communications
earth & environment

ARTICLE

https://doi.org/10.1038/s43247-023-01022-x OPEN

The climate benefit of seagrass blue carbon is reduced by methane fluxes and enhanced by nitrous oxide fluxes

Bradley D. Eyre[1]✉, Nicola Camillini[1,2,3], Ronnie N. Glud[2,4] & Judith A. Rosentreter[1]

Blue carbon is carbon stored long-term in vegetated coastal ecosystems, which constitutes an important sink for atmospheric carbon dioxide (CO_2). However, because methane (CH_4) and nitrous oxide (N_2O) have higher global warming potentials (GWP) than CO_2, their production and release during organic matter diagenesis can affect the climate benefit of blue carbon. Here, we present a meta-analysis synthesizing seagrass CH_4 and N_2O fluxes and long-term organic carbon burial rates, and use these data to estimate the reduced climate benefit (offsets) of seagrass blue carbon using three upscaling approaches. Mean offsets for individual seagrass species (34.7% GWP_{20};1.0% GWP_{100}) and globally (33.4% GWP_{20};7.0% GWP_{100}) were similar, but GWP_{20} offsets were higher, and GWP_{100} offsets were lower than globally, for the Australian region (41.3% GWP_{20};1.1% GWP_{100}). This study highlights the importance of using long-term organic carbon burial rates and accounting for both CH_4 and N_2O fluxes in future seagrass blue carbon assessments.

---

[1] Centre for Coastal Biogeochemistry, Faculty of Science and Engineering, Southern Cross University, Lismore, NSW 2480, Australia. [2] Department of Biology, HADAL, Nordcee and DIAS, University of Southern Denmark, 5230 Odense M, Denmark. [3] Alfred-Wegener-Institute, Helmholtz-Zentrum für Polar- und Meeresforschung, 7 Wattenmeerstation Sylt, Hafenstraße 43, D-25992 List, Germany. [4] Department of Ocean and Environmental Sciences, Tokyo University of Marine Science and Technology, Tokyo 26 108-8477, Japan. ✉email: bradley.eyre@scu.edu.au

Improving the capacity of natural ecosystems to assimilate carbon dioxide (CO_2) and store organic carbon (C_{org}) long-term is an important strategy for mitigating climate change[1]. As such, restoring the carbon sequestration capacity of terrestrial ecosystems, such as tropical rainforests and farmland, has been the focus of many conservation efforts[2]. Vegetated coastal ecosystems, particularly mangroves, salt marshes, and seagrasses also store large amounts of organic matter[3–5]. Seagrass communities account for up to half the global carbon accumulated in vegetated coastal habitats[6]. However, resolving the climatic benefit of marine ecosystems requires knowing the CO_2 sequestration potential through long-term (>100 years) C_{org} burial[7,8], as well as quantification of the methane (CH_4) and nitrous oxide (N_2O) flux during early diagenetic processes[9–11].

Methanogens produce CH_4 via hydrogenotrophic (CO_2 reduced to CH_4 using H_2), acetoclastic (acetate disproportionation used to form CH_4), and methylotrophic (methyl groups of methylated compounds used to form CH_4) pathways[12]. N_2O can be produced during a variety of processes but mostly nitrification and denitrification, e.g. [13]. CH_4 and N_2O have a global warming potential (GWP) that is, depending on the 20-year or 100-year time-horizon, 79.7 to 27.0 for CH_4 or 273 for N_2O times respectively more powerful than CO_2[14]. As such, the production and release of CH_4 and N_2O from marine sediments has the potential to reduce (offset) the climatic benefit of C_{org} sequestered through long-term (>100 years) C_{org} burial (i.e., blue carbon)[9,11]. Similarly, an uptake of CH_4 and N_2O has the potential to enhance the climate benefit of vegetated coastal communities[15–17]. Although CH_4 and N_2O are released during the short-term decomposition of organic matter that is not buried, there long-term influence on the atmosphere supports a comparison to long-term C_{org} burial.

Three studies have used either CH_4 fluxes[18] or CH_4 and N_2O fluxes[11,19] in seagrass communities to estimate offsets for individual sites that range from zero to 10% (GWP_{100}), but none used measured long-term (>100 year) C_{org} burial rates. Two studies used seagrass CH_4 fluxes to estimate global offsets that range from 0.5 to 4.5% (GWP_{100}), but both these studies used global seagrass organic carbon accumulation estimates[20,21], which do not represent long-term C_{org} burial rates. Considering the implications for policies and practice incorporating blue carbon habitat conservation and restoration as a natural strategy for CO_2 removal, there is a clear need to re-assess the climate benefit of seagrass blue carbon based on a synthesis of seagrass CH_4 and N_2O fluxes and long-term C_{org} burial rates.

In this study we present a meta-analysis synthesizing seagrass long-term C_{org} burial rates (and C_{org} accumulation rates for comparison) and CH_4 and N_2O fluxes (Fig. 1 and Supplementary Tables 1–4), and use the combined CO_2-equivalent CH_4 and N_2O fluxes to estimate the reduced climate benefit (offsets) to seagrass blue carbon (1) for individual seagrass species (2) for the Australian region, and (3) globally using the mean and median of all rates. We further present new water-air CH_4 and N_2O fluxes for one study site in Australia (Wallagoot Lake), which increased the limited number of seagrass N_2O fluxes, added N_2O fluxes for a new seagrass species, doubled the number of seagrass water-air N_2O fluxes, and also added an additional seagrass CH_4 flux. We found CH_4 and N_2O fluxes offset on average around 7% to 35% of the global climate benefits of seagrass blue carbon.

Results

Methane and nitrous oxide water-air fluxes in a *Ruppia megacarpa* community. Over the diel cycle (20 h), water overlying the *R. megacarpa* community in Wallagoot Lake had an average temperature and salinity of 25.8 ± 2.2 °C and 29.5 ± 0.2, respectively. The CH_4 concentration varied between 50.4 and 86.2 $nmol\,l^{-1}$ without following a diel pattern. In parallel, the N_2O concentration slightly increased from 4.5 to 5.6 $nmol\,l^{-1}$ in

