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Running title: Blue carbon from saltmarsh restoration

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Abstract

Coastal saltmarshes are found globally, yet are 25–50% reduced compared to their historical cover. Restoration is incentivised by the promise that marshes are efficient storers of ‘blue’ carbon, although the claim lacks substantiation across global contexts. We synthesised data from 435 studies to quantify the benefits of saltmarsh restoration to carbon accumulation and greenhouse gas uptake. The results showed global marshes store approximately 1.41 Pg – 2.44 Pg carbon. Restored marshes had very low greenhouse gas (GHG) fluxes and rapid carbon accumulation, resulting in a mean net accumulation rate of 64.70 t CO_2e ha^{-1} y^{-1}. Using this estimate and potential restoration rates, we find saltmarsh regeneration could result in 12.93 - 207.03 Mt CO_2e accumulation per year, offsetting the equivalent of up to 0.51% global energy related CO_2 emissions – a substantial amount, considering marshes represent <1% of Earth’s surface. Carbon accumulation rates and GHG fluxes varied contextually with temperature, rainfall and dominant vegetation, with the eastern costs of the USA and Australia particular hotspots for carbon storage. Whilst the study reveals paucity of data for some variables and continents, suggesting need for further research, the potential for saltmarsh restoration to offset carbon emissions is clear. The ability to facilitate natural carbon accumulation by saltmarshes now rests principally on the action of the management-policy community and on financial opportunities for supporting restoration.

Key Words

Coastal wetland; marsh creation; climate change; sequestration; greenhouse gas; organic matter

1.0 Introduction

Coastal ecosystems account for 50% of marine sediment carbon burial (Duarte et al. 2005) and offer a promising means for mitigating some of the effects of global carbon emissions. Tidal wetlands, such as mangrove forests and saltmarshes, are particular hotspots for ‘blue’ carbon sequestration. This is due to high carbon accumulation rates (CAR), coupled to slow degradation of organic matter in water-saturated, low-oxygen sediments (Neubauer and Megonigal 2021). Saline environments also have much lower emissions of potent greenhouse gases (GHG) such as methane, when compared to freshwater wetlands (Poffenbarger et al. 2011). Overall, carbon sequestration rates per unit area in saltmarshes exceed those of seagrass meadows, terrestrial forests and the open ocean (Temmink et al. 2022), with tidal marshes globally accumulating 12.63 Tg C y^{-1} (Wang et al. 2021). The processes involved in saltmarsh carbon sequestration are outlined in Figure 1. Recent estimates also show saltmarsh soils are a major carbon store, with an average standing stock of 400 Mg C ha^{-1} (Temmink et al. 2022).

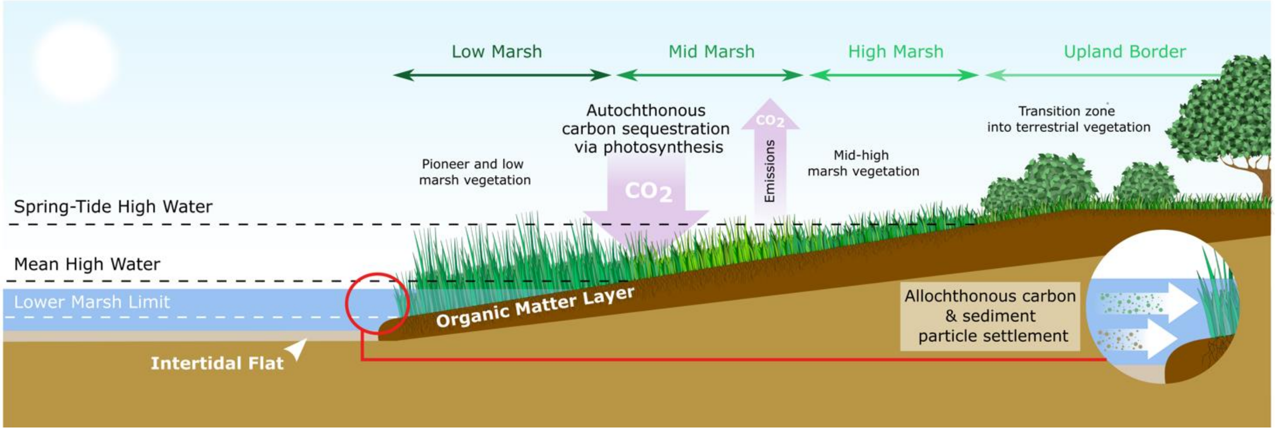


Figure 1: Saltmarsh carbon can be generated by the system itself (autochthonous C) or can originate from outside the system (allochthonous C), entering the marsh through passing water and settling out as particulate matter when the vegetation slows down the currents and waves. Carbon sequestration arises from autochthonous processes, such as plant production, and represents the direct removal of CO_2 from the atmosphere, with fixed carbon ultimately stored in the

sediment as belowground biomass and dead plant matter. Carbon burial refers to the removal of organic carbon from the active carbon cycle, by accumulating it in the soil at depths below the degradation-active surface layer (Middelburg et al. 1997).

Saltmarshes provide an array of other ecosystem services besides climate regulation, including delivering natural flood defence and water quality enhancement, and supplying habitat for biodiversity, commercial fish species and migratory birds (Sharps et al. 2017, Adams et al. 2021, Fairchild et al. 2021, de la Barra et al. 2022). In the United States, coastal wetlands were valued at US$23.2 billion y^{-1} for storm protection services alone (Costanza et al. 2008), and saltmarsh services globally are worth Int$1.07 trillion y^{-1} (Davidson et al. 2019, using 2007 ‘International’ $). Historically, saltmarshes were primarily viewed as valuable for land reclamation to accommodate agriculture and urban sprawl (Gedan et al. 2009, Bu et al. 2015). As a result, global marsh areas decreased by 25–50% (Duarte et al. 2008, Crooks et al. 2011), although regional losses were often much higher, such as San Francisco Bay, which lost 79% of the historical marsh cover (Valiela et al. 2009). Further marsh losses are anticipated from climate-change processes, including coastal squeeze by sea-level rise (SLR) and increased storminess (Saintilan et al. 2022). Reduction in saltmarsh cover and substantial habitat disturbance undoubtedly have caused, and continue to cause, significant emissions of carbon stored in sediment and plant biomass (Macreadie et al. 2013, Lovelock et al. 2017, Campbell et al. 2022).

Saltmarsh restoration provides an opportunity to replenish the carbon stores which have been lost from marsh degradation. Recent estimates suggest that the equivalent of 2.3 – 2.5% of annual global greenhouse gas emissions could be offset through mangrove, seagrass and saltmarsh restoration, collectively (Macreadie et al. 2021). Various methods exist for saltmarsh restoration, here defined as any positive action or active intervention that aims to restore the habitat (Möller et al. 2021). Managed realignment is predominantly used in northern Europe and involves the breaching of existing flood defences to allow the shoreline to migrate landwards (Garbutt et al. 2006). Regulation of tidal exchange is another approach, which reintroduces flow through structures such as sluices or tide gates (Möller et al. 2021). Other methods of marsh restoration include sediment recharge and vegetation transplantation (e.g. Soileau et al. 2018; Shiau et al. 2019).

The timescale over which a restored marsh will attain functional equivalence to a comparative natural site is largely unknown (Burden et al. 2019). Faunal assemblages have been found to be structurally similar to those on natural sites as quickly as 4 years after saltmarsh creation (Rezek et al. 2017), although a much longer time is required for restored sites to function similarly to natural systems (Callaway 2005). Carbon storage appears to reach equivalence over longer timescales (Garbutt and Wolters 2008, Burden et al. 2021). CARs are normally high in the early years after restoration (Mason et al. 2022), due to rapid initial sediment accretion, but accretion then slows over time as bed levels rise (ABPmer 2021). This was the case at managed realignment sites in the UK: carbon accumulation, which was 1.04 t C ha^{-1} y^{-1} in the first 20 years, slowed to 0.65 t C ha^{-1} y^{-1} in later years (Burden et al. 2019). Models resulting from these values suggested ~100 years were required for a restored marsh to reach equivalent carbon stock to natural sites (Burden et al. 2019). Early investment in saltmarsh restoration is therefore paramount if the climate change mitigation potential of marshes is to be reached within the coming decades.

Wetland restoration, alongside effective protection and management, has gained increasing policy focus in recent years, particularly as a contribution to global strategies, such as the Sustainable Development Goals (Macreadie et al. 2021) and the UN's Decade on Ecosystem Restoration (2021–2030). Wetland restoration was highlighted in the IPCC Sixth Assessment Report as having the potential to enhance resilience, productivity and sustainability of ecosystems to climate change (IPCC 2021) and many nations cite blue carbon strategies in their nationally determined contributions to meeting the Paris Agreement (Duarte et al. 2020, Macreadie et al. 2021). However, the definition of restoration success is variable. While some projects incorporate distinct success criteria from early development, many lack clearly defined targets (Wolters et al. 2005). Often natural marshes are used as a reference for the performance of a restored site, for instance contrasting the carbon store of a restored marsh against that of natural sites. Since greenhouse gas fluxes are critical components of calculating the net carbon benefit of saltmarsh habitats, it is imperative to consider fluxes alongside carbon sequestration when quantifying the blue carbon benefit of marsh restoration. Incorporating flux observations is especially important as greenhouse gas flux can be higher at restored than natural sites (e.g., nitrous oxide, Adams et al. 2012). On a global scale, the incorporation of greenhouse gas fluxes into saltmarsh carbon budgets is generally lacking; here we aim to address this knowledge gap.

While several studies of restored marshes have quantified greenhouse gas flux (e.g. Adams et al. 2012, Li and Mitsch 2016, Li et al. 2021, Wang et al. 2021) or CAR (e.g. Calvo-Cubero et al. 2014, Burden et al. 2019, Yang et al. 2020), few have considered these attributes together. Additionally, there has been no quantitative review reporting both greenhouse gas fluxes and the carbon storage benefit for restored saltmarsh across regional or global scales. CAR can vary substantially between global regions, with temperate (30° - 40°) northern hemisphere marshes having an average CAR of 144 ± 6 g C m^{-2} y^{-1} compared to 88.7 ± 3.5 g C m^{-2} y^{-1} in the southern hemisphere (Wang et al. 2021). Site dependent factors, such as vegetation composition, are known to influence carbon accumulation, with species such as *Spartina alterniflora* particularly effective at carbon storing (Unger et al. 2016), and larger scale processes, such as sea level rise, also accelerating carbon storage (Rogers et al. 2019). However, a global synthesis of how these contextual drivers influence carbon and greenhouse gas flux is currently lacking. A global prioritisation of saltmarsh restoration is hindered by a limited understanding of where the global hotspots for carbon accumulation are. As such, the regions where saltmarsh restoration would have the greatest benefit for climate regulation remain unknown.

Here we evaluate how carbon stock, carbon accumulation and greenhouse gas fluxes vary between natural and restored saltmarshes, and contrast these across global geographical regions. Using a systematic review and meta-analysis of data from 435 published studies, we test the expectations that newly restored sites will exhibit high CARs and that older restored sites will have fluxes (overall greenhouse-gas exchange, including uptake and emissions) comparable to those of natural marshes. We hypothesize that variation in greenhouse-gas responses will depend on restoration approach, with tidal re-introduction, for example, resulting in lower emissions than freshwater re-introduction, given lower methane emissions of saline wetlands (Poffenbarger et al. 2011). Finally, we expected greenhouse gas fluxes to be influenced by environmental context, including geomorphology, vegetation type, climate (temperature and rainfall) and salinity. Our analyses allow us to determine the average annual contribution of restored marshes to global carbon accumulation, and to provide the most up to date estimate of global carbon stock buried below coastal salt marshes.

