation; (2) the omission of published sediment accumulation rates and ^{210}Pb geochronology based on measurements in seagrass meadows; and (3) our assertion that carbon burial was more important than inventory. M2017 also asserted that the Kennedy *et al* (2010) global estimates were correct, and stated that they agreed with J&M2016 on the best method to calculate carbon burial. We address each of these points below.

2.1. Global calculation

M2017 pointed out that the units were missing from the global carbon burial estimates in table 1 of J&M2016 and that they could not reproduce our global fluxes

from the values presented in the table. They thought that the rationale behind the calculation was unclear, that we had misrepresented the Kennedy *et al* (2010) global carbon burial rates, and that we had incorrectly calculated global carbon burial.

We did inadvertently omit the units for the global carbon sequestration values from the table, which should have been listed as kg C yr^{-1} (as they were on the first page of the text). In addition, in the table we incorrectly reported the minimum sediment accumulation rate for our calculation as 0.003 g cm^{-2} yr^{-1}, rather than 0.01 g cm^{-2} yr^{-1}. We appreciate the opportunity to correct these errors. We have included a corrected version of that table in box 1, together with an explanation of the calculations and assumptions. Our calculated global carbon sequestration rate was correctly reported in J&M2016, as was the overestimate factor. The Kennedy *et al* (2010) values were correctly represented in the original table, but they were in kg C yr^{-1}, not g C yr^{-1}, as M2017 assumed.

Macreadie *et al* (2017) suggested that we should have used only the autochthonous portion of Kennedy's rate to represent earlier estimates of carbon burial by seagrasses. That would be reasonable, given that we had excluded part (though not all) of the allochthonous carbon from our own calculation by subtracting the average 'outside-patch' carbon concentration from the average 'inside-patch' concentration that Kennedy *et al* (2010) had reported (box 1). If we substitute the autochthonous carbon burial rates provided by M2017 (7–40 Tg C yr^{-1}), the factor of the overestimate (min/min, max/max) is 4—465 times. We could also have calculated a wider range of overestimate (5–7400 times) if we had calculated the ratio as max/min, min/max (see box 1).

The exact factor by which existing global rates are overestimated is not the important point. That factor cannot be calculated with any certainty from the data currently available from seagrass meadows. We included the calculation only to illustrate the effect of the methodological problems raised in J&M2016. The identified problems with the current methods systematically bias the calculation high, for the reasons explained in J&M2016 and in sections 2.2 and 2.3 of this paper.

2.2. ^{210}Pb radiochronology and sediment accumulation rates

M2017 stated that, in citing only Marbà *et al* (2015) as an example of the correct use of ^{210}Pb in seagrass sediments, J&M2017 had missed multiple papers (Mateo *et al* 1997, Serrano *et al* 2012, Macreadie *et al* 2015a, Macreadie *et al* 2015b, Serrano *et al* 2016a, Macreadie *et al* 2012, Greiner *et al* 2013, Serrano *et al* 2016b). We did not miss these papers. Of the eight papers, four were published after or at the same time as our paper was submitted (25 June 2015), so we could not have cited them. In addition, of the eight papers, only four actually include ^{210}Pb dating. In J&M2016 our intention was not to enumerate widespread flaws in individual papers; rather we explained the inadequacies of the methods and concentrated on specific directions on how to improve the international protocols. However, since Macreadie *et al* have raised this specific subset of papers, we will discuss below each of the four that used ^{210}Pb.

Before doing that, we need to explain the effect of bioturbation and other surface mixing on radionuclide profiles in sediments. For laminated sediments (e.g. oligotrophic lake sediments or anoxic sediments) an assumption is frequently made that no post-depositional processes affect the ^{210}Pb profile other than radio-decay. This assumption is not valid where surface mixing occurs (e.g. Appleby 2001). For more than five decades, geochemists have recognized the mixing problem in ocean sediments, and have developed models to deal with its effect on radionuclide profiles (e.g. Goldberg and Koide 1962, Boudreau 1997). The surface layer of oxic marine sediment is almost always mixed.