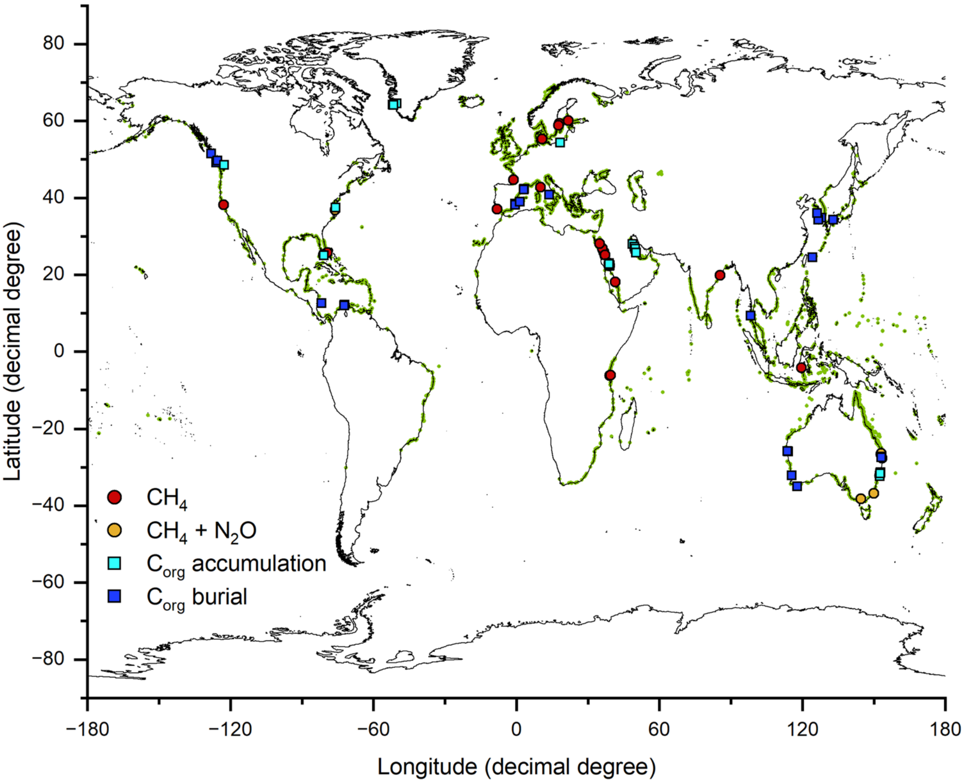

Fig. 1 Global distribution of CH_4 and N_2O fluxes, C_{org} accumulation and long-term C_{org} burial rates measured in seagrass communities. Seagrass areas (green areas) adapted from UNEP-WCMC, 2021 (https://data.unep-wcmc.org/datasets/7; data from Supplementary Tables 1–4). Long-term (>100 years).

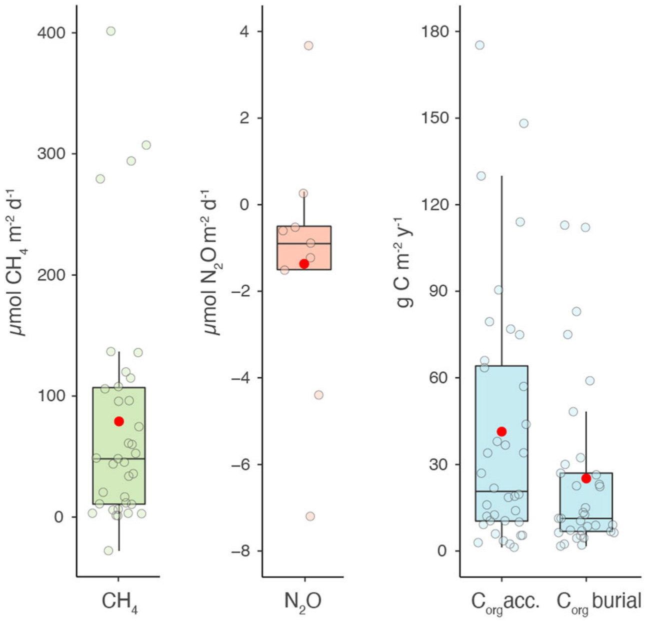

Fig. 2 Boxplots CH_4 and N_2O fluxes, C_{org} accumulation and long-term C_{org} burial rates. Boxplots showing median, mean (red circle), 25th and 75 percentiles (boxes), 10th and 90th percentiles (bars) and data points (circles) of CH_4 (*n* = 35; green) and N_2O fluxes (*n* = 9; pink) and C_{org} accumulation (acc.) (*n* = 36; blue) and long-term (>100 years) C_{org} burial rates (*n* = 33; blue) in seagrass communities (Supplementary Tables 1-4).

the first 4 h of the survey, thereafter gradually decreasing back to the initial concentration. The *R. megacarpa* community was a source of CH_4 and a sink of N_2O to the atmosphere. Water-air CH_4 fluxes ranged from 16.8 to 57.3 μmol CH_4 m^{-2} day^{-1} with a mean of 32.5 ± 0.4 μmol CH_4 m^{-2} day^{-1} (±standard error (SE), *n* = 1202) (Supplementary Fig. 1). Water-air N_2O fluxes ranged from −2.0 to −0.4 μmol N_2O m^{-2} day^{-1} with a mean of −0.9 ± 0.01 μmol N_2O m^{-2} day^{-1} (±SE, *n* = 1202) (Supplementary Figure 1).

Seagrass organic carbon accumulation and burial rates. Global seagrass community C_{org} accumulation rates ranged from 1.3 to 175.3 g C m^{-2} year^{-1} with a mean (±SE) of 41.4 ± 7.4 g C m^{-2} year^{-1} and a median (IQR) of 20.7 (53.8) g C m^{-2} year^{-1} (Fig. 2 and Supplementary Table 1). Global seagrass community long-term C_{org} burial rates (>100 years) ranged from 1.7 to 112.9 g C m^{-2} year^{-1} with a mean (±SE) of 25.1 ± 5.3 g C m^{-2} year^{-1} and a median (IQR) of 11.3 (20.2) g C m^{-2} year^{-1} (Fig. 2 and Supplementary Table 2). Although the mean and median C_{org} accumulation rates were higher than mean and median C_{org} burial rates they were not significantly different ($p = 0.78$). ^{14}C measured long-term burial rates (mean ± SE 24.5 ± 6.7 g C m^{-2} year^{-1}; median (IQR) 9.0 (16.8) g C m^{-2} year^{-1}) were also not significantly different ($p = 0.94$) than ^{210}Pb measured rates (mean ± SE 27.1 ± 6.6 g C m^{-2} year^{-1}; median (IQR) 24.4 (25.3) g C m^{-2} year^{-1}).

Global seagrass methane and nitrous oxide fluxes. Global seagrass community CH_4 fluxes ranged from −27.8 to 401.3 μmol CH_4 m^{-2} day^{-1} with a mean (±SE) of 79.0 ± 16.8 μmol CH_4 m^{-2} day^{-1} and a median (IQR) of 48.2 (96.3) μmol CH_4 m^{-2} day^{-1} (Fig. 2 and Supplementary Table 3). Mean (±SE) (103.6 ± 39.0 μmol CH_4 m^{-2} day^{-1}) and median (IQR) (67.4 (135.2) μmol CH_4 m^{-2} day^{-1}) water-air CH_4 fluxes were higher than mean (70.5 ± 19.5 μmol CH_4 m^{-2} day^{-1}) and median (IQR) (46.8 (97.6) μmol CH_4 m^{-2} day^{-1}) sediment-water CH_4 fluxes, but they were not significantly different ($p = 0.34$). Seagrass community N_2O fluxes ranged from −7.2 to 3.7 μmol N_2O m^{-2} day^{-1} with a mean (±SE) of −1.4 ± 1.0 μmol N_2O m^{-2} day^{-1} and a median (IQR) of −0.9 (1.0) μmol N_2O m^{-2} day^{-1} (Fig. 2 and Supplementary Table 4). Mean (±SE) water-air N_2O fluxes (−1.2 ± 0.3 μmol N_2O m^{-2} day^{-1}) were similar to mean sediment-water N_2O fluxes (−1.4 ± 1.3 μmol N_2O m^{-2} day^{-1}). In contrast, median (IQR) N_2O water-air uptakes (−1.2 (0.3) μmol N_2O m^{-2} day^{-1}) were higher than median N_2O sediment-water uptakes (−0.6 (2.7) μmol N_2O m^{-2} day^{-1}).