2.0 Methodology

2.1 Literature search and data extraction

A systematic literature search for data was done on the 21st January 2022, using standard approaches (Pullin & Stewart 2006, O'Dea et al. 2021) and the search engines *Web of Science* and *Scopus*. No geographical or temporal constraints were applied. The search string was designed to yield studies with data on organic matter content, carbon stock, carbon accumulation and/or greenhouse gas flux (CO_2, CH_4 or N_2O) in natural and/or restored saltmarsh ecosystems. As such, the search terms consisted of three strings connected with the Boolean operator "AND", as below:

factor* OR variable* OR condition* OR characteristic* OR driver* OR natural OR restored OR restoration OR creat* OR "managed realignment" OR reintrod* OR re-introd* OR reestab* OR re-estab* OR "managed retreat" OR "regulated tidal exchange" OR RTE*

AND

carbon OR CO2 OR nitrous* OR N2O OR methane OR CH4 OR “greenhouse gas” OR green*house gas OR GHG* OR “greenhouse gases” OR gas* OR flux* OR storage OR sequestration* OR budget* OR sink* OR removal OR accret* OR exchange* OR accumulation OR erosion OR stock* OR burial OR re-created OR “organic matter” OR “organic content”

AND

saltmarsh* OR "salt marsh*"

The search returned 3,874 results from Web of Science and 29,253 from Scopus. Duplicate results were removed and 2 additional studies were added (ABPmer 2021, Mossman et al. 2022. These were not available on online search engines at the time of the literature search) following consultation with the Saltmarsh Code Consortium (https://www.ceh.ac.uk/our-science/projects/uk-saltmarsh-code), yielding a final list of 29,182 published studies prior to screening. Publications were screened first by title (3443 retained), then by abstract (930 retained) and finally by full text (435 retained: listed in Supplementary Materials, Table S1). Studies that were irrelevant to the research questions and which did not include quantitative data were excluded. Review studies and data derived from modelling were also excluded. Data from brackish (salinity = 0.5 – 18 ppt) and saline marshes (salinity > 18 ppt) were included, while studies on terrestrial wetlands, peatland, freshwater marshes, fens, bogs and permafrost marshes were excluded. Studies pertaining to smaller scale biotic processes (e.g. root respiration within salt marsh vegetation) were not included, unless observations were scaled up to the level of whole-marsh areas. Nutrient fluxes were excluded, except when as a gaseous component of greenhouse gasses (e.g. N_2O emissions). Carbon stores in vegetation biomass were not incorporated, apart from as a component of saltmarsh sediment. Data were extracted from text, tables or graphs in the 435 passed papers, using Automeris WebPlotDigitizer Version 4.4 (Rohatgi 2020). Data were extracted on any organic matter content, carbon stock, carbon sequestration or GHG flux, along with contextual data, such as the average annual air temperature, dominant vegetation, sediment salinity and site geomorphology. In total, 2055 ‘samples’ were extracted from the 435 papers. A ‘sample’ was defined as a distinct condition (e.g. natural vs restored) or contextual setting investigated within a study (e.g. different sampling locations) which were reported as separate values. GHG flux was included from studies using a range of methodologies including static (opaque or transparent) chambers and eddy covariance, on a short-term or seasonal basis. Data gaps in the annual rainfall and average annual air temperature data reported by studies were filled in using the geographical co-ordinates of the study site and the WorldClim climate dataset (Fick & Hijmans 2017). Geomorphology was initially determined for each site using satellite imagery and classifying locations into four types: estuary, coastal marsh, estuarine lagoon and lagoon (Pye and Blott 2014). Since for some studies this was not possible (e.g. where specific sampling coordinates were not provided), this classification was further simplified into fluvial, coastal, loch-head and unknown marsh type, for further analysis.

2.2 Data standardisation

Standardisation of data was required due to considerable variation in approaches and units used by the 435 studies. Meta-data and data concerning environmental context were standardised into common units (e.g., electrical conductivity and salinity into PSU). Marshes were classified into ‘natural’ or ‘restored’ based on their description in the original study, with restored marshes defined as those which had experienced active intervention to alter or restore the state of the marsh. Greenhouse gas fluxes were converted into t CO_2e ha^{-1} y^{-1} using a 100-year timeframe in accordance with IPCC standard approaches (IPCC 2014). For studies which gave a carbon (C) stock estimate to <1m, carbon stock observations were extrapolated to 1m for IPCC comparability (IPCC 2014), assuming a linear distribution of carbon in the top 1m sediment. We expressed the mitigative potential of saltmarshes in units of carbon accumulation (t C ha^{-1} y^{-1}) and in that term amalgamated data on carbon burial, carbon accumulation and carbon sequestration (CO_2 uptake by vegetation). The difference between burial and accumulation is that the former infers the carbon is located below the depth of degradation activity, whereas the latter does not (Middelburg et al. 1997). As the depth of degradation activity was rarely reported, we here use the more conservative ‘C accumulation’ term. Soil organic matter observations (OM) derived from loss on ignition (LOI) were converted to organic carbon content (OC) using the equation:

$$\text{Organic C} = \text{OM} * 0.52$$

where the 0.52 value was based on the OM/OC conversion factor (1.92) of Ouyang and Lee (2020) for LOI observations. Where bulk density data were also reported, percentage organic carbon content was converted into carbon stock using the following equation:

$$\text{C stock (t C ha}^{-1}\text{)} = \text{depth} * \text{bulk density} * \%\ \text{OC} * 10000$$

where ‘depth’ was the core sampling depth and 10000 was the conversion factor from m to ha. The resulting carbon stock values were then extrapolated to 1m depth as described above.

2.3 Data analysis

We contrasted natural and restored saltmarshes for variation in 8 response variables: % OC, bulk density, carbon stock, carbon accumulation rate, net CO_2 flux, CO_2 respiration, CH_4 flux and N_2O flux. Pixel maps were produced from natural marsh data for each response variable to identify ‘hotspots’ including areas with combined high carbon stock and high CARs. Significant differences between natural and restored sites were assessed using non-parametric Mann Whitney-U tests. A generalised linear mixed model (GLMM) tested for differences between natural and restored marshes (included as a binary factor) for each response variable. To account for variation due to the contextual or environmental setting, the GLMM model also incorporated six environmental and geographical predictor variables. These were: continent (categorical; 5 levels), annual rainfall (continuous), salinity type (categorical; 6 levels), average annual temperature (continuous), simplified marsh geomorphology (categorical; 4 levels) and vegetation type (categorical; 6 levels). We included Study ID as a random effect to account for non-independence of multiple values extracted from the same study. The *performance* package was used to visually inspect global model residuals, test for collinearity among the six predictor variables, and ensure that model assumptions were met (Lüdecke et al. 2020). To meet model assumptions, data for carbon stock and net CO_2 flux were rescaled between 0 and 1, with the lowest and highest values in the dataset becoming 0 and 1, then square root transformed (untransformed values are stated in the results of this study). For all other variables, raw data were used. In the GLMM, we identified the predictor variables that best explained variation in each response variable, using a theoretic-based model selection process (Burnham et al. 2011) and only considering models which included ‘natural vs restored’ as a predictor. Statistical significance of model fit was assessed using a Chi-squared test between the optimal model and a null model that contained only the random factor (Study ID). The *emmeans* package (Lenth 2022) was used to (a) extract the estimated difference in marginal means (EMMs) between natural and restored marshes for each response variable and (b) to test for significance.

GLMMs were also used to test for the influence of environmental context, restoration approach (defined in Table S3) and marsh age on the response variables of restored marshes. The same methods and environmental predictors were used as for the first GLMM analysis, except natural vs restored was replaced by restoration approach and site age (time since restoration). Approach to restoration was grouped into the following six categories: artificial structure implementation, freshwater reintroduction, marsh creation (usually sediment addition and vegetation planting, and often fertilisation), sediment alteration, tidal re-introduction (included managed realignment and regulated tidal exchange) and unknown (Table S3). One extremely high and outlying observation (10.4 g cm^{-3}) was removed from the bulk density dataset, as its inclusion caused the assumptions of the global GLMM model to be violated. This observation was likely an error value, given it was an order of magnitude larger than the next highest value (1.58 g cm^{-3}). Insufficient data were available to use GLMMs for CO_2 respiration, CH_4 flux and N_2O flux, but their averages are nevertheless reported, and available data shown in figures. All analyses were run using R Version

3.6.3 (R Core Team 2020). Statistically significant relationships were inferred where $p < 0.05$.

Finally, we used recent estimates of saltmarsh cover continentally (Mcowen et al. 2017) and globally (Mcowen et al. 2017, Murray et al. 2022, Worthington et al. 2023) to derive, from our data, an up-to-date estimate of blue carbon stock held by saltmarsh habitats globally, in which we accounted for differences in carbon stocks between geographical regions. We estimated the net carbon accumulation of marshes per continent using CO_2 equivalent values for CARs and accounting for greenhouse gases emissions and uptake. From the net values, we determined the potential global and regional carbon-benefit (t CO_2e ha^{-1} y^{-1}) from marsh restoration. Net values were also used to quantify the missed opportunity for carbon accumulation arising each year from reported net saltmarsh losses of 1,452.84 (733.1–2,172.07) km^2 between 2000 and 2019 (Campbell et al. 2022).

3.0 Results

3.1 Literature search and data extraction

The past decade saw a rapid increase in the number of relevant studies published, with an average of 29.27 new studies per year in 2012–2022, compared to 3.42 studies per year over 1977–2011 (Figure 2). North American and Asian studies made up 37.5% and 31.0% of the 435 papers included, respectively. There were very few studies from South America and Africa (8 and 1 studies, respectively) (Figure S1). A number of the studies included observations from different conditions and/or contextual settings (e.g. natural vs restored sites, brackish vs saline sites), leading to a total of 2055 samples. Far more data were available for natural than restored marshes: out of 2055 samples, 1757 were from natural and 298 were from restored marshes. Out of the 298 samples for restored marshes, most originated from North America (57%) and Europe (35%), with only 18 samples from Asia, 5 from Oceania and 1 from South America. Across the 8 response variables that were derived from the extracted data, 3623 individual data points were taken for further analysis.

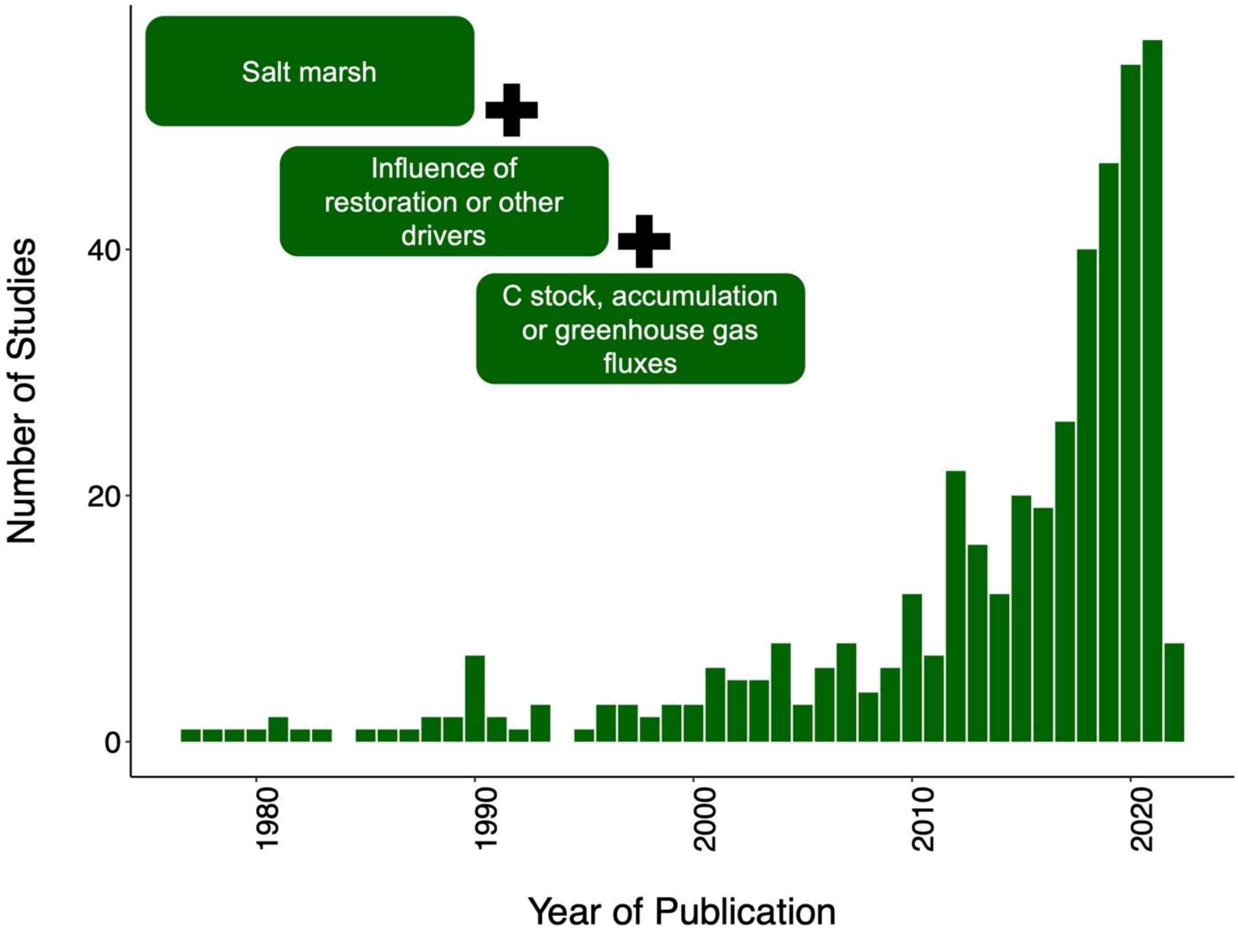


Figure 2. Number of relevant studies included in meta-analysis (n = 435) published per year. Text in boxes describes criteria a paper needed to fulfil to be included in the analysis.

Based on these studies, three areas of particularly high carbon stock were identified in natural saltmarshes (Figure 3a): one in the North America, one in north-eastern Europe and one on the eastern coast of Australia. Although data on carbon accumulation were more sparsely distributed, reported accumulation rates were highest on the east coasts of Australia, China, the UK and the USA (Figure 3b).

