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Peter I. Macreadie

Carolyn J. Ewers-Lewis

Ashley A. Whitt

Quinn Ollivier

Stacey M. Trevathan-Tackett

See next page for additional authors

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COMMENT

Comment on 'Geoengineering with seagrasses: is credit due where credit is given?'

Peter I Macreadie[1,4], Carolyn J Ewers-Lewis[1], Ashley A Whitt[1], Quinn Ollivier[1], Stacey M Trevathan-Tackett[1], Paul Carnell[1] and Oscar Serrano[3]

1 Deakin University, School of Life and Environmental Sciences, Centre for Integrative Ecology, 221 Burwood Highway, Burwood, VIC 3125, Australia
2 Climate Change Cluster, University of Technology Sydney, Sydney 2007, Australia
3 School of Science and Centre for Marine Ecosystems Research, Edith Cowan University, Joondalup, WA 6027, Australia
4 Author to whom any correspondence should be addressed.

E-mail: p.macreadie@deakin.edu.au

Over the past decade scientists around the world have sought to estimate the capacity of seagrass meadows to sequester carbon, and thereby understand their role in climate change mitigation. The number of studies reporting on seagrass carbon accumulation rates is still limited, but growing scientific evidence supports the hypothesis that seagrasses have been efficiently locking away CO_2 for decades to millennia (e.g. Macreadie *et al* 2014, Mateo *et al* 1997, Serrano *et al* 2012). Johannessen and Macdonald (2016), however, challenge the role of seagrasses as carbon traps, claiming that gains in carbon storage by seagrasses may be 'illusionary' and that 'their contribution to the global burial of carbon has not yet been established'. The authors warn that misunderstandings of how sediments receive, process and store carbon have led to an overestimation of carbon burial by seagrasses. Here we would like to clarify some of the questions raised by Johannessen and Macdonald (2016), with the aim to promote discussion within the scientific community about the evidence for carbon sequestration by seagrasses with a view to awarding carbon credits.

Reliability of global estimates of seagrass carbon sequestration

Johannessen and Macdonald (Johannessen and Macdonald 2016) reported that estimates of global carbon burial by seagrasses have been overestimated by 11- to 3100 fold (table 1, Johannessen and Macdonald 2016). Their claims are based on existing literature but their calculations are not clear and their interpretations seem to be misleading, which may have resulted in erroneous conclusions.

First, Johannessen and Macdonald (2016) misinterpreted the global carbon burial estimates reported by Kennedy *et al* (2010). Kennedy *et al* (2010) reported estimates of mean seagrass net community production (120 g C m^{-2} yr^{-1}; Duarte *et al* 2010), accumulation of seagrass autochthonous organic carbon (41–66 g C m^{-2} yr^{-1}), and allochthonous organic carbon (42–67 g C m^{-2} yr^{-1}). Assuming that there is net export of seagrass organic carbon from the meadow, Kennedy *et al* (2010) concluded that carbon sequestration by seagrass meadows may be better approximated by the sum of their net community production and the allochthonous carbon trapped in their sediments, which results in an estimated sequestration rates of 160–186 g C m^{-2} yr^{-1}. This approach taken by Kennedy *et al* (2010) does not account for post-depositional processes in marine sediments (e.g. biomixing and remineralization), as raised by Johannessen and Macdonald (2016), however, it is important to note that Kennedy *et al* (2010) aimed to provide estimates of seagrass carbon burial, as opposed to estimating carbon crediting opportunities (i.e. autochthonous carbon only). In order to estimate crediting opportunities from seagrass carbon burial, the data presented by Kennedy *et al* (2010) should be interpreted in a different way: based only on the accumulation of autochthonous organic carbon (41–66 g C m^{-2} yr^{-1}; 12–40 Tg C yr^{-1} globally). Using the updated minimum seagrass area reported by Pendleton *et al* (2012) (170 000 km^2), as used by Johannessen and Macdonald (2016), the seagrass global carbon burial estimates (i.e. autochthonous carbon only) that may have implication for crediting would range from 7–40 Tg C yr^{-1}.

Second, we were unable to reproduce the 11- to 3100 fold overestimation reported by Johannessen and Macdonald (2016), their calculation for this overestimation is not provided and the units are missing, plus the calculation likely involves some misconceptions. For example, Johannessen and Macdonald (2016) used sediment accumulation rates from general coastal areas to estimate global carbon burial by seagrasses (Alvisi 2009, Boudreau 1994, Emeis *et al* 2000, Junttila *et al* 2014, Kuzyk *et al* 2013, Zuo *et al* 1991), rather than use data from actual seagrass ecosystems (e.g. Serrano *et al* 2012, Macreadie *et al* 2015a, Serrano *et al* 2014a, Miyajima *et al* 1998, Serrano *et al* 2016a). Moreover, Johannessen and Macdonald (2016) used carbon data from studies where carbon in sediments—both in and outside the seagrass meadows—have been measured (Kennedy *et al* 2010) to determine the % additional organic carbon due to seagrass. However, it seems they did not account for the % of autochthonous and allochthonous carbon in their calculations presented in table 1, despite the fact that they clearly stated in section 4.5 that allochthonous carbon capture does not necessarily represent additional burial. Additionally, the previous global estimates by Kennedy *et al* (2010) seem to be wrongly reproduced in table 1 from Johannessen and Macdonald (2016): ranging from 4.8×10^{10} and 1.12×10^{11}. Assuming that the units reported by Johannessen and Macdonald (2016) are grams (units not shown), then it should be 48×10^{12} and 112×10^{12}. As previously indicated, the calculation for this overestimation is not provided, the units of most variables used are missing, literature data is misreported, and the rationale behind the assumptions is not provided; thereby we were not able to reproduce their computations and we believe that Johannessen and Macdonald (2016) have incorrectly estimated global carbon burial by seagrasses.