Reduced climate benefit of seagrass communities. Measurements of CH_4 and N_2O fluxes and long-term C_{org} burial rates were available for only three seagrass species (Supplementary Tables 2–4). All three species were a source of CH_4 and a sink for N_2O. *Zostera sp.* and *Halophila sp.* were a $CH_4 + N_2O$-CO_2-equivalent (CO_2e) source when using 20-year global warming potential (GWP_{20}) and a $CH_4 + N_2O$-CO_2e sink when using the 100-year global warming potential (GWP_{100}), and *Posidonia sp.* was a $CH_4 + N_2O$-CO_2-equivalent (CO_2e) source ($GWP_{20,100}$). All three species were net CO_2e sinks when long-term C_{org} burial was included. The mean seagrass community $CH_4 + N_2O$-CO_2e sources reduces the climate benefit of C_{org} long-term burial 15.8 to 58.3% (GWP_{20}) (average of means 34.7%) across the three seagrass species (median 25.8 to 89.9% (average of medians 54.0%) (Table 1). CO_2e offsets were much lower using GWP_{100} reducing the climate benefit of C_{org} long-term burial from −16.9 to 18.5% (average of means 1.0%) across the four seagrass species (median −6.5 to 28.6% (average of medians 7.1%)).

All seagrass communities in Australia were a source of CH_4, except for one site (Supplementary Table 3), and a sink for N_2O, except for one site (Supplementary Table 4), and an overall $CH_4 + N_2O$-CO_2e source. Seagrasses in the Australian region were a net CO_2e sink when long-term C_{org} burial was included. Using the GWP_{20}, the mean Australian seagrass community CO_2e source reduces the climate benefit of C_{org} long-term burial by 41.3% (median 33.9%) (Table 1). Seagrass $CH_4 + N_2O$-CO_2e offsets in Australia were much lower using the GWP_{100} with a mean reduction of the climate benefit of C_{org} long-term burial of 1.1% (median 2.1%).

Globally, seagrass communities were a source of CH_4, except for one site (Supplementary Table 3), and seven of the nine seagrass communities were a sink for N_2O (Supplementary Table 4), and an overall $CH_4 + N_2O$-CO_2e source. Seagrasses globally were a net CO_2e sink when long-term C_{org} burial was included. Using the GWP_{20}, the mean global seagrass $CH_4 + N_2O$-CO_2e source reduces the climate benefit of C_{org} long-term burial by 44.6% (median 33.9%). Seagrass $CH_4 + N_2O$-CO_2e offsets were lower using the GWP_{100} with a mean reduction of the climate benefit of C_{org} long-term burial of 8.8% (median 7.0%).

Discussion

Burial, methane and nitrous oxide processes in seagrass communities. The range of seagrass long-term C_{org} burial rates (1.7 to 112.9 g C_{org} m^{-2} year^{-1}) in this synthesis (Supplementary Table 2) is similar to previous global ranges of long-term burial rates (e.g., 9 to 122 g C_{org} m^{-2} year^{-1} [5]); However, our mean ± SE global long-term C_{org} burial rate (25.1 ± 5.3 g C_{org} m^{-2} year^{-1}; *n* = 33) is much lower than a previous estimate of the mean long-term burial rate based on only *P. oceanica* from the Mediterranean (58 g C_{org} m^{-2} year^{-1} [5]); Similarly, our mean seagrass accumulation rate (41.4 ± 7.4 g C_{org} m^{-2} year^{-1}; *n* = 36) is lower than previous estimates that have also included C_{org} mass balances (53 g C_{org} m^{-2} year^{-1} [5]); Using the most recent global

Table 1 Seagrass long-term burial rates, CH_4 and N_2O fluxes, net climate benefit and offsets.

	Community	Burial	Burial	CH_4 flux	CH_4 flux	CH_4 flux	N_2O flux	N_2O flux	N_2O flux	Net climate benefit	Net climate benefit	Offset	Offset
					GWP_{20}	GWP_{100}		GWP_{20}	GWP_{100}	GWP_{20}	GWP_{100}	GWP_{20}	GWP_{100}
		g C_{org} m^{-2} $year^{-1}$	g CO_2 m^{-2} $year^{-1}$	µmol CH_4 m^{-2} day^{-1}	g CO_2e m^{-2} $year^{-1}$	g CO_2e m^{-2} $year^{-1}$	µmol N_2O m^{-2} day^{-1}	g CO_2e m^{-2} $year^{-1}$	g CO2e m^{-2} $year^{-1}$	g CO_2e m^{-2} $year^{-1}$	g CO_2e m^{-2} $year^{-1}$	%	%
Global													
Median (IQR)	Mixed	11.3 (20.2)	41.4 (74.1)	48.2 (96.3)	22.4 (44.8)	7.6 (15.2)	−0.9 (1.0)	−3.9 (4.4)	−3.9 (4.4)	23.0	37.8	44.6	8.8
Mean ± SE	Mixed	25.1 ± 5.3	92.1 ± 20.9	79.0 ± 18.8	36.8 ± 8.7	12.5 ± 3.0	−1.4 ± 0.6	−6.0 ± 2.5	−6.0 ± 2.5	61.3	85.6	33.4	7.0
Seagrass species													
Median (IQR)	*Zostera sp.*	11.3 (23.5)	41.4 (86.2)	35.8 (97.4)	16.6 (45.3)	5.6 (15.4)	−1.4 (1.9)	−6.0 (8.3)	−6.0 (8.3)	30.8	41.8	25.8	−0.8
Mean ± SE		22.9 ± 6.5	84.1 ± 9.0	79.1 ± 26.9	36.8 ± 13.8	12.5 ± 4.7	−2.6 ± 1.6	−11.4 ± 6.8	−11.4 ± 6.8	58.7	83.1	30.2	1.2
Median (IQR)	*Halophila sp.*	7.2 (0.0)	26.4 (0.0)	45.4 (58.6)	21.1 (27.8)	7.2 (9.2)	−2.0 (2.4)	−8.9 (10.3)	−8.9 (10.3)	14.1	28.1	46.5	−6.5
Mean ± SE		7.2 ± 0.0	26.4 ± 0.0	28.0 ± 17.7	13.0 ± 8.2	4.4 ± 2.8	−2.0 ± 3.3	−8.9 ± 10.3	−8.9 ± 10.3	22.2	30.9	15.8	−16.9
Median (IQR)	*Posidonia sp.*	26.4 (62.4)	96.8 (228.8)	192.7 (86.7)	89.7 (40.3)	30.4 (13.7)	−0.6 (0.0)	−2.7 (0.0)	−2.7 (0.0)	9.8	69.1	89.9	28.6
Mean ± SE		40.7 ± 11.1	149.2 ± 40.8	192.7 ± 86.7	89.7 ± 40.3	30.4 ± 13.7	−0.6 ± 0.0	−2.7 ± 0.0	−2.7 ± 0.0	62.2	121.5	58.3	18.5
Australian region													
Median (IQR)	Mixed	8.9 (8.6)	32.6 (31.5)	33.8 (41.7)	15.7 (19.4)	5.3 (6.6)	−1.1 (1.6)	−4.6 (7.2)	−4.6 (7.2)	21.6	32.0	33.9	2.1
Mean ± SE	Mixed	12.3 ± 2.3	45.1 ± 8.5	58.8 ± 40.6	27.4 ± 18.9	9.3 ± 6.4	−2.0 ± 1.1	−8.8 ± 5.0	−8.8 ± 5.0	26.5	44.6	41.3	1.1

Table 2 Published reduction in the net climate benefit of seagrass communities due to methane and nitrous oxide fluxes (% offsets).