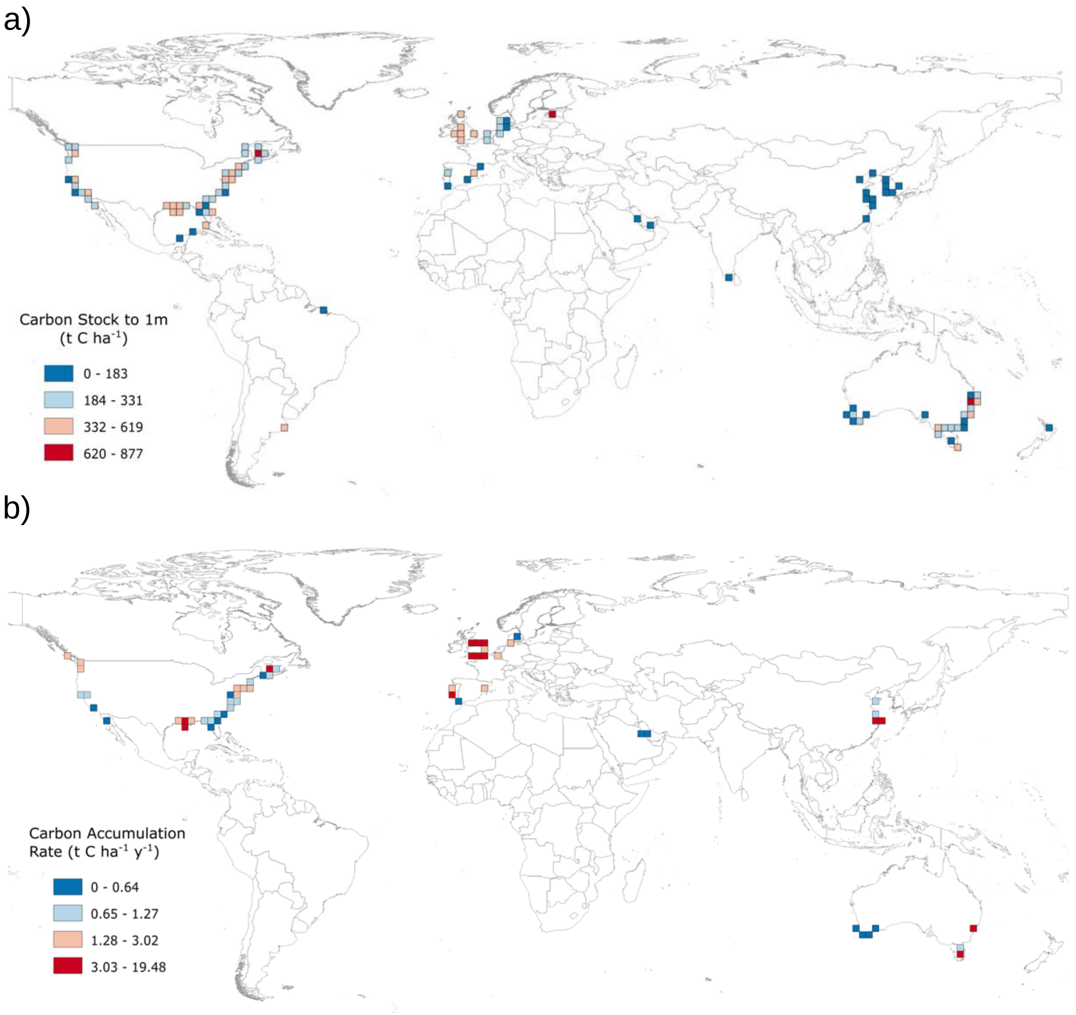


Figure 3. Pixel maps of A) saltmarsh carbon stock to 1m sediment depth (t C ha^{-1}) and B) saltmarsh carbon accumulation rate (t C ha^{-1} y^{-1}) for global regions. Map lines delineate study areas and do not necessarily depict accepted national boundaries.

3.2 Natural vs restored saltmarshes

Globally, natural and restored marshes varied significantly in %OC, carbon accumulation rate, net CO_2 flux and CO_2 respiration (Table 1, Figure 4). Restored marshes had greater carbon accumulation and net CO_2 uptake (lower net CO_2 flux value), and lower %OC and CO_2 respiration, than natural marshes (Table 1, Figure 4). When separated by continent, significant differences in response variables between natural and restored marshes were predominantly restricted to Europe and

North America, likely due to paucity of data for other continents. Carbon stock varied significantly between natural and restored marshes in both Europe and North America, although effects were opposite (Table 1): restored marshes had greater carbon stock in Europe, but lower stock in North America. Differences between continents were evident even when considering only natural marshes. Organic carbon content was particularly high in the North America (Table 1). Methane emissions of natural and restored marshes in Europe were 25 and 332 times lower than the global average, respectively (Table 1, Figure S2).

Table 1. Continental and global mean values (± SD) of organic carbon (%OC), bulk density, carbon stock (to 1m depth), carbon accumulation rate, net CO_2 flux, CO_2 respiration, CH_4 flux and N_2O flux. Brackets show numbers of samples (n) per mean. Blue values were significantly different between natural and restored sites (Mann-Whitney U test. Significant if $p < 0.05$).

	% OC	**Bulk density (g cm^{-3})**	**C stock (t C ha^{-1})**	**C acc. rate (t C ha^{-1} y^{-1})**	**Net CO_2 flux (t CO_2 ha^{-1} y^{-1})**	**CO_2 respiration (t CO_2 ha^{-1} y^{-1})**	**CH_4 flux (t CO_2e ha^{-1} y^{-1})**	**N_2O flux (t CO_2e ha^{-1} y^{-1})**
Europe								
Natural	7.00 ± 7.13 (211)	0.65 ± 0.32 (122)	342.10 ± 223.45 (154)	1.87 ± 1.77 (30)	NA	20.42 ± 50.88 (11)	0.20 ± 0.30 (20)	0.06 ± 1.00 (14)
Restored	4.37 ± 4.60 (88)	0.88 ± 0.33 (24)	438.83 ± 191.97 (22)	5.70 ± 8.81 (15)	NA	29.08 ± 35.11 (2)	0.05 ± 0.08 (4)	0.58 ± 0.67 (4)
North America								
Natural	11.39 ± 8.80 (464)	0.39 ± 0.29 (273)	360.00 ± 214.16 (295)	1.69 ± 2.25 (236)	-57.73 ± 84.26 (47)	30.32 ± 23.90 (57)	6.67 ± 25.99 (69)	-0.03 ± 0.77 (24)
Restored	8.52 ± 10.41 (99)	0.60 ± 1.14 (87)	247.23 ± 169.56 (79)	3.77 ± 4.53 (63)	-80.10 ± 48.13 (19)	5.33 ± 1.46 (6)	23.17 ± 54.47 (16)	0.19 ± 0.75 (16)
South America								
Natural	2.37 ± 1.73 (15)	1.14 ± 0.18 (4)	156.29 ± 142.83 (4)	NA	-10.5 (1)	NA	NA	NA
Restored	2.39 (1)	NA	NA	NA	NA	NA	NA	NA
Asia								
Natural	5.14 ± 8.55 (132)	1.30 ± 0.35 (106)	90.52 ± 101.97 (161)	3.82 ± 6.48 (29)	-14.25 ± 19.11 (26)	22.26 ± 26.77 (70)	4.70 ± 15.14 (106)	0.44 ± 0.83 (53)
Restored	1.58 ± 0.60 (4)	1.39 ± 0.14 (4)	59.45 ± 49.3 (5)	18.38 ± 1.56 (2)	-19.04 ± 22.11 (3)	20.09 ± 22.10 (8)	15.76 ± 27.13 (8)	0.77 ± 1.75 (7)
Africa								
Natural	5.38 ± 2.64 (6)	NA	NA	NA	NA	NA	NA	NA
Restored	NA	NA	NA	NA	NA	NA	NA	NA
Oceania								
Natural	6.72 ± 6.82 (78)	0.82 ± 0.39 (76)	309.94 ± 304.25 (106)	5.81 ± 14.70 (17)	3.44 ± 11.23 (2)	10.31 ± 19.00 (2)	8.26 ± 14.30 (3)	0.78 ± 1.03 (2)
Restored	10.42 ± 9.25 (3)	1.57 (1)	84.54 ± 71.15 (3)	0.74 ± 0.28 (2)	NA	NA	0.19 ± 0.53 (2)	NA
Global								
Natural	8.86 ± 8.56 (906)	0.67 ± 0.46 (581)	287.39 ± 238.64 (720)	2.13 ± 4.49 (312)	-41.82 ± 71.03 (74)	25.23 ± 28.19 (140)	4.99 ± 19.00 (198)	0.27 ± 0.86 (93)
Restored	6.50 ± 8.37 (195)	0.69 ± 1.01 (116)	272.81 ± 193.13 (109)	4.41 ± 5.91 (82)	-65.51 ± 52.27 (24)	15.68 ± 19.70 (16)	16.58 ± 42.34 (30)	0.39 ± 1.08 (27)

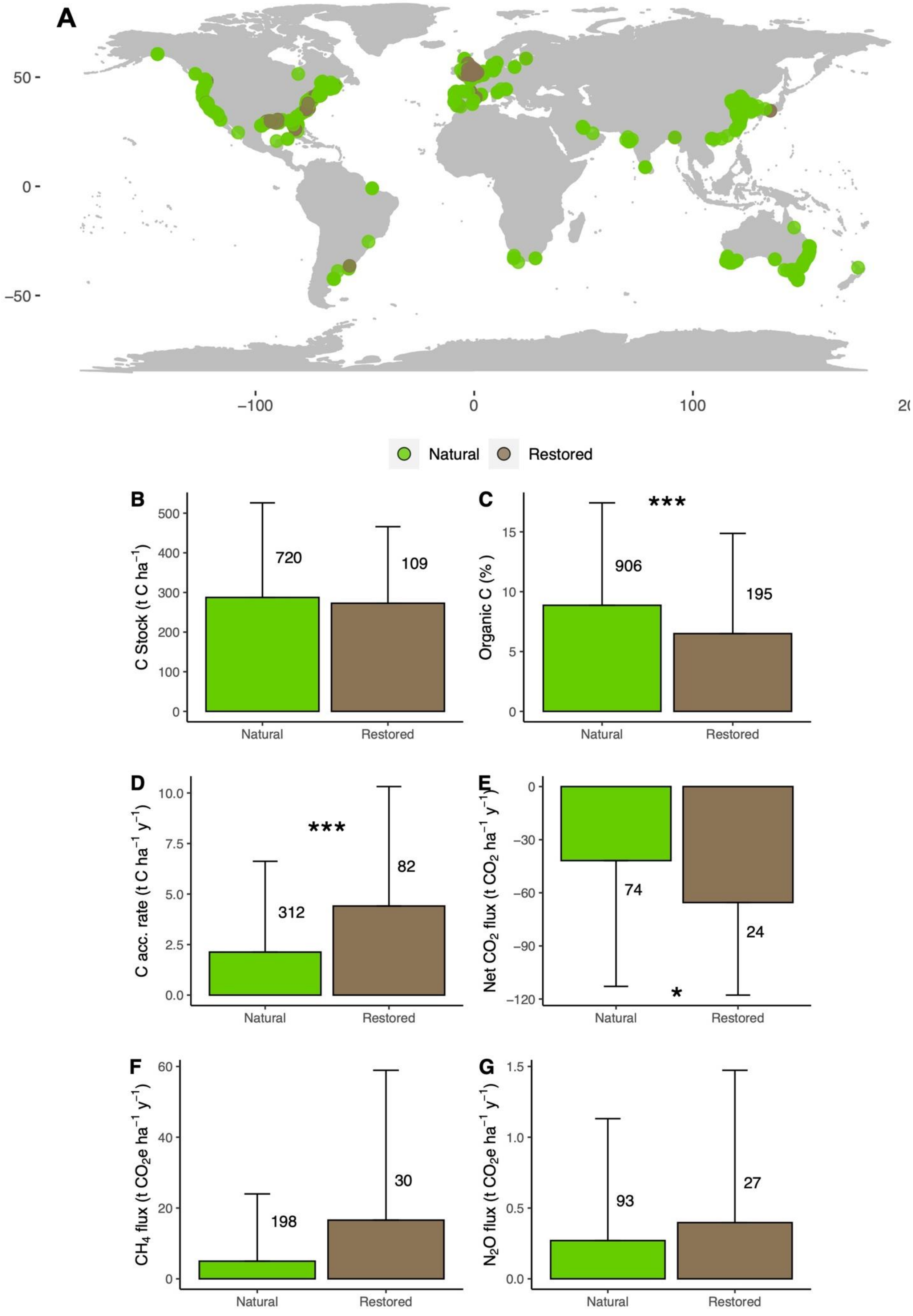

A
50
0
−50
−100
0
100
Natural
Restored
B
C Stock (t C ha^{-1})
0
100
200
300
400
500
720
109
Natural
Restored
C
Organic C (%)
0
5
10
15
***
906
195
Natural
Restored
D
C acc. rate (t C ha^{-1} y^{-1})
0.0
2.5
5.0
7.5
10.0
***
312
82
Natural
Restored
E
Net CO$_2$ flux (t CO$_2$ ha^{-1} y^{-1})
0
−30
−60
−90
−120
74
24
*
Natural
Restored
F
CH$_4$ flux (t CO$_2$e ha^{-1} y^{-1})
0
20
40
60
198
30
Natural
Restored
G
N$_2$O flux (t CO$_2$e ha^{-1} y^{-1})
0.0
0.5
1.0
1.5
93
27
Natural
Restored

Figure 4. A) Distribution of samples across natural and restored saltmarshes (total n = 2055). Global mean values (± SD) of B) carbon stock, C) organic carbon (%OC), D) carbon accumulation rate, E) net CO_2 flux, F) CH_4 flux and G) N_2O flux. Numbers above bars indicate numbers of samples per mean. * denotes p<0.05 and *** denotes p<0.001 (Mann-Whitney U test).