Neglecting the effects of mixing leads to sedimentation rate estimates that are too high (Silverberg *et al* 1986). Where surface mixing occurs, any specific layer within the sediments will contain material deposited over a range of years approximated by the depth of the mixed layer (cm) divided by the sedimentation rate (cm yr^{-1}) (e.g. see Guinasso and Schink 1975, Johannessen and Macdonald 2012). Therefore, in mixed sediments specific layers cannot be identified with a particular year of deposition.

The cores presented by Greiner *et al* (2013) were not interpretable using ^{210}Pb. In the core for which they reported a sedimentation rate, older material had clearly been deposited on top of younger material, as evidenced by the inverted ^{210}Pb profile. It is not clear how the sedimentation velocity of 0.66 cm yr^{-1} was derived, nor how the authors then arrived at a detailed, 100 year history of variability in sedimentation rate. The Year-4 core showed a lower inventory of ^{210}Pb over its whole length than did the Year-0 core, which, contrary to the authors' suggestion, could not be explained as the result of bioturbation. They also assigned discrete ages to each depth in the bioturbated core.

In the Macreadie *et al* (2012) paper, the sampling resolution (3 cm thick slices at 4 cm or 10 cm intervals) was insufficient to resolve the surface mixed layer. Despite commenting that the cores were bioturbated, based on the observed sediment mottling, the authors assigned a discrete age to each depth in the core and then used those ages to calculate a sedimentation velocity (cm yr^{-1}).

The remaining two papers cited by M2017 were published after J&M2016 was submitted. These more recent papers avoided many of the problems associated with the earlier papers, but they still contain errors in interpretation, as discussed below.

Serrano *et al* (2016a) calculated the sedimentation rate below the surface mixed layer and explicitly

Box 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	(a)
Sediment accumulation rate ($g\,cm^{-2}\,yr^{-1}$)	0.01	1.0	(b)
Global C sequestration by seagrasses ($kg\,C\,yr^{-1}$)	1.5×10^7	1.0×10^{10}	Calculated from values above (c)
Previous global estimates ($kg\,C\,yr^{-1}$)	4.8×10^{10}	1.12×10^{11}	e.g. Kennedy *et al* 2010 (48–112 $Tg\,C\,yr^{-1}$)
Previous global est. autochthonous only ($kg\,C\,yr^{-1}$)	1.2×10^{10}	4.0×10^{10}	Macreadie *et al* this issue (12–40 $Tg\,C\,yr^{-1}$)
Overestimate factor	11	3200	Ratio of previous to this estimate: (d) Min factor = max:max, Max factor = min:min
Overestimate factor autochthonous only	4	800	Ratio of previous autochthonous to this estimate max:max, min:min

a. To calculate additional C burial represented by seagrasses, we used the Kennedy *et al* (2010) inside/outside seagrass patch comparison that was based on 82 sites from around the world (not only in *Posidonia* beds). Kennedy found an average of 0.34% organic C inside the patch, 0.17% outside. The maximum contribution from seagrass is 0.34% – 0.17% = 0.17%. Assuming that half the organic carbon in the top 5–10 cm is remineralized before burial, the % burial of additional carbon would be 0.17% ÷ 2 = 0.085%. We used 0.085% as a minimum (although that value could be lower, because sometimes the burial % is less than half the surface concentration, and because not all of the additional carbon found inside the patch is from the seagrasses themselves.)

b. For sediment accumulation rate we used a range of values from coastal sediments around the world (0.01–1.0 $g\,cm^{-2}\,yr^{-1}$; Boudreau 1994 and references therein; Kuzyk *et al* 2013, Marbà *et al* 2015, Junttila *et al* 2013, Zuo *et al* 1991, Alvisi 2009, 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, coastal Australia and the Mediterranean Sea—because reliable values were not available for seagrass meadows. See comments in section 2.2 about accumulation rate calculations. The sediment accumulation rate reported by Marbà *et al* (2015), which we cited in J&M2016, is 0.04 $g\,cm^{-2}\,yr^{-1}$, which falls within the range of coastal values that we used.

c. Global C sequestration = global area of seagrasses × % additional organic C × sediment accumulation rate

d. We calculated the range of the overestimate as:
Minimum factor = Kennedy max (1.12×10^{11} $kg\,C\,yr^{-1}$)/J&M2016 max (1.0×10^{10} $kg\,C\,yr^{-1}$) = 11
Maximum factor = Kennedy min (4.8×10^{10} $kg\,C\,yr^{-1}$)/J&M2016 min (1.5×10^7 $kg\,C\,yr^{-1}$) = 3200
(The factor of 3100 reported in J&M2016 resulted from later rounding.)
Calculating the overestimate factor as Minimum = Kennedy min/J&M2016 max, and Maximum = Kennedy max/J&M2016 min, gives a wider range of overestimate factor (5–7500 times).