	Community	Accumulation	CH_4 flux	N_2O flux	Recalculated GWP_{20} Offset	Recalculated GWP_{100} Offset	Published GWP_{20} Offset	Published GWP_{100} Offset	Reference
		g C_{org} m^{-2} $year^{-1}$	µmol CH_4 m^{-2} day^{-1}	µmol N_2O m^{-2} day^{-1}	%	%	%	%	
Lower		69.0	105.8	-	19.5	6.6	-		Garcias-Bonet and Duarte[20]
Upper		169.0	105.8	-	7.9	2.7	-		
Median						4.6	-	4.8	
Mean	Mixed	138.0	108.2	-	10.0	4.0	-	0.3	Al-Haj and Fulweller[21]
Bare sediment removed	*Zostera sp.*	42.0	119.0	2.3	31.8	16.0	-	10	Oreska et al.[11]
	Posidonia sp.	337.3	106.0	-	4.0	1.4		4-5	Schorn et al.[18]
	Zostera sp.	-	10.5	−1.46	-	0	0	-	Ollivier et al.[19]

Offsets have also been recalculated using Eqs. (1)–(6) and the CH_4 and N_2O fluxes and organic carbon accumulation rates from the publication.

seagrass area of 160,387 km^2 [22] gives mean and median global seagrass long-term C_{org} burial of 4.0 and 1.8 Tg C_{org} year^{-1} respectively, which represents a minor coastal sink compared to the 250 Tg C year^{-1} uptake of CO_2 on the continental shelf[23]. Most importantly, our mean ± SE global seagrass C_{org} burial rate of 25.1 ± 5.3 g C_{org} m^{-2} year^{-1} is also much lower than mean global accumulation estimates that have been used in previous global offset estimates (e.g., 119 g C_{org} m^{-2} year^{-1} [20]; 138 ± 38 g C_{org} m^{-2} year^{-1} [21]. Global seagrass C_{org} accumulation estimates of refs. [20,21] do not reflect long-term C_{org} burial because many of the estimates are based on carbon mass balances, not long-term (<100 year) ^{14}C and ^{210}Pb C_{org} burial rates, and are biased toward the "matte"-forming *P. oceanica*[7,8]. Therefore, we argue that the long-term C_{org} burial rates we used here are a better estimate of blue carbon[7] to compare to Green House Gas-CO_2e fluxes and to estimate offsets.

Our revised global mean ± SE seagrass community CH_4 flux of 79.0 ± 16.8 μmol CH_4 m^{-2} day^{-1} (median(IQR) 48.2 (96.3) μmol CH_4 m^{-2} day^{-1}; $n = 35$; Supplementary Table 3) in this study is lower than the most recent seagrass compilation (mean 112.5 ± 62.5 μmol CH_4 m^{-2} day^{-1}; median 81.2 (87.5) μmol CH_4 m^{-2} day^{-1}; $n = 18$[24]; and based upon almost twice as many measurements. Although seagrass CH_4 emissions are lower than from mangroves and salt marshes[24], seagrasses cover a larger surface area, globally. Using the most recent global seagrass area of 160,387 km^2 [22] gives mean and median global seagrass CH_4 fluxes of 0.074 and 0.045 Tg CH_4 year^{-1}, respectively. Our revised global CH_4 emission estimates are about 40% of the most recent estimate[24], due to a lower mean and median CH_4 flux rate and a smaller surface area of seagrass, and as such, represents a small contribution to global estuarine CH_4 emissions (mean 0.9 Tg CH_4 year^{-1} [24].

Our compilation demonstrates that CH_4 production in seagrass communities is widespread, with rates up to 401.3 μmol CH_4 m^{-2} day^{-1} (Supplementary Table 3), despite seagrasses being found in marine waters where sediments are considered to have negligible CH_4 emissions[25]. The release of methylated compounds from plants may fuel CH_4 production; a recent study showed that seagrass CH_4 production was sustained exclusively via methylated compounds produced and released by the plant[18]. The more common pathways of hydrogenotrophic and acetoclastic CH_4 production in anoxic sediment were undetected in seagrasses and were most likely outcompeted by sulfate-reducing bacteria[18].

This is the first compilation of measured N_2O fluxes for seagrass communities (Supplementary Table 4). Although[26] included seagrass N_2O fluxes in the estimation of coastal and inland water N_2O emissions, a separate seagrass N_2O flux was not presented. A recent synthesis of N_2O rates for seagrasses[27] were based on denitrification rates in seagrasses and N_2O:N_2 ratios and not on direct N_2O flux measurements. Using the most recent global seagrass area[22] gives mean and median global seagrass N_2O uptakes of −0.004 and −0.002 Tg N_2O year^{-1} respectively, which represents a minor sink in marine N_2O emissions[26,27]. Previous global estimates have suggested that seagrasses are a source of N_2O[27], which highlights the problem with using N_2O:N_2 ratios and denitrification rates to estimate seagrass N_2O fluxes.

Seven of the nine seagrass sites showed an uptake of N_2O, with uptakes as high as −7.2 μmol N_2O m^{-2} day^{-1} in the Noosa Estuary, Australia (Supplementary Table 4). This is similar to mangrove and estuarine systems that show an uptake of N_2O when NO_3^- concentrations are below 5 μmol l^{-1} [28,29]. However, some of the N_2O uptakes in the seagrasses were greater than N_2O uptakes in mangroves[15,29]. This may reflect even lower water column NO_3^- concentrations at some seagrass sites. For example, NO_3^- concentrations in Wallis Lake and the Noosa and Maroochy estuaries were all below 1.0 μmol l^{-1} [16,17]. This combination of low NO_3^- concentrations and high rates of denitrification in seagrasses[30–32] may result in N_2O consumption via denitrification. Conversely, nutrient enrichment would increase N_2O fluxes and reduce the climate benefit of seagrass communities.

Implications for the climate benefit of seagrass blue carbon. We present three approaches for estimating the mean and median reduction of the climate benefit of seagrass C_{org} long-term burial (offsets). Mean and median offsets were similar for the individual seagrass species and globally (Table 1). Although this might be expected since the individual seagrass species were calculated from a subset of the data used in the global offsets. The reduced climate benefit of the Australian region was also calculated from a subset of the global data, but the mean and median GWP_{20} offsets were much higher mostly due to lower long-term burial rates, but the GWP_{100} offsets were lower due to the N_2O-CO_2e sink reducing the CH_4-CO_2e source. As such, the resolved geographic variability in long-term burial rates and greenhouse gas fluxes has important implications for evaluating the climate benefit of seagrass across different regions. Offsets calculated using the GWP_{100} were much lower than those calculated using GWP_{20} because the CH_4 GWP_{100} multiplier (27.0) is much lower than the CH_4 GWP_{20} multiplier (79.7), while the N_2O multiplier is the same for GWP_{20} and GWP_{100}. By reducing the GWP_{100} CH_4-CO_2e source it allows the GWP_{100} N_2O-CO_2e sink to greatly reduce the combined GWP_{100} CO_2e CH_4 and N_2O reduction of the climate benefit of long-term seagrass C_{org} burial.