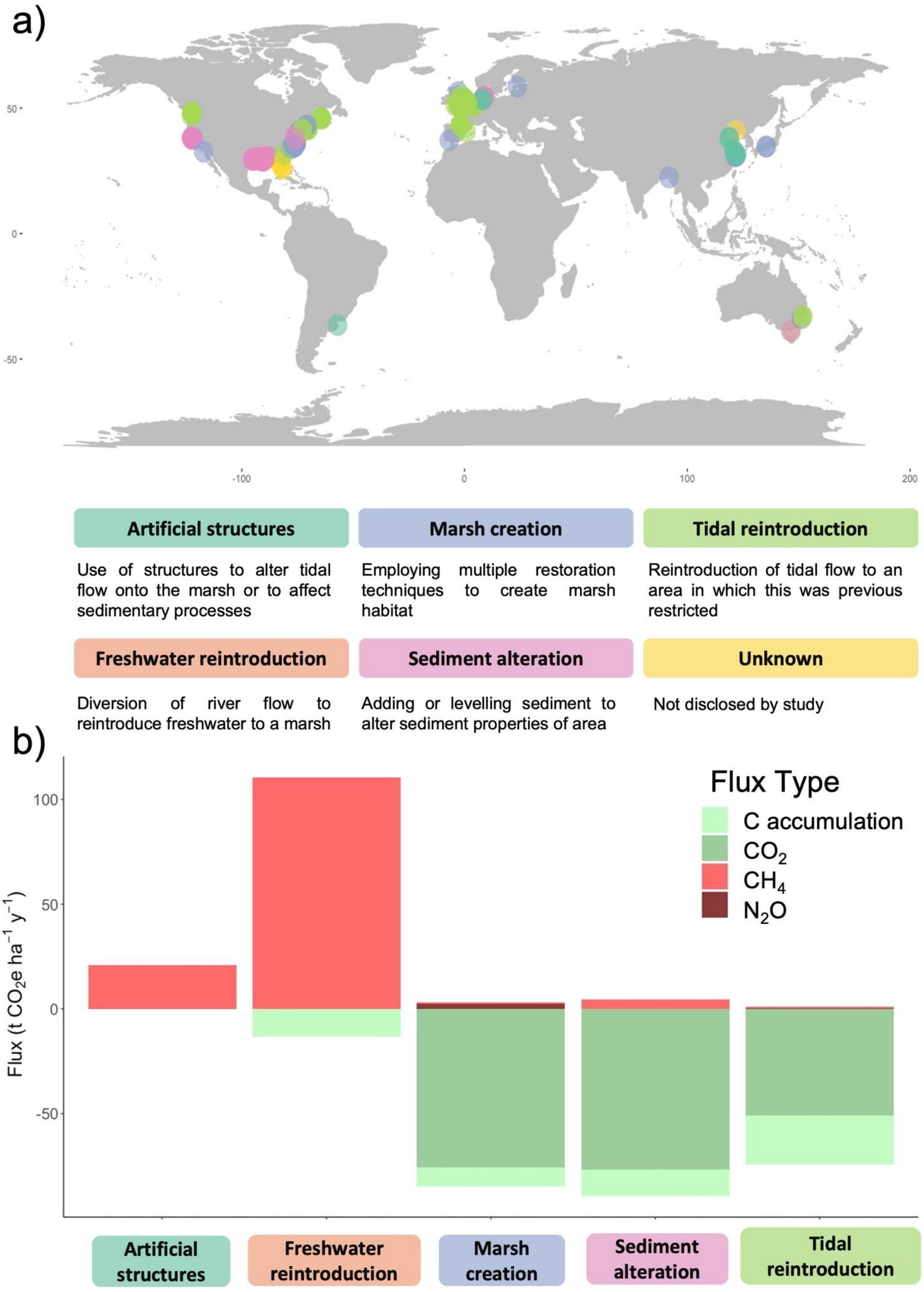
Variation in carbon and greenhouse gas variables was explained by a number of bio-environmental contextual variables, besides whether or not the marsh was natural or restored. For all variables other than CH_4 flux and CO_2 respiration, significant optimal models including natural vs restored included at least one other additional contextual variable (Table 2). For example, continent, annual rainfall, sediment salinity, average annual temperature and vegetation type were all significant predictors of organic carbon stock on a global scale, in addition to whether the marsh was natural or restored ($\chi^2_{18} = 104.22$, $p < 0.001$). When accounting for these contextual variations between saltmarshes, %OC was an average of 3.25 ± 0.65% higher in natural marshes compared to restored (pairwise EMM: $p<0.001$), with carbon stock following a similar pattern (Table 2). Despite statistically significant optimal models, carbon accumulation, net CO_2 flux and N_2O flux did not significantly differ between natural and restored marshes, suggesting more complex interactions between environmental predictor variables. In short, the statistically optimal models showed that the values of direct parameters of carbon stock (%OC, bulk density and carbon stock) differed between natural and restored marshes, and variation in these three parameters depended on the environmental context.

Table 2. Contextual drivers of spatial variation in soil physical and chemical variables across all saltmarsh sites, as indicated by GLMM models. Differences (±SE) in pairwise estimated marginalised means (EMMs) are given between natural and restored saltmarshes. C = continent, R = annual rainfall (mm), Re = natural or restored, S = salinity (categorical), T = average annual temperature (°C), V = vegetation type, SI = study ID. Carbon stock was to 1m soil depth.

								Natural vs restored pairwise EMM				
Variable	**Best supported model**	**AICc**	**R^2c**	**R^2m**	**χ^2**	**df**	**P-value**	**Difference**	**SE**	**df**	**T ratio**	**P-value**
% OC	1 + C + R + Re + S + T + V + (1 | SI)	7154.94	0.742	0.145	104.22	18	<0.001	3.25	0.653	1035	4.978	<0.001
Bulk Density (g cm-^{3})	1 + C + Re + (1 | SI)	871.77	0.586	0.258	105.63	6	<0.001	-0.346	0.059	688	-5.896	<0.001
C stock (t ha^{-1})	1 + C + Re + (1 | SI)	-1468.92	0.756	0.232	71.99	5	<0.001	9.56	7.82	765	2.821	0.005
C accumulation (t ha^{-1} y^{-1})	1 + C + Re + (1 | SI)	2219.66	0.719	0.110	37.70	9	<0.001	-1.21	0.855	370	-1.420	0.156
Net CO_2 flux (t CO_2 ha^{-1} y^{-1})	1 + Re + S + V + (1 | SI)	-265.77	0.979	0.076	25.85	9	0.002	28.74	28.72	55	0.612	0.543
CO_2 respiration (t CO_2 ha^{-1} y^{-1})	1 + Re + (1 | SI)	1392.56	0.842	0.001	0.130	1	0.719	-2.75	7.46	140	-0.368	0.713
CH_4 flux (t CO_2e ha^{-1} y^{-1})	1 + R + Re + (1 | SI)	2057.14	0.479	0.029	4.26	2	0.119	-4.56	5.14	215	-0.887	0.376
N_2O flux (t CO_2 e ha^{-1} y^{-1})	1 + Re + T + V + (1 | SI)	308.88	0.599	0.215	17.61	6	0.007	-0.438	0.25	108	-1.752	0.08

3.3 Covariation between environmental setting and carbon flux in restored marshes

GLMM models to identify covariations in fluxes between restored marshes could only be fitted to the response variables % OC, bulk density, carbon stock, carbon accumulation and net CO_2 flux, due to a paucity of data for other response variables. Restoration approach explained 28.7% of the variation in %OC of restored marshes (Table 3). %OC was by far the highest in marshes restored via freshwater introduction and lowest where the approach was undefined by the authors of the study (Table S4). Bulk density reduced with marsh age, although the rate of change was very low (Table S4: slope). Bulk density was highest in Asia and Oceania, and low at sites restored by freshwater introduction (Table S4), which was a restoration approach used only in North America and reported by just 2 studies (Figure 5). Carbon stock decreased with marsh age and increase in temperature, and peaked in marshes dominated by *Phragmites* spp. plants, which had double the stock of *Spartina* spp. marshes and three times that of *Suaeda* spp. marshes (Table S4). The optimal model for net CO_2 flux included continent and rainfall ($R^2c = 0.626$, $\chi^2 = 11.54$, $p = 0.009$), but neither restoration approach nor time since restoration. Net CO_2 uptake by restored marshes, as indicated by negative net CO_2 flux values (Table S4), was stimulated by increasing rainfall and was 8 and 19 times greater in North American than Asian and Oceanian restored marshes. CH_4 flux for restored marshes could not be modelled due to paucity of data, although it tended to be greater in marshes restored via freshwater introduction compared to other approaches (Figure 5).



Artificial structures

Use of structures to alter tidal flow onto the marsh or to affect sedimentary processes

Marsh creation

Employing multiple restoration techniques to create marsh habitat

Tidal reintroduction

Reintroduction of tidal flow to an area in which this was previous restricted

Freshwater reintroduction

Diversion of river flow to reintroduce freshwater to a marsh

Sediment alteration

Adding or levelling sediment to alter sediment properties of area

Unknown

Not disclosed by study

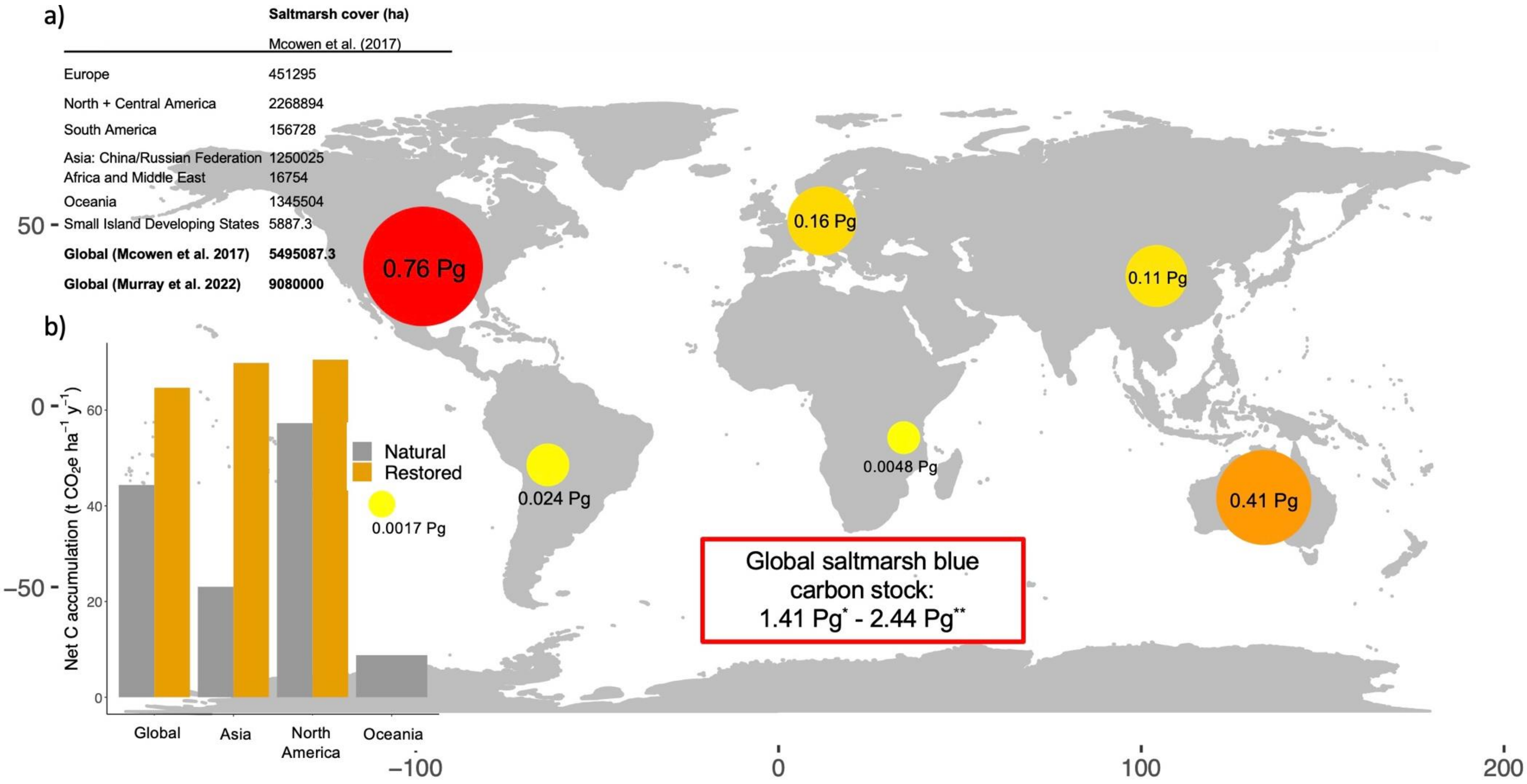
Figure 5. A) Distribution of marsh restoration approaches used by studies (total n = 298). B) means of soil and flux variables per restoration approach, t CO_2e ha^{-1} y^{-1}. Values above 0 represent emissions (red), values below 0 show uptake (green). Note a lack of carbon accumulation data for artificial structure sites. More detailed descriptions of restoration approach can be found in Table S3.