We reported the minimum overestimate factor in the 'Min' column for clarity, even though it was calculated from a ratio of values in the 'Max' column.

accounted for supported ^{210}Pb in the core. These are appropriate steps. However, a comparison with the ^{210}Pb inventory shows that some of their calculated sedimentation rates cannot be correct. In one core, for example ('*P. sinuosa* 2 m'), ^{210}Pb was indistinguishable from background by 15 cm depth; since ^{210}Pb decays to background after ~110 years (5 half-lives), the maximum sedimentation velocity possible (even in the absence of mixing, which pushes younger ^{210}Pb deeper into the core) is 0.14 $cm\,yr^{-1}$, but the authors reported a sedimentation velocity of 0.3 $cm\,yr^{-1}$.

Serrano *et al* (2016b) appear to have calculated sedimentation velocity correctly, but then, after stating that there was a 15 cm mixed layer, they assigned dates (13 years apart at the tops of the cores) to depths down the core and used those dates to determine the depth for the 100 year inventory. With the reported sedimentation velocity of 0.27 $cm\,yr^{-1}$, mixing in the 15 cm surface mixed layer would have smeared together about 56 years of accumulated sediment.

M2017 also questioned our use of sediment accumulation rates from general coastal areas. They suggested that we should have used rates calculated specifically from seagrass ecosystems, citing, in addition to the papers discussed above, Miyajima *et al* (1998), Serrano *et al* (2012), Serrano *et al* (2014) and Macreadie *et al* (2015a).

Miyajima *et al* (1998) did not estimate a sediment accumulation rate. Serrano *et al* (2012, 2014) calculated the rate of *Posidonia* plant material burial down the core, by measuring the ^{14}C age of pieces of plant material throughout the core. This seems like a reasonable approach for this particular type of seagrass that forms enormous root mattes, although it would be impractical for other seagrasses. From the rate of burial of plant material, they calculated a sediment accumulation rate of 0.09 $g\,cm^{-2}\,yr^{-1}$, which fits within the global range that we used.

The Macreadie *et al* (2015a) paper was published after J&M2016 was submitted. The authors reported sedimentation velocities of 0.01–0.19 $cm\,yr^{-1}$ but did not provide information that would permit the calculation of sediment accumulation rate in $g\,cm^{-2}\,yr^{-1}$.

The rates that we used in our calculation were drawn from coastal sites all over the world, which made them more representative than a set of rates measured only in coastal Australia. We only included rates given in or convertible to units of $g\,cm^{-2}\,yr^{-1}$, which permitted a direct calculation of carbon burial ($g\,C\,cm^{-2}\,yr^{-1}$). Including a wider range of sediment accumulation rates, as we did, actually yielded a higher global

carbon burial rate and a lower overestimate factor than would have been derived using only seagrass sites.

2.3. Calculating carbon burial from inventory

Macreadie *et al* stated that they agreed with J&M 2016 'that carbon stock estimates in combination with ^{210}Pb age dating is one of the best approaches to accurately calculate carbon accumulation rates in seagrass meadows.' They appear to have misunderstood the method that we recommend. (see section 3). It is not correct to divide carbon inventory, or 'stock,' over a particular depth range by the age calculated for that depth range, as presented in several recent studies (e.g. Serrano *et al* 2016a, 2016b). This method has two problems. (1) The inventory includes the enriched layer of labile organic carbon at the surface of the sediments, which is recycled to CO_2, not buried, on the timescale of 100 years. (According to Miyajima *et al* the top 10 cm of sediment in a seagrass meadow on the Great Barrier Reef was turned over/resuspended on the timescale of 17–170 d.) (2) In sediments that are physically or biologically mixed, this method also underestimates the age of the sediments in the interval considered, because younger (higher-activity) ^{210}Pb is mixed downward in the core. Each of these errors overestimates the rate of carbon burial. Multiplied together, the overestimates are compounded.