Despite accounting for N_2O uptakes in seagrass (i.e., increasing the climate benefit seagrass C_{org} long-term burial) the mean global seagrass CH_4 and N_2O offset (33.4% GWP_{20}) is still higher than the global CH_4 offset estimated for mangroves (20.5% GWP_{20} [9]). Although CH_4 fluxes are higher in mangroves (0 to 2127.2 μmol CH_4 m^{-2} day^{-1}), the lower mangrove offset reflects the much higher C_{org} burial rates in mangroves (56.6 to 651.0 g C m^{-2} year^{-1} [9]; compared to seagrass communities (Supplementary Table 2). The mangrove CH_4 offset would also be further reduced, particularly for GWP_{100}, if N_2O uptake, which is common in mangrove waterways[15], were included.

Mean offsets for the individual seagrass species from our synthesis are much higher than previous offset estimates (Table 2). The higher offsets in this study were mostly due to the use of long-term C_{org} burial rates, compared to short-term C_{org} accumulation rates being used in previous studies. Our mean global offsets (GWP_{100}) in seagrasses are only a little higher than two previous global offset estimates[20,21]; Table 2). However, this similarity is a coincidence, and not an agreement, due to the high C_{org} accumulation rates used in the previous offset estimates and the N_2O fluxes used in our estimates, which cancel each other out when using GWP_{100}. The difference between previously published offsets and our offsets due to different combinations of C_{org} long-term burial rates, and CH_4 and N_2O fluxes, highlights importance of measuring all three parameters when assessing the net climate benefit (Blue Carbon) of seagrass communities (Table 1), and when deciding which seagrass communities to include in restoration projects. We argue that our global seagrass Green House Gas offsets are more realistic because we include a larger number of CH_4 fluxes, we include N_2O fluxes and we only include long-term C_{org} burial rates. In addition, we also provide the first estimates of seagrass global offsets using GWP_{20}.

Uncertainties in offsets and future research. Our three offset estimates show that CH_4 can reduce the climate benefit of seagrass communities for GWP_{20} and with a reduced effect for

Table 3 Uncertainties in the reduction of the net climate benefit of seagrass communities due to methane and nitrous oxide fluxes.

Uncertainty likely to result in offsets being under-estimated
- Emission of other greenhouse gases (e.g., isoprene)
- $CaCO_3$ burial
- Choice of global warming potential

Uncertainty likely to result in offsets being over-estimated
- Sediment-water fluxes higher than water-air fluxes
- Differences in timescales of long-term burial and greenhouse gas production
- Low 100 year burial rates from ^{14}C measurements

Unknown which way offsets may be affected
- Limited spatial and temporal measurements of seagrass CH_4 and N_2O fluxes and long-term organic carbon burial rates
- Allochthonous organic carbon (net heterotrophic seagrass communities)
- Export and burial of seagrass organic carbon off site
- Bias due to measurements used in synthesis not being undertaken at the same location

GWP_{100} and N_2O fluxes can enhance the climate benefit of seagrass communities ($GWP_{20,100}$). However, there are a number of uncertainties in our synthesis that should be considered, as they may result in either over- or under-estimations of seagrass offsets (Table 3). These uncertainties also highlight areas for further research.

The seagrass species approach for estimating offsets shows a large range in the possible seagrass blue carbon offset by CH_4 and N_2O fluxes. *Posidonia* had the highest offsets (GWP_{20} and GWP_{100}) due to high CH_4 fluxes. However, this high offset estimate may be due to the limited data availability, with *Posidonia* estimate based on only two measurements of CH_4 fluxes and one N_2O flux (Supplementary Tables 3 and 4). *Halophila sp*. showed a net $CH_4 + N_2O\text{-}CO_2e$ uptake (GWP_{100}) due to low CH_4 fluxes and high N_2O fluxes, but this was based on only two measurements of N_2O fluxes and one long-term burial rate. Globally, there was limited N_2O flux data (9 sites globally). In particular, there were few, or no, measurements from Africa, South America and Southeast Asia (Fig. 1). There were also no simultaneous measurements of CH_4 and N_2O fluxes and C_{org} long-term burial from the one location which may result in a bias in our offsets[33]. Clearly, more measurements of CH_4 and N_2O fluxes and C_{org} long-term burial in the same seagrass communities, and across a range of seagrass species and locations, is required for accurate blue carbon assessments.

CH_4 offsets were mostly based on seagrass sediment-water CH_4 fluxes (26 sites) with less water-air CH_4 fluxes (9 sites; Supplementary Table 3). Although it is unknown if sediment-water CH_4 fluxes from seagrass communities reach the atmosphere, water column CH_4 oxidation rates at salinities >6 are typically low[34]. This is consistent with negligible water column oxidation at the Wallis Lake site[16]. Mean and median seagrass water-air CH_4 fluxes were also higher, but not significantly different ($p = 0.34$), than seagrass sediment-water CH_4 fluxes suggesting sediment-water fluxes do not systematically overestimate seagrass CH_4 fluxes to the atmosphere. Similarly, some of the CH_4 and N_2O flux studies were only undertaken in one season, and some were undertaken multiple seasons. However, the was no significant difference between single season and multiple season CH_4 fluxes ($p = 0.64$). As such, differences in the temporal scale of collection, does not appear to have added any bias into our analysis.

This study has only considered two (long-term burial, CH_4 and N_2O fluxes) of the many processes that determine the net climate benefit of seagrass communities. For example, we have not considered $CaCO_3$ burial which greatly reduces, and in some cases completely removes, the climate benefit of seagrasses (e.g. refs. [16,35,36]). Seagrasses also emit other climate warming greenhouse gases like isoprene[37], which we have not considered. In addition, we have not compared the net climate benefit of seagrass communities to the net climate benefit of adjacent unvegetated sediments. Without comparing CH_4 and N_2O fluxes to adjacent bare sediments the CH_4 and N_2O fluxes in this synthesis are a maximum attributable to the seagrass community (see refs. [11,38]). Similarly, without comparing long-term burial rates to adjacent bare sediments the long-term burial rates in this synthesis are a maximum attributable to the seagrass community.

An input of allochthonous C_{org} is major process not considered by this study. Although we only used ^{210}Pb and ^{14}C measured rates of seagrass C_{org} long-term burial across a broad range of seagrass species and locations, these estimates may still be too high because of an input allochthonous C_{org}, both recalcitrant and labile[8,39]. For example, up to 50% of the C_{org} in seagrass communities may be derived from non-seagrass sources, including macroalgae (e.g. refs. [40–42]). In some seagrass communities that are net heterotrophic there can even be a net flux of CO_2 due to an input of allochthonous organic carbon[43]. If we assume 50% of the seagrass C_{org} long-term burial is from non-seagrass sources, this would increase our global mean offsets from 33.4% GWP_{20} and 7.0% GWP_{100} to 66.8% GWP_{20} and 14.0% GWP_{100}. As such, our seagrass offsets should be considered a lower estimate as an input of any allochthonous C_{org} would result in higher offsets. However, this assumes that the allochthonous C_{org} is not included as seagrass "Blue Carbon" but the CH_4 and N_2O produced during its decomposition are included. It could be argued that the CH_4 and N_2O fluxes associated with the allochthonous C_{org} should also not be included, and therefore the allochthonous component would not affect the offsets, unless it produces CH_4 and N_2O differently to the autochthonous C_{org} (Table 3). Similarly, C_{org} produced by the seagrass community, but transported offsite and buried is unaccounted for by the long-term burial rates measured in the seagrass community. However, when this material is buried offsite it will still result in the production or consumption of CH_4 and N_2O, which would also contribute to an offset. The local conditions of long-term burial and associated production or consumption of CH_4 and N_2O would determine if this results in an over- or under-estimate of the offset (Table 3).