Table 3. Contextual drivers of spatial variation in the % organic carbon (%OC), bulk density, carbon stock (to 1m), carbon accumulation rate and net CO_2 flux of restored marshes, as indicated by GLMM models. C = continent, R = annual rainfall (mm), RA = restoration approach, A = marsh age, S = salinity (categorical), T = average annual temperature (°C), V = vegetation type, SI = study ID. Significant model fit was found for all response variables except for accumulation.

Variable	**Best supported model**	**AICc**	**R^2c**	**R^2m**	**χ^2**	**df**	**P-value**
% OC	1 + RA + (1 | SI)	1155.57	0.901	0.287	11.69	5	0.039
Bulk Density (g cm^{-3})	1 + RA + A + C + (1 | SI)	-9.62	0.883	0.631	47.20	9	<0.001
C stock (t C ha^{-1})	1 + A + T + V + (1 | SI)	1337.40	0.895	0.360	26.66	6	<0.001
C accumulation (t C ha^{-1} y^{-1})	1 + (1 | SI)	480.08	0.866	0.000	NA	NA	NA
Net CO_2 flux (t CO_2e ha^{-1} y^{-1})	1 + C + R + (1 | SI)	252.97	0.626	0.566	11.54	3	0.009

3.4 Global blue carbon potential

Using our continental average carbon stock values and the saltmarsh cover values of Mcowen et al. (2017), Campbell et al. (2022) and Worthington et al. (2023), we estimate the current blue carbon stock of global saltmarshes is 1.41 Pg – 2.44 Pg (Figure 6). This is likely to be a conservative figure, since cover estimates tend to have limited inclusion of high latitude areas (Mcowen et al. 2017, Murray et al. 2022, Worthington et al. 2023). Assuming a saltmarsh net loss of 1,452 km^2 (733–2,172 km^2) between 2000 and 2019 (Campbell et al. 2019) and using our estimates of net carbon accumulation per unit marsh area, the current annual net carbon accumulation is 0.06 Mt (0.03 – 1.00 Mt) lower than in 2000. Given many marshes were lost prior to 2000 (Mcowen et al. 2017), the total reduction in carbon accumulation due to marsh loss will be much higher. Our data show that when taking GHG fluxes into account, saltmarshes of all continents provide a net carbon removal benefit, with restored marshes consistently soliciting the greatest gain (Figure 6b). Accounting for greenhouse gas emissions, restored saltmarshes had a net carbon burial rate of -64.70 t CO_2e ha^{-1} y^{-1}, 45.8% higher than that of natural marshes. Griscom et al. (2017) estimated that 0.2–3.2 million ha saltmarsh could potentially be restored globally, based on data compiled from 76 sources. Using these values alongside our calculated CARs for restored marshes, we estimate that an additional 12.93–207.03 Mt CO_2e could be buried per year through marsh restoration, equating to 0.03–0.51% of global energy-related CO_2 emissions in 2021 (IEA 2022).



a)

	Saltmarsh cover (ha) Mcowen et al. (2017)
Europe	451295
North + Central America	2268894
South America	156728
Asia: China/Russian Federation	1250025
Africa and Middle East	16754
Oceania	1345504
Small Island Developing States	5887.3
Global (Mcowen et al. 2017)	**5495087.3**
Global (Murray et al. 2022)	**9080000**

Figure 6. Estimated total saltmarsh blue carbon stock per continent to 1m depth. Estimates were based on the marsh area coverage of Mcowen et al. (2017), Murray et al. (2022) and Worthington et al. (2023) listed in table a) (units: ha). Figure (b) shows the average net carbon accumulation rates (accounting for greenhouse gas emissions) for continents where sufficient data were

available. For the ‘Global saltmarsh blue carbon stock’ box, * refers to stock calculated with values from Worthington et al. (2023) and ** for stock calculated from Murray et al. (2022). The value calculated with continental saltmarsh areas from Mcowen at al. (2023) was 1.47 Pg, used to scale up/down to the global area values from Murray et al. (2022) and Worthington et al. (2023).

4.0 Discussion

4.1 Global and regional blue carbon benefits

This study offers a firm endorsement of the benefit of saltmarsh restoration to mitigating global greenhouse gas emissions. Restored saltmarshes have very low GHG fluxes and rapid CARs, resulting in an overall net carbon accumulation rate of 64.70 t CO_2e ha^{-1} y^{-1}. Incorporating greenhouse gas fluxes into global-scale estimates of net carbon accumulation, we show that saltmarsh restoration provides opportunity for offsetting up to 0.51% of global CO_2 emissions, based on 2021 emission values (IEA 2022) and considering that up to 3.2 million ha saltmarsh are potentially restorable (Griscom et al. 2017). Half a percent of global emissions is a substantial amount, considering marshes occupy much less than 1% Earth's surface (Costanza et al. 2014). The climate mitigating benefit of marsh restoration will be coupled to other significant socio-ecological gains, including natural flood protection and the provisioning of habitat for threatened wildlife and fisheries species (Barbier et al. 2011), the value of which typically outweighs the cost of restoration 1.3 to 1.0 (Alvis and Avison 2021). Our study provides an up-to-date blue carbon estimate of 1.41 – 2.44 Pg stored in the top 1m of saltmarsh sediment globally, a higher quantity than recent estimates of 1.35 Pg (Macreadie et al. 2021) and 1.37 Pg (Temmink et al. 2022), but still lower than recent estimates of total carbon stock for mangroves (7.13 Pg) and seagrasses (3.58 Pg) (Lovelock and Reef 2020). For IPCC comparability (IPCC 2014), the present study extrapolated original observations of carbon stock to 1m when studies had not sampled carbon to this depth. This approach does incur uncertainties to our global stock estimate. A definitive estimate of global carbon stock in saltmarshes would require consistent measurements across the complete soil profile in a greater number of studies. Our estimate is based on a substantially higher number of published studies compared to previous studies (e.g. Ouyang and Lee 2014, Temmink et al. 2022) and used the most recent saltmarsh coverage estimates (Mcowen et al. 2017, Murray et al. 2022). The substantial carbon store held by marshes highlights the importance not just of marsh restoration, but of effective policy to protect existing marshes.

Global differences in carbon and GHG fluxes of natural and restored marshes were explained by variation in bio-physical context, with vegetation species composition and rainfall particularly strong drivers of variation in carbon stock and net CO_2 flux. The effect of vegetation type was expected, since plant community shifts are known to alter GHG emissions of saltmarshes (Martin et al. 2018) and plant composition is a reliable predictor of carbon stock (Ford et al. 2019, Smeaton et al. 2022). The eastern coasts of the North America and Australia were particular hotspots for carbon storage, being areas with high carbon stocks and high CARs. Eastern Australia is recognised as an area with strong carbon benefits from saltmarsh restoration (Macreadie et al. 2017, Gulliver et al. 2020). Our study also confirms that the eastern coast of North America is a global hotspot for saltmarsh carbon sequestration. These high carbon stocks may result from previously high rates of relative sea level rise (RSLR) in the late Holocene, which may have led to surficial carbon densities 1.7 – 3.7 times higher than those in times, or regions, of stable sea level (Rogers et al. 2019). In addition, US *Spartina alterniflora* dominated saltmarshes are highly productive and have long been recognised as having higher carbon stocks than other marsh regions (Cebrian 2002). Belowground decomposition of *S. alterniflora* is slower compared to other species, with a lignin half-life twice as long (3.6 years) as that of other saltmarsh vegetation (Benner et al.

1987, Unger et al. 2016). These species traits result in high densities of roots in surface sediments and the trapping of substantial quantities of carbon (Tripathee and Schäfer 2014, Redelstein et al. 2018), which causes North American marshes to have higher average organic carbon content and lower sediment bulk density than other continents, as observed here. Prioritising restoration efforts in areas with such naturally high carbon burial rates could offer early climate-mitigatory wins from saltmarsh restoration.

Future climate change may cause losses to some marsh areas, with associated emissions and reduced carbon accumulation in eroded areas. Recent estimates show that 83% of existing coastal marshes across 6 mid-USA states could be lost with 1.2m RSLR before 2104 (Warnell et al. 2022). Based on our calculations of net carbon accumulation in North American marshes, this could equate to a loss of annual carbon accumulation up to 17.64 Mt CO_2e y^{-1}. Yet, that rate of sea-level rise may also convert 270,000 ha of forest and forested wetland areas into saltmarsh (Warnell et al. 2022). Areas with greater tidal range and higher suspended sediment supply will be less vulnerable to SLR (Saintilan et al. 2022) and actually experience an increase in carbon storage via greater accommodation space for sediment deposition (Gonneea et al. 2019). In the process of selecting which areas to restore it is evidently prudent to consult spatial projections of future gains and losses to marsh areas arising from SLR.

We found greenhouse gas emissions were a very negligible portion of saltmarsh carbon fluxes, although climatic drivers such as temperature were found to drive small variations in N_2O flux, for example. The CO_2e radiative forcing of N_2O and CH_4 emissions was dwarfed by the net CO_2 uptake, in restored marshes by 4 and 168 times, respectively, and CH_4 and N_2O fluxes did not vary significantly between natural and restored marshes. Clearly, the potential carbon benefit of marsh restoration greatly exceeds any potential warming effect from greenhouse gas emissions. This is in contrast to peatland restoration, where rewetting to improve habitat condition can lead to increased CH_4 emissions due to the anaerobic decomposition of organic material by methanogenic bacteria (Evans et al. 2021). Methane emissions are less substantial in saline environments because the presence of sulphates causes sulphate-reducing bacteria to outcompete methanogens (Bartlett et al 1987). European marshes had 25 times lower methane flux than the global average. The causes for this are unclear, but we expect differences to be largely attributable to differences in salinity between study sites (Figure S3), with a potential influence of annual temperature and tidal regime (see e.g. Li et al. 2021). Within the extracted data, fresher and brackish sites, without high presence of sulphates to inhibit methanogenesis (Bartlett et al. 1987), were more prevalent in Asia and North America, compared to Europe. Recent reviews of methane fluxes from aquatic ecosystems also show that higher organic matter content can boost methane emissions (Al-Haj and Fulweiler 2020, Rosentreter et al. 2021), which may have contributed to the higher methane emissions found in the present study from US marshes, for example.

4.2 Carbon storage via saltmarsh restoration

The result that restored saltmarshes had higher CARs than comparative natural marshes was unsurprising, since many restored sites were sampled in the first 5 years after restoration, when sediment accretion and associated carbon burial is rapid (ABPmer 2021, Mason et al. 2022). The maintenance of substantial CARs over time in restored marshes indicates the additionality from marsh restoration is enduring (even if all potential areas for restoration became restored), albeit carbon accumulation here does not equate directly to the atmospheric sequestration of CO_2. Carbon accumulation here comprised observations of carbon burial, carbon accumulation and CO_2 uptake by marsh vegetation. International standards for carbon offsetting from marsh restoration can use CARs and carbon stock changes rather than sequestration as the basis for calculating and issuing tradable carbon credits, as long as deductions for allochthonous carbon (Figure 1) are made when necessary (e.g. VERRA VM0033: VCS Methodology, 2021). To limit the risk of 'double accounting' allochthonous carbon (Williamson and Gattuso 2022), projects aiming to offset emissions via wetland restoration should aim to distinguish between carbon sequestered by the system itself (autochthonous) and carbon trapped by the marsh from passing water, but originally fixed by another ecosystem (allochthonous, Figure 1) and already accounted for there. Ultimately, the calculations of carbon benefits from blue carbon ecosystems should incorporate all lateral carbon fluxes, including imports of allochthonous material, as well as the export of autochthonous marsh-carbon to other systems, such as the seabed (Sulpis and Middleburg 2023). Marshes are highly dynamic and have spatial and temporal patterns of expansion and erosion (Ladd et al. 2019, 2021). There has been little research into the carbon implications from such dynamics, although the presence of marsh material in other systems further illustrates the offsetting potential of saltmarshes (Zhu et al. 2022).