Third, despite early estimates by Kennedy *et al* (2010) being based on limited available data and an indirect approach (accounting for plant productivity rather than sediment carbon accumulation), the range they provided is reasonable (12–40 Tg autochthonous C yr^{-1} globally, or 48–112 Tg total C yr^{-1}). Here we show that previous global estimates are within the range of estimates based on seagrass carbon burial data published in peer-reviewed literature. Using the lowest seagrass carbon burial rate (2 g C m^{-2} yr^{-1} in *Posidonia* meadows, burial estimated in a 1 m-thick sedimentary deposit based on ^{14}C geochronology) (Serrano *et al* 2014b, Serrano *et al* 2016b) and the highest seagrass carbon burial rate (249 g C m^{-2} yr^{-1} in a *Posidonia oceanica* meadow, burial estimated in a 2 m-thick sedimentary deposit based on ^{14}C geochronology) (Serrano *et al* 2016b) reported to date, one could estimate the range of global seagrass carbon burial. Following the approach taken by Johannessen and Macdonald (2016) (global area of seagrass ranging from 177 000–600 000 km^2) but assuming that 43%–94% of sediment carbon is due to seagrass presence (based on direct measurements in seagrass cores; Serrano *et al* 2016a), we estimate that global seagrass carbon burial range 0.26–140 Tg C yr^{-1}. Therefore, despite the limitations of the early estimates of global seagrass burial provided by Kennedy *et al* (2010) (48–112 Tg C yr^{-1} for total carbon, or 7–40 Tg C yr^{-1} for autochthonous carbon), here we demonstrate that these were not necessarily overestimates, but rather that the variability of seagrass carbon sequestration is larger than initially thought.

Overall, we agree with Johannessen and Macdonald (2016) that the methods used by previous authors were indirect and therefore relied on large assumptions, and that further studies are required to understand differences in carbon burial among seagrass ecosystems, including biological and habitat characteristics, to further refine estimates of global seagrass carbon sequestration capacity. We also agree with Johannessen and Macdonald (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. We disagree, however, that only one previous study (Marba *et al* 2015) has used ^{210}Pb dating to create seagrass sediment chronologies; Johannessen and Macdonald (2016) have missed multiple papers that previously determined decadal to millennial-scale age dating for seagrass sediments (e.g. Mateo *et al* 1997, Serrano *et al* 2012, Macreadie *et al* 2015a, Serrano *et al* 2016a, Macreadie *et al* 2012, Macreadie *et al* 2015b, Greiner *et al* 2013, Serrano *et al* 2016c). Finally, our calculations based on peer-reviewed literature reporting long-term carbon burial by seagrasses and % contribution of seagrass matter to the sediment carbon pool, we concluded that previous estimates by Kennedy *et al* (4) could either represent over- or under-estimates owing to the large variability in carbon sequestration among seagrass ecosystems.

The motivation for seagrass carbon offsetting

Johannessen and Macdonald (Johannessen and Macdonald 2016) stated that 'For climate change mitigation, it is the change in the long-term sequestration *rate* that ultimately matters'. Here we would like to clarify that the real potential of seagrass ecosystems to mitigate greenhouse gas emissions is towards the preservation of existing meadows and restoration of lost meadows, which can result in avoided emissions from disturbed sediments after canopy loss. The vast majority of carbon stores in seagrass meadows are found in their sediments (Fourqurean *et al* 2012), and recent literature shows that disturbance of sediments after meadow loss can result in carbon dioxide emissions (Marba *et al* 2015, Macreadie *et al* 2015b, Serrano *et al* 2016c). Indeed the carbon burial capacity of seagrass meadows (ranging from 2–249 g C m^{-2} yr^{-1}; Serrano *et al* 2016a) is small in terms of potential for crediting: the restoration of 1 ha of seagrass could result in then enhanced sequestration of 0.02–2.5 ton C yr^{-1} (valued at \$0.88–\$110, assuming a price of \$12 per ton CO_2). However, avoided emissions through the preservation of seagrass meadows and the carbon stocks underneath could result in a much larger crediting benefit: the preservation of 1 ha of seagrass could result in avoided emissions of 19–220 ton C (assuming, conservatively, that 25% of stocks in 1 m-thick deposits are remineralized after meadow loss, data from (Serrano *et al* 2016b, Marba *et al* 2015, Macreadie *et al* 2015b); 7.5–88 kg C in 1 m-thick sediments), valued at \$826–\$9689 (assuming a price of \$12 ton CO_2). Therefore, further initiatives aiming to determine the potential of seagrass meadows to mitigate climate change emissions should primarily focus on the understanding of the loss and fate of carbon stores after meadow loss.

Moving forward

In conclusion, we argue that global carbon sequestration by seagrasses has not been properly established, but current estimates are within the range reported by growing scientific evidence. Increasing research on carbon sequestration rates by seagrasses showed that their capacity to sequester carbon can be highly variable due to biological, physical and chemical factors. Perhaps the largest current cause of high variance in estimates of global seagrass carbon sequestration is from the high uncertainty in global seagrass area (Macreadie *et al* 2014). In addition, we need to better understand the fate of allochthonous carbon if it weren't trapped and buried by seagrass meadows. Further research is needed to constrain the range of estimates of seagrass carbon burial rates at local, regional and global scales.

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ORCID iDs

Peter I Macreadie https://orcid.org/0000-0001-7362-0882

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