The long-term burial rates may also be too low. Although there was no significant difference between the ^{14}C and ^{210}Pb measured long-term burial rates in this synthesis, ^{14}C long-term burial rates are up to 1000's of years old, and may be lower than seagrass long-term burial rates over 100's of years (e.g. ref. [44]), resulting in an over-estimate of offsets (Table 3). There are also timescale differences between the long-term burial rates and CH_4 and N_2O fluxes. Long-term burial is C_{org} that has been sequestered for

>100 years compared to CH_4 and N_2O fluxes which are a recent measurement, typically only undertaken once or over one annual cycle (Supplementary Tables 3 and 4). It is unknown if the recently measured CH_4 and N_2O fluxes are representative of the seagrass community for the longer period over which C_{org} has been buried. In particular, recent disturbance of the seagrass community may change the CH_4 and N_2O fluxes. For example, warming and shading could result in higher seagrass CH_4 fluxes[20,45] and nitrogen enrichment may reduce the uptake of N_2O in seagrasses[17], both of which would result in an over-estimate of offsets (Table 1).

Our choice of global warming potential (i.e., IPCC 2021) also influences the net climate benefit offset estimates. For example had we chosen to use the sustained global warming potential (SGWP[46]) our global mean offset would have increased from 33.4% GWP_{20} and 7.0% GWP_{100} to 41.8% GWP_{20} and 14.8% GWP_{100}. Despite a higher $SGWP_{100}$ value of 349 for N_2O uptakes, which would reduce the offset, the offset is still higher due to the higher $SGWP_{100}$ value for CH_4 (45[4]).

In summary, this study shows that CH_4 fluxes can reduce, and N_2O fluxes can enhance, the climate benefit of seagrass blue carbon. We also highlight the importance of using long-term C_{org} burial rates when assessing the climate benefit of seagrass blue carbon. These findings will contribute to policies and practice incorporating blue carbon habitat conservation and restoration as a natural strategy for CO_2 removal.

Materials and methods

Wallagoot Lake study area, experimental procedure, and calculations. Wallagoot Lake is a small slightly degraded temperate Intermittently Closed and Open Lake and Lagoon (ICOLL) on the southern New South Wales coast. *R. megacarpa* occurs in the shallow water (<2 m) around the edge of the whole lake. A 20-h time-series measuring continuous water CH_4 and N_2O concentrations over a *R. megacarpa* seagrass community (S36°47'39"; E 149°56'19") was undertaken in summer 2016. Water was pumped from 30 cm water depth and passed through a shower-head equilibrator connected to a cavity-ring-down spectroscopy (Picarro, G2308) analyzer. CH_4 and N_2O concentrations were measured at ~1 Hz (precision at 1 min <7 ppb ± 0.05% of reading). Wind speed was measured hourly with a digital anemometer (Q1411, Dick Smith Electronics), as well as water temperature and salinity at 15 min intervals (Hydrolab HL4 Sonde, Aqualab).

The CH_4 and N_2O water-air flux (F) was estimated as $F = k\ K_0\ (C_{water} – C_{air})$, where k is the gas transfer velocity (m day^{-1}), K_0 is the solubility coefficient (mol kg^{-1} atm^{-1}) at the measured water temperature and salinity[47,48], and C_{water} and C_{air} are the partial pressures (μatm) of CH_4 or N_2O in the water and air, respectively[49]. Due to variability in k obtained by different empirical models[50], three models were selected as adequate for the investigated area to determine the gas transfer velocity[51–53], and the resulting fluxes were averaged.

Blue carbon offset calculations. Scopus and google scholar were searched for "seagrass" AND methane", "seagrass AND nitrous oxide" and "seagrass AND burial". Additional papers were identified from reading the papers found in the searches. Sediment-water (cores, benthic chambers) and water-air (open water, floating chambers) seagrass CH_4 and N_2O fluxes were included in the synthesis. Because we were interested in the seagrass CO_2e offset to long-term (>100 years) seagrass C_{org} burial, only seagrass accumulation rates obtained using ^{210}Pb and ^{14}C dating were included[7]. Studies that used sediment accumulation rates from the literature were excluded (i.e. refs. [54,55]). Multiple CH_4 and N_2O fluxes and long-term C_{org} burial rates for a given seagrass species at a given site were averaged (site mean). Temporal CH_4 and N_2O flux measurements (e.g., diel, seasonal) were also averaged.

Each of the seagrass C_{org} accumulation studies identified were further assessed to determine if they could be considered long-term (>100 years) seagrass C_{org} burial following the best practice outlined in ref. [8]. To be considered long-term (>100 years) seagrass C_{org} burial for cores dated using ^{210}Pb the study had to show ^{210}Pb concentrations profiles so we could determine that there was no sediment mixing and C_{org} concentration profiles to determine if C_{org} was buried below the zone of rapid carbon remineralisation (i.e., where concentrations no longer decrease and become constant[8]); If an average of the C_{org} concentration profile was used, but the C_{org} concentration profile increased or was constant with depth this was considered acceptable. To be considered long-term (<100 years) seagrass C_{org} burial for cores dated using ^{14}C C_{org} concentration profiles were required. All studies that did not meet the long-term burial criteria were assigned to C_{org} accumulation.

CH_4 and N_2O fluxes were converted to CO_2 equivalents using the 20-year and 100-year GWP of each gas. The GWP_{20} and GWP_{100} for CH_4 are 79.7 and 27 respectively, and the GWP_{20} and GWP_{100} for N_2O is 273[14]. The reduced climate benefit of seagrass blue carbon was calculated three ways. Firstly, seagrass species offsets were calculated using the mean and median of long-term C_{org} burial rates and CH_4 and N_2O fluxes rates for all individual seagrass species for which all three parameters were available (Supplementary Tables 2–4 and Fig. 1). Secondly, the Australian seagrass offset was calculated using the mean and median of all seagrass long-term C_{org} burial rates and CH_4 and N_2O fluxes for the Australian region (Supplementary Tables 2–4 and Fig. 1). This was done because Australia is the only region were there was sufficient data for this calculation. Thirdly, the global offset was calculated using the mean and median of all seagrass long-term C_{org} burial rates and CH_4 and N_2O fluxes (Supplementary Tables 2–4 and Fig. 1). Although we use the term "global" this doesn't reflect the mean or median long-term C_{org} burial rates, CH_4 and N_2O fluxes and %offsets at any given location, as this will depend on site specific factors. Both the mean and median as the central statistic is presented as per[24] to allow comparisons with past and future studies. The following six equations were used to calculate offsets from the mean and median of long-term C_{org} burial rates and CH_4 and N_2O fluxes:

$$\text{Offset}(\%) = (\text{Total}\,CO_2\text{e source}/CO_2\text{e long term}\,C_{org}\,\text{burial}) \times 100\% \tag{1}$$

$$\text{Net climate benefit} = C_{org}CO_2\text{e long term burial} - CH_4CO_2\text{e flux} - N_2OCO_2\text{e flux} \tag{2}$$

$$\text{Total}\,CO_2\text{e source} = CH_4CO_2\text{e flux} + N_2OCO_2\text{e flux} \tag{3}$$

$$CH_4CO_2\text{e flux}(\text{g}\,CO_2\,\text{m}^{-2}\,\text{year}^{-1}) = CH_4\,\text{flux}(\mu\text{mol}\,CH_4\text{m}^{-2}\,\text{day}^{-1}) \times 10^6 \times 365 \times 16 \times 79.7(GWP_{20})\ \text{or} \times 27.0(GWP_{100}) \tag{4}$$

$$N_2OCO_2\text{e flux}(\text{g}\,CO_2\,\text{m}^{-2}\,\text{year}^{-1}) = N_2O\,\text{flux}(\mu\text{mol}\,N_2O\,\text{m}^{-2}\,\text{day}^{-1}) \times 10^6 \times 365 \times 44 \times 273(GWP_{20,100}) \tag{5}$$

$$C_{org}CO_2\text{e long term burial}(\text{g}\,CO_2\,\text{m}^{-2}\text{year}^{-1}) = \text{g}\,C_{org}\,\text{m}^{-2}\,\text{year}^{-1} \times 12/44 \tag{6}$$

Statistical analysis. The Welch two sample *t*-test was used to test whether the means of two sample populations are different, assuming independent samples for unequal variances and sample sizes under normality. The *t*-tests were performed in R (R version 4.0.3 (2020-10-10)[56].

Data availability

The dataset is published in the repository Figshare 10.6084/m9.figshare.24070998.

Received: 2 February 2023; Accepted: 22 September 2023;

References

1. Fawzy, S., Osman, A. I., Doran, J. & Rooney, D. W. Strategies for mitigation of climate change: a review. *Environ. Chem. Lett.* **18**, 2069–2094 (2020).
2. Amelung, W. et al. Towards a global-scale soil climate mitigation strategy. *Nat. Commun.* **11**, 5427 (2020).
3. Smith, S. V. Marine macrophytes as a global carbon sink. *Science* **211**, 838–840 (1981).
4. Nellemann, C. et al. *Blue Carbon: The Role of Healthy Oceans in Binding Carbon: A Rapid Response Assessment* (GRID-Arendal, 2009).
5. Duarte, C. M., Kennedy, H., Marbà, N. & Hendriks, I. Assessing the capacity of seagrass meadows for carbon burial: current limitations and future strategies. *Ocean Coast. Manag.* **83**, 32–38 (2013).
6. McLeod, E. et al. A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO2. *Front. Ecol. Environ.* **9**, 552–560 (2011).
7. Johannessen, S. C. & Macdonald, R. W. Geoengineering with seagrasses: is credit due where credit is given? *Environ. Res. Lett.* **11**, 113001 (2016).
8. Johannessen, S. C. How can blue carbon burial in seagrass meadows increase long-term, net sequestration of carbon? A critical review. *Environ. Res. Lett.* **17**, 093004 (2022).
9. Rosentreter, J. A., Maher, D. T., Erler, D. V., Murray, R. H. & Eyre, B. D. Methane emissions partially offset "blue carbon" burial in mangroves. *Sci. Adv.* **4**, eaao4985 (2018).
10. Macreadie, P. I. et al. The future of Blue Carbon science. *Nat. Commun.* **10**, 3998 (2019).
11. Oreska, M. P. J. et al. The greenhouse gas offset potential from seagrass restoration. *Sci. Rep.* **10**, 7325 (2020).
12. Whiticar, M. J. in *Hydrocarbons, Oils and Lipids: Diversity, Origin, Chemistry and Fate. Handbook of Hydrocarbon and Lipid Microbiology* (ed Wilkes, H.) (Springer, 2020).
13. Meyer, R. L., Allen, D. E. & Schmidt, S. Nitrification and denitrification as sources of sediment nitrous oxide production: a microsensor approach. *Mar. Chem.* **110**, 68–76 (2008).
14. Forster, P. et al. The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (eds Masson-Delmotte, V. et al.) 923–1054 (Cambridge University Press, 2021).
15. Murray, R., Erler, D., Rosentreter, J., Maher, D. & Eyre, B. D. A seasonal source and sink of N2O in mangroves: insights from concentration, isotope, and isotopomer measurements. *Geochim. Cosmochim. Acta* **238**, 169–192 (2018).
16. Camillini, N. *Carbon and Nitrogen Cycling in Seagrass Ecosystems*. PhD thesis, Southern Cross University and University of Southern Denmark (2020).
17. Chen, J.-J., Wells, N. S., Erler, D. V. & Eyre, B. D. Land use intensity increases benthic N_2O emissions across three sub-tropical estuaries. *J. Geophys. Res. Biogeosci.* **127**, e2022JG006899 (2022).
18. Schorn, S. et al. Diverse methylotrophic methanogenic archaea cause high methane emissions from seagrass meadows. *PNAS* **119**, e2106628119 (2022).
19. Ollivier, Q., Maher, D. T., Pitfield, C. & Macreadie, P. I. Net drawdown of greenhouse gases (CO_2, CH_4 and N_2O) by a temperate Australian seagrass meadow. *Estuaries Coast.* **45**, 2026–2039 (2022).
20. Garcias-Bonet, N. & Duarte, C. M. Methane production by seagrass ecosystems in the Red Sea. *Front. Mar. Sci.* **4**, 340 (2017).
21. Al-Haj, A. N. & Fulweiler, R. W. A synthesis of methane emissions from shallow vegetated coastal ecosystems. *Glob. Change Biol.* **26**, 2988–3005 (2020).
22. McKenzie, L. J. et al. The global distribution of seagrass meadows. *Environ. Res. Lett.* **15**, 074041 (2020).
23. Cai, W. J. Estuarine and coastal ocean carbon paradox: CO_2 sinks or sites of terrestrial carbon incineration? *Annu. Rev. Mar. Sci.* **3**, 123–145 (2011).
24. Rosentreter, J. A. et al. Half of global methane emissions come from highly variable aquatics ecosystem sources. *Nat. Geosci.* **14**, 225–230 (2021).
25. Poffenbarger, H. J., Needelman, B. A. & Megonigal, J. P. Salinity influence on methane emissions from tidal marshes. *Wetlands* **31**, 831–842 (2011).
26. Tian, H. et al. A comprehensive quantification of global nitrous oxide sources and sinks. *Nature* **586**, 248–256 (2020).
27. Murray, R. H., Erler, D. V. & Eyre, B. D. Nitrous oxide fluxes in estuarine environments: response to global change. *Glob. Change Biol.* **21**, 3219–3245 (2015).
28. Wells, N. S. et al. Estuaries as sources and sinks of N_2O across a land use gradient in subtropical Australia. *Glob. Biogeochem. Cycles* **32**, 877–894 (2018).
29. Murray, R., Erler, D. V., Rosentreter, J., Wells, N. S. & Eyre, B. D. Seasonal and spatial controls on N2O concentrations and emissions in lownitrogen estuaries: evidence from three tropical systems. *Mar. Chem.* **221**, 103779 (2020).
30. Eyre, B. D. & Ferguson, A. J. P. Comparison of carbon production and decomposition, benthic nutrient fluxes and denitrification in seagrass, phytoplankton, benthic microalgae- and macroalgae-dominated warm-temperate Australian lagoons. *Mar. Ecol. Prog. Ser.* **229**, 43–59 (2002).
31. Eyre, B. D., Maher, D. T. & Squire, P. Quantity and quality of organic matter (detritus) drives N2 effluxes (net denitrification) across seasons, benthic habitats, and estuaries. *Glob. Biogeochem. Cycles* **27**, 1083–1095 (2013).
32. Eyre, B. D., Maher, D. T. & Sanders, C. The contribution of denitrification and burial to the nitrogen budgets of three geomorphically distinct Australian estuaries: importance of seagrass habitats. *Limnol. Oceanogr.* **61**, 1144–1156 (2016).
33. Rosenbaum, P. R. & Rubin, D. B. The bias due to incomplete matching. *Biometrics* **41**, 103–116 (1985).
34. Abril, G. & Borges, A. in *Greenhouse Gases Emissions from Natural Environments and Hydroelectric Reservoirs: Fluxes and Processes Environmental Science Series* (eds Tremblay, A., Varfalvy, L., Roehm, C. & Garneau, M.) Ch. 7, 187–207 (Springer, 2004).
35. Sanders, C. J., Maher, D. T., Smoak, J. M. & Eyre, B. D. Large variability in organic carbon and CaCO3 burial in seagrass meadows: a case study from three Australian estuaries. *Mar. Ecol. Prog. Ser.* **616**, 211–218 (2019).
36. Van Dam, B. R. et al. Calcification-driven CO2 emissions exceed "Blue Carbon" sequestration in a carbonate seagrass meadow. *Sci. Adv.* **7**, eabj1372 (2022).
37. Hrebien, V., Deschaseaux, E. & Eyre, B. D. Isoprene flux from warm temperate and tropical seagrass communities. *Mar. Ecol. Prog. Ser.* **676**, 1–17 (2021).
38. Saderne, V. et al. Seasonality of methane and carbon dioxide emissions in tropical seagrass and unvegetated ecosystems. *Commun. Earth Environ.* **4**, 99 (2023).
39. Gallagher, J. B., Zhang, K. & Chuan, C. H. A re-evaluation of wetland carbon sink mitigation concepts and measurements: a diagenetic solution. *Wetlands* **42**, 23 (2022).
40. Kennedy, H. et al. Seagrass sediments as a global carbon sink: isotopic constraints. *Glob. Biogeochem. Cycles* **24**, 1–8 (2010).
41. Miyajima, T., Hori, M., Hamaguchi, M., Shimabukuro, H. & Yoshida, G. Geophysical constraints for organic carbon sequestration capacity of Zostera marina seagrass meadows and surrounding habitats. *Limnol. Oceanogr.* **62**, 954–972 (2017).
42. Prentice, C. & Hessing-Lewis, M. Reduced water motion enhances organic carbon stocks in temperate eelgrass meadows. *Limnol. Oceanogr.* **64**, 2389–2404 (2019).
43. Duarte, C. M. & Prairie, Y. T. Prevalence of heterotrophy and atmospheric CO_2 emissions from aquatic ecosystems. *Ecosystems* **8**, 862–870 (2005).
44. Arias-Ortiz, A. et al. A marine heatwave drives massive losses from the world's largest seagrass carbon stocks. *Nat. Clim. Change* **8**, 338–344 (2018).
45. Lyimo, L. D. et al. Shading and simulated grazing increase the sulphide pool and methane emission in a tropical seagrass meadow. *Mar. Pollut. Bull.* **134**, 89–93 (2018).
46. Neubauer, S. C. & Megonigal, J. P. Moving beyond global warming potentials to quantify the climatic role of ecosystems. *Ecosystems* **18**, 1000–1013 (2015).
47. Wiesenburg, D. A. & Guinasso, N. J. J. Equilibrium solubilities of methane, carbon monoxide, and hydrogen in water and sea water. *J. Chem. Eng. Data* **24**, 356–360 (1979).
48. Weiss, R. F. & Price, B. A. Nitrous oxide solubility in water and seawater. *Mar. Chem.* **8**, 347–359 (1980).
49. Pierrot, D. et al. Recommendations for autonomous underway pCO_2 measuring systems and data-reduction routines. *Deep Sea Res. II* **56**, 512–522 (2009).
50. Rovelli, L. et al. Headwater gas exchange quantified from O_2 mass balances at the reach scale. *Limnol. Oceanogr. Methods* **16**, 696–709 (2018).