Restoration approach explained significant amounts of variation in soil organic carbon content (%OC) and bulk density. Soil organic carbon content was highest in marshes restored via freshwater introduction, as were methane emissions, although not statistically testable due to insufficient data. The potential of saltmarshes as blue carbon ecosystems relates not only to carbon accumulation, but also to their low methane emissions, as methanogenesis is inhibited at high salinities and methane flux is widely regarded to be negligible above 18 ppt (Poffenbarger et al. 2011, Needelman et al. 2018) – patterns corroborated here through evidence of low mean global methane emissions by natural and restored saltmarsh sites. Salinity will be reduced when freshwater introduction is the mode of restoration, resulting in higher methane fluxes than, for example, when marshes are restored through the reintroduction of tidal flooding. Carbon stock appeared higher in marshes restored via sediment alteration and tidal reintroduction than through methods based on planting, sediment addition and fertilisation (e.g., Li and Mitsch 2016). In practice, the choice of restoration approach will be constrained by environmental context and may be directed by objectives other than carbon benefits, such as enhancing biodiversity and/or providing natural flood defence (Barbier et al. 2011, Adams et al. 2021).

Bundled socio-ecological gains through ecosystem-service provisioning are generally ensured by marsh restoration (Barbier et al. 2011, Stewart-Sinclair et al. 2020, Sánchez-Arcilla et al. 2022), although the choice of restoration can drive trade-offs between benefits. For instance, whilst this study showed *Phragmites* reed beds had the highest carbon accumulation of all vegetation communities, the removal of *Phragmites australis* in regions where this is invasive would increase plant and faunal diversity (Findlay et al. 2003, Gratton and Denno 2005, 2006). Natural flood protection is an important driver of marsh restoration in many global regions and has great potential for co-benefits to carbon and biodiversity (e.g., Mossman et al. 2022, Barbier et al. 2011), but it can also result in trade-offs of other ecosystem services, depending on design (Loon-Steensma and Vellinga 2013, Auerswald et al. 2019). While trade-offs from flood protection projects are relatively well-studied (see e.g.

van Loon-Steensma and Vellinga 2013), insight into trade-offs resulting from projects targeting saltmarsh carbon sequestration is comparatively lacking. The goal and approach of restoration should always be clearly thought through to manage benefit trade-offs. Empirical observations of some marsh ecosystem services are patchily distributed, making it a challenge to deliver holistic trade-off evaluations across all global contexts.

4.3 Data gaps and areas for further research

While we have confidence in our global estimates and the deduced contribution of marshes to climate regulation, the study did face data scarcity for some geographical regions, environmental contexts and carbon response variables. Our overall estimates of saltmarsh carbon stock, CARs and restoration potentials were based on continental averages, as the spatial cover was insufficiently consistent to go to regional or national levels. In particular, there was spatial paucity in empirical observations of CARs and greenhouse gas fluxes, especially for restored marshes and including otherwise well-studied continents such as Europe. Undoubtedly, boosting the spatial cover of empirical flux observations would give greater confidence in net greenhouse gas budgets and a finer resolution for examining how marsh restoration benefits vary with environmental context. Our statistical models were additive and based on generalised linear distributions. These relatively simple model constructs allowed us to explore the contextual drivers of a wide variety of carbon flux components across natural and restored marsh settings. A more complex modelling approach that considers non-uniform distributions and potential multi-way interactions between different drivers could provide a more detailed understanding into the effects of environmental drivers on carbon flux. Additionally, predictive spatial models might be explored, for example, through machine learning techniques, to move from global/continental mean estimates to point level predictions at small spatial scales.

4.4 Implications for policy and management

Overall, our findings support the assertion of the IPCC Sixth Assessment Report that habitat restoration offers a significant route to mitigating climate change (IPCC 2021) and meeting Nationally Determined Contributions (NDCs). Many nations already have statutory obligations or stated commitments to restore marshes and the carbon gains from such restoration can be calculated from the data synthesized here. Evidently, the more marsh areas are restored, the less will be the unexplored potential of marshes to contribute further reductions to atmospheric carbon. Marsh restoration is only one of many actionable climate solutions. However, nature-based solutions do offer an effective, short-term opportunity to mitigate global emissions and are, arguably, a critical route for meeting the shorter-term ambitions of the Paris Agreement (Seddon et al. 2020). For example, if the recommended 22,000 ha (Dickie et al. 2015) saltmarsh area in the UK were successfully restored, an additional 0.14 Mt C y^{-1} would be sequestered, equating to 0.05% of the UK’s 2020 CO_2 emissions (IEA 2022). While the investment in wetland restoration typically has very positive cost-benefit ratios (Alvis and Avison 2021), projects do need to have the buy-in from multiple stakeholders, including local communities, the finance sector and environmental managers, before restorable areas can be successfully converted into functional saltmarshes (Figure 7). Much of the policy and science exists, but the roll-out of marsh restoration can stumble on processes associated with practical limitations, such as land availability and the cost of upscaling. Agricultural need for land was a key driver for historical marsh losses (Mcowen et al. 2017) and may still restrict available areas for restoration, given that there is increasing demand for land for food and housing to meet the needs of a continually growing coastal population (Nicholls et al. 2007). Practical recognition of the bundled benefits associated with marsh restoration (see e.g. Stewart-Sinclair et al. 2020, Sánchez-Arcilla et al. 2022) (Figure 7) may become an important factor in overcoming such restoration ‘stumbling blocks’. Linking targets for saltmarsh carbon to planning for nature-based flood solutions may provide such an opportunity.

The expense of saltmarsh restoration can be substantial, depending on geographical region and method of restoration, with replanting most expensive ($89-140,000 ha^{-1}) and hydrological or sediment restoration the cheapest ($24-65,000 ha^{-1}) (Wang et al. 2022). In countries like the United Kingdom, costs may be covered through governmental commitment to flood protection (Carvalho and Spataru 2023), particularly incorporating nature-based solutions. While high up-front costs and long-term investment can put off private investors in ecological restoration (Wainaina et al. 2020), co-investment to explore a rapidly expanding carbon market offers a promising way to accelerate marsh restoration (Macreadie et al. 2021). Cost-benefit analysis accounting for ecosystem-service gains show the cost of restoration is recovered within 5 to 30 years, for 20% to 40% of projects, respectively, with small-scale projects taking longer to recover expenses and increase in carbon value substantially reducing the timescale (Wang et al. 2022). Currently, only carbon has a significant market to help offset restoration costs and attract investors, but other saltmarsh ecosystem-services, such as nutrient-remediation and recreational space, have strong market potentials and unquestionable societal cost-benefits (Lillebø et al. 2010, Adams et al. 2021, Wang et al. 2022).

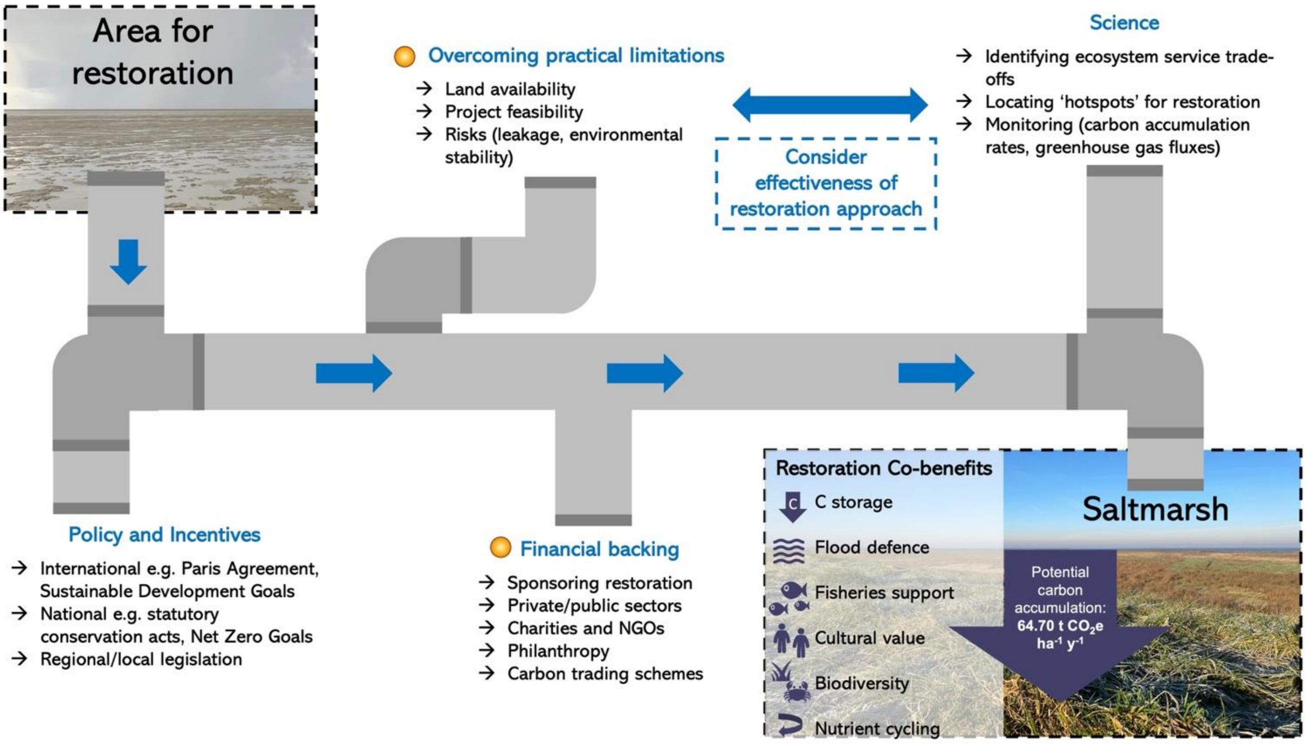


Figure 7 Key processes underpinning the transformation of restorable areas into saltmarshes, with multiple societal co-benefits, including carbon storage. Major current challenges which may limit the upscaling of marsh restoration are highlighted in yellow.

4.5 Conclusions

Additional data on saltmarsh greenhouse gas fluxes and CARs are required on a global scale for constructing net carbon budgets. While the priority must remain to reduce global greenhouse gas emissions, the potential of saltmarsh restoration to contribute to climate regulation is clear. Our ability to facilitate that natural carbon burial now rests principally on the availability of land to restore, the management of larger-scale processes that threaten marsh area, such as accelerating sea level rise, and the willingness and action of the management-policy community to connect to multi-sectoral financial opportunities for supporting restoration.

6.0 Acknowledgements

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Supplementary Materials

Blue carbon benefits from global saltmarsh restoration

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Table S1. Reference information for final studies from which data was extracted following the literature search and screening process. ID number the “ref_no” in the final data extraction spreadsheet (Table S2).

ID	Author	Year	Title	Journal	DOI
115	Puchkoff et al.	2022	Experimental sediment addition in salt-marsh management: Plant-soil carbon dynamics in southern New England	Ecological Engineering	10.1016/j.ecoleng.2021.10649
118	Liu et al.	2022	Response of methanotrophic activity and community structure to plant invasion in China's coastal wetlands	Geoderma	10.1016/j.geoderma.2021.115
120	Xiong et al.	2022	Comparative study of methane emission in the reclamation-restored wetlands and natural marshes in the Hangzhou Bay coastal wetland	Ecological Engineering	10.1016/j.ecoleng.2021.10647
190	Graversen et al.	2022	Carbon sequestration is not inhibited by livestock grazing in Danish salt marshes	Limnology and Oceanography	10.1002/lno.12011
245	Derby et al.	2022	Vegetation and hydrology stratification as proxies to estimate methane emission from tidal marshes	Biogeochemistry	10.1007/s10533-021-00870-z
261	Feng et al.	2022	Nitrogen cycling in plant and soil subsystems is driven by changes in soil salinity following coastal embankment in typical coastal saltmarsh ecosystems of Eastern China	Ecological Engineering	10.1016/j.ecoleng.2021.10640
288	Li et al.	2022	Imbalanced nitrogen√±phosphorus input alters soil organic carbon storage and mineralisation in a salt marsh	Catena	10.1016/j.catena.2021.10572
294	Capooci & Vargas	2022	Diel and seasonal patterns of soil CO2 efflux in a temperate tidal marsh	Science of the Total Environment	10.1016/j.scitotenv.2021.1497
313	Barry et al.	2021	Vegetation Zonation Predicts Soil Carbon Mineralization and Microbial Communities in Southern New England Salt Marshes	Estuaries and Coasts	10.1007/s12237-021-00943-0
357	Pace et al.	2001	Importance of quantifying the full-depth carbon reservoir of Jamaica Bay salt Marshes, New York	City and Environment Interactions	10.1016/j.cacint.2021.100073
369	Yang et al.	2021	Factors affecting soil organic carbon content between natural and reclaimed sites in rudong coast, jiangsu province, china	Journal of Marine Science and Engineering	10.3390/jmse9121453