2.4. Long-term burial vs instantaneous inventory

M2017 disagreed with our statement that it was the long-term sequestration rate, rather than instantaneous inventory, that ultimately mattered. They stated that the real potential of seagrass protection was to avoid 'emissions from disturbed sediments after canopy loss,' and that 'the burial capacity of seagrass meadows is small in terms of potential crediting.'

In fact, burial is more important than inventory, because the inventory in the surface sediments is volatile. It can be wiped out at any time by moorings, trawling, or other destructive processes. According to Macreadie *et al* (2015b), at one site half of the lost inventory was recovered within 5–10 years of replanting. Such volatility is not equivalent to burial on the timescale of 100 years, as required for carbon credits.

We agree that both the surface sediment inventory and the seagrass meadows themselves are valuable and should be preserved where possible, but to qualify for carbon credits, it is long-term burial, not deposition, that matters. Net community production, as raised by M2017, is irrelevant to long-term sequestration, since most of the new organic carbon is remineralized on the timescale of weeks to years.

2.5. Consistency of previous estimates

M2017 stated that the Kennedy *et al* (2010) global estimates (48–112 Tg total C yr^{-1} globally, or 12–40 Tg C yr^{-1} autochthonous only) were reasonable, because they were 'within the range of estimates based on seagrass carbon burial data published in peer-reviewed literature.' Claiming that the global estimates summarized by Kennedy are reasonable because they agree with the earlier estimates on which they were based seems like a circular argument. We would suggest, rather, that since the earlier estimates were based on incorrect assumptions which systematically overestimated the carbon burial rates, the Kennedy estimates are also too high. For example, it is not reasonable to estimate global carbon burial rates in seagrass meadows based only on measurements made in *Posidonia* beds, since this genus produces unusually large root mattes that are not found in other types of seagrasses, nor is it correct to base carbon burial rates on carbon concentrations measured in the top 5–10 cm of the sediment.

3. Development of robust international protocols

We recommend that future estimates of blue carbon burial in seagrass meadows include the following steps.

1. Collect a sediment core at least 40 cm long and subsection it at 1 cm resolution (at least for the top 10 cm; a coarser resolution is likely sufficient deeper in the core). Surface grab samples are not acceptable substitutes, since they give no information about sediment accumulation rate or about the concentration of organic carbon below the burial depth.
2. Calculate sedimentation velocity (cm yr^{-1}) below the surface mixed layer from ^{210}Pb (Lavelle *et al* 1986), accounting for the supported ^{210}Pb, using the deep, background activity of ^{210}Pb or with a few measurements of ^{226}Ra, and convert that to the sediment accumulation rate (g cm^{-2} yr^{-1}) using the porosity of the sediment (Lavelle *et al* 1986).
3. Measure the concentration of organic carbon throughout the core and plot its depth profile, identifying the depth below which the % organic C becomes approximately constant (often ∼30–50 cm). This is the burial depth, below which carbon is buried on the timescale of $>$100 years required for carbon credits.
4. Multiply the concentration of organic carbon below the burial depth by the sediment accumulation rate. This is the carbon burial rate.
5. Estimate the proportion of the buried carbon that represents seagrass remains (using biomarkers, stable isotopes, etc.).

If the sediment accumulates too slowly for accurate ^{210}Pb dating (∼100 years), ^{14}C could be substituted (100s–1000s of years). High-resolution sampling near the sediment surface is still required, and the SML for such sediments may comprise far more years because of the slow accumulation rate. Error terms should also accompany such estimates.

4. Conclusion: from local measurements to global significance

At a very local scale, seagrass meadows do seem to bury carbon more rapidly than do adjacent bare patches (Kennedy *et al* 2010). However, among coastal environments, the coarse-grained, intertidal or shallow subtidal sediments where seagrasses grow are among the least effective at burying carbon. Sedimentation tends to be slow in those areas (usually <0.2 cm year^{-1}), relative to that in coastal basins, and the sediments are coarse (fine to medium sand). Rapidly-accumulating sediment near river mouths buries carbon much more rapidly, as do slowly-accumulating, fine-grained sediments (mud to silt) in fjords and other coastal basins (Hedges and Keil 1995). Even the very slowly-accumulating, fine-grained open ocean sediments are likely more important to carbon burial (Barange *et al* 2017).