51. Cole, J. J., Bade, D. L., Bastviken, D., Pace, M. L. & Van de Bogert, M. Multiple approaches to estimating air-water gas exchange in small lakes. *Limnol. Oceanogr. Methods* **8**, 285–293 (2010).
52. Crusius, J. & Wanninkhof, R. Gas transfer velocities measured at low wind speed over a lake. *Limnol. Oceanogr.* **48**, 1010–1017 (2003).
53. Upstill-Goddard, R. C., Watson, A. J., Liss, P. S. & Liddicoat, M. I. Gas transfer velocities in lakes measured with SF_6. *Tellus B Chem. Phys. Meteorol.* **42**, 364–377 (1990).
54. Lavery, P. S., Mateo, M. A., Serrano, O. & Rozaimi, M. Variability in the carbon storage of seagrass habitats and its implications for global estimates of blue carbon ecosystem service. *PLoS ONE* **8**, e73748 (2013).
55. Röhr, M. E., Boström, C., Canal-Vergés, P. & Holmer, M. Blue carbon stocks in Baltic Sea eelgrass (*Zostera marina*) meadows. *Biogeosciences* **13**, 6139–6153 (2016).
56. R Core Team. R: A language and environment for statistical computing. R Foundation for Statistical Computing. https://www.R-project.org/ (Vienna, Austria, 2020).

Acknowledgements

We would like to thank Philip Rickenberg for assistance in the field, and four reviewers for comments that improved the manuscript. In particular, we would like to thank one of the reviewers for their detailed comments that helped with determining which studies were long-term organic carbon burial. This project was supported by ARC Grant DP160100248 awarded to B.D.E. and R.N.G. In addition, R.N.G and N.C were supported by grants from the European Research Council grant no 669947(HADES-ERC), Danish National Research Foundation grant no DNRF145 (HADAL) and the Danish National Research Council (FNU7014-00078).

Author contributions

B.D.E., N.C., J.A.R. and R.N.G. contributed to the conceptual development of the manuscript, and reviewed and edited the manuscript. B.D.E. compiled the datasets, did the data analysis and wrote the manuscript with input from the other authors. N.C. helped with compiling the datasets. J.A.R. helped with the data analysis.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s43247-023-01022-x.

Correspondence and requests for materials should be addressed to Bradley D. Eyre.

Peer review information *Communications Earth & Environment thanks* Sophia Johannessen, John Gallagher, Mohammad Rozaimi and Brent McKee for their contribution to the peer review of this work. Primary Handling Editors: Christopher Cornwall, Clare Davis, Aliénor Lavergne. A peer review file is available