371	Arias-Ortiz et al.	2021	Tidal and Nontidal Marsh Restoration: A Trade-Off Between Carbon Sequestration, Methane Emissions, and Soil Accretion	Biogeosciences	10.1029/2021JG006573
408	Gao et al.	2021	Lateral detrital C transfer across a Spartina alterniflora invaded estuarine wetland	Ecological Processes	10.1186/s13717-021-00340-
513	He et al.	2021	Impact of Spartina alterniflora invasion on soil bacterial community and associated greenhouse gas emission in the Jiuduansha wetland of China	Applied Soil Ecology	10.1016/j.apsoil.2021.104168
611	Voltz et al.	2012	A multiproxy study of intertidal surface sediments from two macrotidal estuarine systems (Canche, Authie) in northern France: Insights into environmental processes	Continental Shelf Research	10.1016/j.csr.2021.104554
664	van Ardenne et al.	2021	Tidal Marsh Sediment and Carbon Accretion on a Geomorphologically Dynamic Coastline	Biogeosciences	10.1029/2021JG006507
674	Li et al.	2021	The impact of sea embankment reclamation on greenhouse gas ghg fluxes and stocks in invasive spartina alterniflora and native phragmites australis wetland marshes of east china	Sustainability (Switzerland)	10.3390/su132212740
795	McClellan	2021	Root-zone carbon and nitrogen pools across two chronosequences of coastal marshes formed using different restoration techniques: Dredge sediment versus river sediment diversion	Ecological Engineering	10.1016/j.ecoleng.2021.1063
797	Lee et al.	2021	The first national scale evaluation of organic carbon stocks and sequestration rates of coastal sediments along the West Sea, South Sea, and East Sea of South Korea	Science of the Total Environment	10.1016/j.scitotenv.2021.148
821	Van Allen et al.	2021	Changes in organic carbon source and storage with sea level rise-induced transgression in a Chesapeake Bay marsh	Estuarine, Coastal and Shelf Science	10.1016/j.ecss.2021.107550
822	Hidalgo et al.	2021	Black fire ant mounds modify soil properties and enhanced plant growth in a salt marsh in Argentina	Estuarine, Coastal and Shelf Science	10.1016/j.ecss.2021.107534
858	Chu et al.	2021	Seasonal not annual precipitation drives 8-year variability of interannual net CO2 exchange in a salt marsh	Agricultural and Forest Meteorology	10.1016/j.agrformet.2021.108
995	Zhang et al.	2021	Livestock grazing promotes ecosystem multifunctionality of a coastal salt marsh	Journal of Applied Ecology	10.1111/1365-2664.13957

1016	Cui et al.	2021	Interactive effects of groundwater level and salinity on soil respiration in coastal wetlands of a Chinese delta	Environmental Pollution	10.1016/j.envpol.2021.11740
1026	Liu et al.	2021	Spartina alterniflora saltmarsh soil organic carbon properties and sources in coastal wetlands	Journal of Soils and Sediments	10.1007/s11368-021-02969-
1045	Schulte Ostermann et al.	2021	Hydrodynamics affect plant traits in estuarine ecotones with impact on carbon sequestration potentials	Estuarine, Coastal and Shelf Science	10.1016/j.ecss.2021.107464
1064	Iram et al.	2021	Soil greenhouse gas fluxes from tropical coastal wetlands and alternative agricultural land uses	Biogeosciences	10.5194/bg-18-5085-2021
1078	Gorham et al.	2021	Heterogeneous tidal marsh soil organic carbon accumulation among and within temperate estuaries in Australia	Science of the Total Environment	10.1016/j.scitotenv.2021.147
1127	Poppe et al.	2021	Tidal marsh restoration enhances sediment accretion and carbon accumulation in the Stillaguamish River estuary, Washington	PLoS ONE	10.1371/journal.pone.025724
1187	Ledford et al.	2021	Ecosystem carbon exchange and nitrogen removal rates in two 33-year-old constructed salt marshes are similar to those in a nearby natural marsh	Restoration Ecology	10.1111/rec.13439
1285	Ward et al.	2021	Blue carbon stocks and exchanges along the California coast	Biogeosciences	10.5194/bg-18-4717-2021
1485	Smith et al.	2021	Sea Level-Driven Marsh Migration Results in Rapid Net Loss of Carbon	Geophysical Research Letters	10.1029/2021GL092420
1546	Allen et al.	2021	Contributions of organic and mineral matter to vertical accretion in tidal wetlands across a chesapeake bay subestuary	Journal of Marine Science and Engineering	10.3390/jmse9070751
1557	Islam et al.	2021	Eco-engineering of coastal environment through saltmarsh restoration towards climate change impact mitigation and community adaptation in Bangladesh	Regional Studies in Marine Science	10.1016/j.rsma.2021.101880
1616	Pollmann et al.	2021	Young soils of a temperate barrier island under the impact of formation and resetting by tides and wind	Catena	10.1016/j.catena.2021.10527
1619	Valentine et al.	2021	Brackish marshes erode twice as fast as saline marshes in the Mississippi Delta region	Earth Surface Processes and Landforms	10.1002/esp.5108

1654	Xuehui et al.	2021	Impacts of Spartina alterniflora invasion on soil carbon contents and stability in the Yellow River Delta, China	Science of the Total Environment	10.1016/j.scitotenv.2021.1451
1711	Gret et al,	2021	Geochemical mapping of a blue carbon zone: Investigation of the influence of riverine input on tidal affected zones in Bull Island	Regional Studies in Marine Science	10.1016/j.rsma.2021.101834
1730	Gallagher et al.	2021	Inorganic and Black Carbon Hotspots Constrain Blue Carbon Mitigation Services Across Tropical Seagrass and Temperate Tidal Marshes	Wetlands	10.1007/s13157-021-01460-3
1745	Cacho et al.	2021	Local geomorphological gradients affect sedimentary organic carbon storage: A Blue Carbon case study from sub-tropical Australia	Regional Studies in Marine Science	10.1016/j.rsma.2021.101840
1901	Gispert et al.	2021	Appraising soil carbon storage potential under perennial and annual Chenopodiaceae in salt marsh of NE Spain	Estuarine, Coastal and Shelf Science	10.1016/j.ecss.2021.107240
1904	Yang et al.	2021	Invasive Spartina alterniflora changes the Yangtze Estuary salt marsh from CH4 sink to source	Estuarine, Coastal and Shelf Science	10.1016/j.ecss.2021.107258
1921	Hikouei et al.	2021	Use of random forest model to identify the relationships among vegetative species, salt marsh soil properties, and interstitial water along the atlantic coast of georgia	Infrastructures	10.3390/infrastructures60500
2075	Noyce and Megonigal	2021	Biogeochemical and plant trait mechanisms drive enhanced methane emissions in response to whole-ecosystem warming	Biogeosciences	10.5194/bg-18-2449-2021
2079	Lule and Vargas	2021	Biophysical drivers of net ecosystem and methane exchange across phenological phases in a tidal salt marsh	Agricultural and Forest Meteorology	10.1016/j.agrformet.2020.108
2134	Fernadez et al.	2021	Influence of microphytobenthos on the sedimentary organic matter composition in two contrasting estuarine microhabitats	Environmental Monitoring and Assessment	10.1007/s10661-021-08888-4
2159	Palacios et al.	2021	Effects of a nutrient enrichment pulse on blue carbon ecosystems	Marine Pollution Bulletin	10.1016/j.marpolbul.2021.112

2167	Xia et al.	2020	Spartina alterniflora invasion controls organic carbon stocks in coastal marsh and mangrove soils across tropics and subtropics	Global Change Biology	10.1111/gcb.15516
2214	Chi et al.	2021	Soil organic matter and salinity as critical factors affecting the bacterial community and function of Phragmites australis dominated riparian and coastal wetlands	Science of the Total Environment	10.1016/j.scitotenv.2020.143
2391	Gorham et al.	2021	Soil Carbon Stocks Vary Across Geomorphic Settings in Australian Temperate Tidal Marsh Ecosystems	Ecosystems	10.1007/s10021-020-00520-
2442	Vaughn et al.	2021	Blue Carbon Soil Stock Development and Estimates Within Northern Florida Wetlands	Frontiers in Earth Science	10.3389/feart.2021.552721
2487	Li et al.	2021	Methane emissions during the tide cycle of a yangtze estuary salt marsh	Atmosphere	10.3390/atmos12020245
2515	Cheng et al.	2021	Estimating the gaseous carbon budget of a degraded tidal wetland	Ecological Engineering	10.1016/j.ecoleng.2021.1061
2569	Guan et al.	2021	Effects of groundwater tables and salinity levels on soil organic carbon and total nitrogen accumulation in coastal wetlands with different plant cover types in a Chinese estuary	Ecological Indicators	10.1016/j.ecolind.2020.10696
2573	Jiang et al.	2021	Variations of dissimilatory nitrate reduction processes along reclamation chronosequences in Chongming Island, China	Soil and Tillage Research	10.1016/j.still.2020.104815
2586	Luk et al.	2021	Soil Organic Carbon Development and Turnover in Natural and Disturbed Salt Marsh Environments	Geophysical Research Letters	10.1029/2020GL090287
2593	Sapkota et al.	2021	Long-term fate of rapidly eroding carbon stock soil profiles in coastal wetlands	Science of the Total Environment	10.1016/j.scitotenv.2020.141
2697	Correa et al.	2021	Groundwater Carbon Exports Exceed Sediment Carbon Burial in a Salt Marsh	Estuaries and Coasts	10.1007/s12237-021-01021-
2769	Archer et al.	2021	Assessing Vegetation, Nutrient Content and Soil Dynamics Along a Coastal Elevation Gradient in a Mississippi Estuary	Estuaries and Coasts	10.1007/s12237-021-01012-
2852	Gailis et al.	2021	Quantifying blue carbon for the largest salt marsh in southern British Columbia: implications for regional coastal management	Coastal Engineering Journal	10.1080/21664250.2021.189
2896	Martins et al.	2021	Carbon and Nitrogen Stocks and Burial Rates in Intertidal Vegetated Habitats of a Mesotidal Coastal Lagoon	Ecosystems	10.1007/s10021-021-00660-

2922	Langston et al.	2021	The Effect of Marsh Age on Ecosystem Function in a Rapidly Transgressing Marsh	Ecosystems	10.1007/s10021-021-00652-6
3012	Granville et al.	2021	Seasonal Patterns of Denitrification and N2O Production in a Southern New England Salt Marsh	Wetlands	10.1007/s13157-021-01393-x
3077	Xia et al.	2020	Distribution, sources, and decomposition of soil organic matter along a salinity gradient in estuarine wetlands characterized by C:N ratio, ?13C-?15N, and lignin biomarker	Global Change Biology	10.1111/gcb.15403
3106	Pinsonneault et al.	2020	Dissolved organic carbon sorption dynamics in tidal marsh soils	Limnology and Oceanography	10.1002/lno.11598
3131	Wang et al.	2020	Plant biomass and rates of carbon dioxide uptake are enhanced by successful restoration of tidal connectivity in salt marshes	Science of the Total Environment	10.1016/j.scitotenv.2020.1415
3137	Zhang et al.	2021	Soil carbon storage and carbon sources under different Spartina alterniflora invasion periods in a salt marsh ecosystem	Catena	10.1016/j.catena.2020.10483
3210	Li et al.	2020	Sea-level rise will reduce net CO2 uptake in subtropical coastal marshes	Science of the Total Environment	10.1016/j.scitotenv.2020.1412
3300	St. Laurent et al.	2020	Assessing coastal carbon variability in two Delaware tidal marshes	Journal of Coastal Conservation	10.1007/s11852-020-00783-3
3333	Liu and Chi	2020	Horizontal and vertical distributions of estuarine soil total organic carbon and total nitrogen under complex land surface characteristics	Global Ecology and Conservation	10.1016/j.gecco.2020.e01268
3340	Ishtiaq and Abdul-Aziz	2020	Ecological parameter reductions, environmental regimes, and characteristic process diagram of carbon dioxide fluxes in coastal salt marshes	Scientific Reports	10.1038/s41598-020-72066-8
3384	Xie et al.	2020	Potential Effect of Bioturbation by Burrowing Crabs on Sediment Parameters in Coastal Salt Marshes	Wetlands	10.1007/s13157-020-01341-1
3400	Li et al.	2020	Molecular Fingerprints of Soil Organic Carbon in Wetlands Covered by Native and Non-native Plants in the Yellow River Delta	Wetlands	10.1007/s13157-020-01340-2
3430	Staver et al.	2020	Tidal Marsh Restoration at Poplar Island: II. Elevation Trends, Vegetation Development, and Carbon Dynamics	Wetlands	10.1007/s13157-020-01295-4