There are many ecological benefits to protecting and re-establishing eelgrass ecosystems. There may also be an incremental carbon-burial benefit to planting or protecting seagrass meadows, but to establish that quantitatively, standard methods that account properly for the sediment accumulation rate, surface sediment mixing and the remineralization of organic carbon are required.

Acknowledgments

We thank Dr. James Christian, Dr. Andrew Ross, the Editor and an anonymous reviewer for their insightful comments on an earlier draft of this manuscript.

ORCID iDs

Sophia C Johannessen https://orcid.org/0000-0003-3788-2994

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

Appleby P G 2001 Chronostratigraphic techniques in recent sediments *Tracking Environmental Change Using Lake Sediments* ed W M Last and J P Smol (Dordrecht: Klewer) pp 171–203

Barange M, Butenschön M, Yool A, Beaumont N, Fernandes J A, Martin A P and Allen J I 2017 The cost of reducing the North Atlantic ocean biological carbon pump *Front. Mar.* **10**

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

Boudreau B P 1997 *Diagenetic Models and Their Implementation* vol 16 (New York: Springer) p 414

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

Goldberg E D and Koide M 1962 Geochronological studies of deep sea sediments by the ionium/thorium method *Geochim. Cosmochim. Acta* **26** 417–50

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

Johannessen S C and Macdonald R W 2016 Geoengineering with seagrasses: is credit due where credit is given? *Environ. Res. Lett.* **11**

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

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

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

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

Macreadie P I, Ewers C, Whitt A, Ollivier Q, Trevathan-Tackett S, Carnell P, Thomson A and Serrano O 2018 Comment on Geoengineering with seagrasses: is credit due where credit is given? *Environ. Res. Lett.* in preparation

Macreadie P I, Rolph T C, Boyd R, Schröder-Adams C J and Skilbeck C G 2015a Do ENSO and coastal development enhance coastal burial of terrestrial carbon? *PLoS ONE* **10** e0145136

Macreadie P I, Trevathan-Tackett S, Skilbeck C G, Sanderman J, Curlevski N, Jacobsen G and Seymour J R 2015b Losses and recovery of organic carbon from a seagrass ecosystem following disturbance *Proc. R. Soc.* B **282** 20151537

Macreadie P I, Allen K, Kelaher B P, Ralph P J and Skilbeck C G 2012 Paleoreconstruction of estuarine sediments reveal human-induced weakening of coastal carbon sinks *Glob. Change Biol.* **18** 891–901

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

Mateo M A, Romero J, Pérez M, Littler M M and Littler D S 1997 Dynamics of millenary organic deposits resulting from the growth of the Mediterranean seagrass Posidonia oceanica *Estuarine Coastal Shelf Sci.* **44** 103–10

Miyajima T, Koike I, Yamano H and Iizumi H 1998 Accumulation and transport of seagrass-derived organic matter in a reef flat sediment of Green Island, Great Barrier Reef *Mar. Ecol. Prog. Ser.* **175** 251–9

Pendleton L *et al* 2012 Estimating global 'blue carbon' emissions from conversion and degradation of vegetated coastal ecosystems *PLoS ONE* **7** e43542

Serrano O, Mateo M A, Renom P and Julià R 2012 Characterization of soils beneath a Posidonia oceanica meadow *Geoderma* **185–186** 26–36

Serrano O, Ricart A M, Lavery P S, Mateo M A, Arias-Ortiz A, Masque P, Rozaimi M, Steven A and Duarte C M 2016a Key biogeochemical factors affecting soil carbon storage in Posidonia meadows *Biogeosciences* **13** 4581–94

Serrano O, Ruhon R, Lavery P S, Kendrick G A, Hickey S, Masqué P, Arias-Ortiz A, Steven A and Duarte C M 2016b Impact of mooring activities on carbon stocks in seagrass meadows *Sci. Rep.* **6** 23193

Serrano O, Lavery P S, Rozaimi M and Mateo M A 2014 Influence of water depth on the carbon sequestration capacity of seagrasses *Glob. Biogeochem. Cycles* **28** 950–61

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

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