3491	Kaal et al.	2020	Deciphering organic matter sources and ecological shifts in blue carbon ecosystems based on molecular fingerprinting	Science of the Total Environment	10.1016/j.scitotenv.2020.1405
3584	Li et al.	2020	Climatic temperature controls the geographical patterns of coastal marshes greenhouse gases emissions over China	Journal of Hydrology	10.1016/j.jhydrol.2020.125378
3587	Yang et al.	2020	Organic carbon and reduced inorganic sulfur accumulation in subtropical saltmarsh sediments along a dynamic coast, Yancheng, China	Journal of Marine Systems	10.1016/j.jmarsys.2020.10341
3614	Mariotti et al.	2020	Mud-associated organic matter and its direct and indirect role in marsh organic matter accumulation and vertical accretion	Limnology and Oceanography	10.1002/lno.11475
3663	Huang et al.	2020	Tidal effects on ecosystem CO2 exchange in a Phragmites salt marsh of an intertidal shoal	Agricultural and Forest Meteorology	10.1016/j.agrformet.2020.108
3679	Steinmuller et al.	2020	Characterization of herbaceous encroachment on soil biogeochemical cycling within a coastal marsh	Science of the Total Environment	10.1016/j.scitotenv.2020.1395
3719	Czapla et al.	2020	The Effect of Fertilization on Biomass and Metabolism in North Carolina Salt Marshes: Modulated by Location-Specific Factors	Biogeosciences	10.1029/2019JG005238
3778	Kauffman et al.	2020	Total ecosystem carbon stocks at the marine-terrestrial interface: Blue carbon of the Pacific Northwest Coast, United States	Global Change Biology	10.1111/gcb.15248
3847	Zhao et al.	2020	Soil organic carbon content and stock in wetlands with different hydrologic conditions in the Yellow River Delta, China	Ecohydrology and Hydrobiology	10.1016/j.ecohyd.2019.10.008
3868	Yuan et al.	2020	Distribution of organic carbon storage in different salt-marsh plant communities: A case study at the Yangtze Estuary	Estuarine, Coastal and Shelf Science	10.1016/j.ecss.2020.106900
3970	Dong et al.	2020	Evaluation of the carbon accumulation capability and carbon storage of different types of wetlands in the Nanhui tidal flat of the Yangtze River estuary	Environmental Monitoring and Assessment	10.1007/s10661-020-08547-0
4117	Gu et al.	2020	Invasive Phragmites Increases Blue Carbon Stock and Soil Volume in a St. Lawrence Estuary Marsh	Biogeosciences	10.1029/2019JG005473

4155	Seyfferth et al.	2020	Spatial and temporal heterogeneity of geochemical controls on carbon cycling in a tidal salt marsh	Geochimica et Cosmochimica Acta	10.1016/j.gca.2020.05.013
4155	Seyfferth et al.	2020	Spatial and temporal heterogeneity of geochemical controls on carbon cycling in a tidal salt marsh	Geochimica et Cosmochimica Acta	10.1016/j.gca.2020.05.013
4196	Brown et al.	2020	Multiple Stressors Influence Salt Marsh Recovery after a Spring Fire at Mugu Lagoon, CA	Wetlands	10.1007/s13157-019-01210-6
4331	Jiménez-Arias et al.	2020	Tidal elevation is the key factor modulating burial rates and composition of organic matter in a coastal wetland with multiple habitats	Science of the Total Environment	10.1016/j.scitotenv.2020.1382
4383	Kim et al.	2020	Mechanisms of enhanced methane emission due to introduction of Spartina anglica and Phragmites australis in a temperate tidal salt marsh	Ecological Engineering	10.1016/j.ecoleng.2020.1059
4396	Bulmer et al.	2020	Blue Carbon Stocks and Cross-Habitat Subsidies	Frontiers in Marine Science	10.3389/fmars.2020.00380
4508	Kumar et al.	2020	Characteristics of organic matter sources from Guadiana Estuary salt marsh sediments (SW Iberian Peninsula)	Continental Shelf Research	10.1016/j.csr.2020.104076
4515	Alldred et al.	2020	Marsh Plants Enhance Coastal Marsh Resilience by Changing Sediment Oxygen and Sulfide Concentrations in an Urban, Eutrophic Estuary	Estuaries and Coasts	10.1007/s12237-020-00700-9
4536	Gulliver et al.	2020	Estimating the Potential Blue Carbon Gains From Tidal Marsh Rehabilitation: A Case Study From South Eastern Australia	Frontiers in Marine Science	10.3389/fmars.2020.00403
4561	Yan et al.	2020	Conversion behaviors of litter-derived organic carbon of two halophytes in soil and their influence on SOC stabilization of wetland in the Yangtze River Estuary	Science of the Total Environment	10.1016/j.scitotenv.2020.1371
4596	Vaughn et al.	2019	Increased Organic Carbon Burial in Northern Florida Mangrove-Salt Marsh Transition Zones	Global Biogeochemical Cycles	10.1029/2019GB006334
4709	Ewers-Lewis et al.	2020	Drivers and modelling of blue carbon stock variability in sediments of southeastern Australia	Biogeosciences	10.5194/bg-17-2041-2020

4733	Owers et al.	2020	Temperate coastal wetland near-surface carbon storage: Spatial patterns and variability	Estuarine, Coastal and Shelf Science	10.1016/j.ecss.2020.106584
4745	Brown and Rajkaran	2020	Biomass partitioning in an endemic southern African salt marsh species Salicornia tegetaria (Chenopodiaceae)	African Journal of Aquatic Science	10.2989/16085914.2019.1687
4769	Wan et al.	2020	Comparison of Carbon, Nitrogen, and Sulfur in Coastal Wetlands Dominated by Native and Invasive Plants in the Yancheng National Nature Reserve, China	Chinese Geographical Science	10.1007/s11769-020-1108-1
4821	Smeaton et al.	2020	Coring and compaction: Best practice in blue carbon stock and burial estimations	Geoderma	10.1016/j.geoderma.2020.114
4837	Ge et al.	2020	Succession of macrofaunal communities and environmental properties along a gradient of smooth cordgrass Spartina alterniflora invasion stages	Marine Environmental Research	10.1016/j.marenvres.2019.10
4841	Steinmuller et al.	2020	Does edge erosion alter coastal wetland soil properties? A multi-method biogeochemical study	Catena	10.1016/j.catena.2019.10437
4843	Haywood et al.	2020	Potential fate of wetland soil carbon in a deltaic coastal wetland subjected to high relative sea level rise	Science of the Total Environment	10.1016/j.scitotenv.2019.1351
4861	Zhang et al.	2020	Bacterial Succession in Salt Marsh Soils Along a Short-term Invasion Chronosequence of Spartina alterniflora in the Yellow River Estuary, China	Microbial Ecology	10.1007/s00248-019-01430-7
4894	Yang et al.	2020	Invasive Spartina alterniflora can mitigate N2O emission in coastal salt marshes	Ecological Engineering	10.1016/j.ecoleng.2020.1057
4900	Yang	2020	Characterization of the salt marsh soils and visible-near-infrared spectroscopy along a chronosequence of Spartina alterniflora invasion in a coastal wetland of eastern China	Geoderma	10.1016/j.geoderma.2019.114
4919	Yang et al.	2020	System-specific complex interactions shape soil organic carbon distribution in coastal salt marshes	International Journal of Environmental Research and Public Health	10.3390/ijerph17062037

4961	Champlin et al.	2020	Carbon sequestration rate estimates in delaware bay and barnegat bay tidal wetlands using interpolation mapping	Data	10.3390/data5010011
5103	Powell et al.	2020	Pond Excavation Reduces Coastal Wetland Carbon Dioxide Assimilation	Biogeosciences	10.1029/2019JG005187
5112	Zhou and Bi	2020	Seawall effects in a coastal wetland landscape: spatial changes in soil carbon and nitrogen pools	Journal of Coastal Conservation	10.1007/s11852-019-00718-7
5161	Gispert et al.	2020	The role of soil as a carbon sink in coastal salt-marsh and agropastoral systems at La Pletera, NE Spain	Catena	10.1016/j.catena.2019.10433
5221	Wei et al.	2020	Effect of tidal flooding on ecosystem CO2 and CH4 fluxes in a salt marsh in the Yellow River Delta	Estuarine, Coastal and Shelf Science	10.1016/j.ecss.2019.106512
5386	Xue et al.	2020	Salinity Affects Topsoil Organic Carbon Concentrations Through Regulating Vegetation Structure and Productivity	Biogeosciences	10.1029/2019JG005217
5391	Yang et al.	2020	Enhanced Carbon Uptake and Reduced Methane Emissions in a Newly Restored Wetland	Biogeosciences	10.1029/2019JG005222
5429	Mueller et al.	2020	Unrecognized controls on microbial functioning in Blue Carbon ecosystems: The role of mineral enzyme stabilization and allochthonous substrate supply	Ecology and Evolution	10.1002/ece3.5962
5442	Cao et al.	2020	Spatial and temporal variations of the greenhouse gas emissions in coastal saline wetlands in southeastern China	Environmental Science and Pollution Research	10.1007/s11356-019-06951-9
5476	Kim et al.	2020	Microbial mechanism for enhanced methane emission in deep soil layer of Phragmites-introduced tidal marsh	Environment International	10.1016/j.envint.2019.105251
5575	Dítê et al.	2019	Salt marsh vegetation on the Croatian coast: plant communities and ecological characteristics	Plant Systematics and Evolution	10.1007/s00606-019-01617-y
5601	Qian et al.	2019	Spatial distribution patterns of annual soil carbon accumulation and carbon storage in the Jiuduansha wetland of the Yangtze River estuary	Environmental Monitoring and Assessment	10.1007/s10661-019-7914-1

5611	Qiu et al.	2019	Effect of burrowing crabs on retention and accumulation of soil carbon and nitrogen in an intertidal salt marsh	Journal of Sea Research	10.1016/j.seares.2019.10180
5653	Santini et al.	2019	Natural and Regenerated Saltmarshes Exhibit Similar Soil and Belowground Organic Carbon Stocks, Root Production and Soil Respiration	Ecosystems	10.1007/s10021-019-00373-x
5694	Yang et al.	2019	Shift in soil organic carbon and nitrogen pools in different reclaimed lands following intensive coastal reclamation on the coasts of eastern China	Scientific Reports	10.1038/s41598-019-42048-6
5698	Negandhi et al.	2019	Blue carbon potential of coastal wetland restoration varies with inundation and rainfall	Scientific Reports	10.1038/s41598-019-40763-8
5706	Santos et al.	2019	Superficial sedimentary stocks and sources of carbon and nitrogen in coastal vegetated assemblages along a flow gradient	Scientific Reports	10.1038/s41598-018-37031-6
5839	Xiangzhen et al.	2019	Impacts of Age and Expansion Direction of Invasive Spartina alterniflora on Soil Organic Carbon Dynamics in Coastal Salt Marshes Along Eastern China	Estuaries and Coasts	10.1007/s12237-019-00611-4
5901	Sapkota and White	2019	Marsh edge erosion and associated carbon dynamics in coastal Louisiana: A proxy for future wetland-dominated coastlines world-wide	Estuarine, Coastal and Shelf Science	10.1016/j.ecss.2019.106289
5905	Vaccare et al.	2019	The denitrification potential of eroding wetlands in Barataria Bay, LA, USA: Implications for river reconnection	Science of the Total Environment	10.1016/j.scitotenv.2019.05.4
5935	McTigue et al.	2019	Sea Level Rise Explains Changing Carbon Accumulation Rates in a Salt Marsh Over the Past Two Millennia	Biogeosciences	10.1029/2019JG005207
6009	Xi et al.	2019	CO2 exchange under different vegetation covers in a coastal wetland of Jiaozhou Bay, China	Ecological Engineering	10.1016/j.ecoleng.2018.12.02
6043	Zhang et al.	2019	Nitrous oxide emission rate in response to plant, soil and microbial properties in marshes impacted by alien Spartina alterniflora	Biologia	10.2478/s11756-019-00267-2
6044	Sharp and Angelini	2019	The role of landscape composition and disturbance type in mediating salt marsh resilience to feral hog invasion	Biological Invasions	10.1007/s10530-019-02018-5
6105	Gao et al.	2019	Exotic Spartina alterniflora invasion alters soil nitrous oxide emission dynamics in a coastal wetland of China	Plant and Soil	10.1007/s11104-019-04179-7

6137	Xie et al.	2019	Changes in sediment nutrients following Spartina alterniflora invasion in a subtropical estuarine wetland, China	Catena	10.1016/j.catena.2019.04.016
6166	Steinmuller and Chambers	2019	Characterization of coastal wetland soil organic matter: Implications for wetland submergence	Science of the Total Environment	10.1016/j.scitotenv.2019.04.4
6179	Abbott et al.	2019	Factors influencing blue carbon accumulation across a 32-year chronosequence of created coastal marshes	Ecosphere	10.1002/ecs2.2828
6185	Huang et al.	2019	Effects of tidal scenarios on the methane emission dynamics in the subtropical tidal marshes of the min river estuary in southeast China	International Journal of Environmental Research and Public Health	10.3390/ijerph16152790
6251	Doroski et al.	2019	Denitrification Potential and Carbon Mineralization in Restored and Unrestored Coastal Wetland Soils Across an Urban Landscape	Wetlands	10.1007/s13157-019-01128-z
6280	Cuellar-Martinez et al.	2019	Relevance of carbon burial and storage in two contrasting blue carbon ecosystems of a north-east Pacific coastal lagoon	Science of the Total Environment	10.1016/j.scitotenv.2019.03.3
6350	Ewers Lewis et al.	2019	Impacts of land reclamation on tidal marsh √´blue carbon√≠ stocks	Science of the Total Environment	10.1016/j.scitotenv.2019.03.3
6363	Fennessy et al.	2019	Environmental controls on carbon sequestration, sediment accretion, and elevation change in the Ebro River Delta: Implications for wetland restoration	Estuarine, Coastal and Shelf Science	10.1016/j.ecss.2019.03.023
6369	Antler et al.	2019	The sedimentary carbon-sulfur-iron interplay √± A lesson from east Anglian Salt Marsh sediments	Frontiers in Earth Science	10.3389/feart.2019.00140
6389	He et al.	2019	Linking Improvement of Soil Structure to Soil Carbon Storage Following Invasion by a C4 Plant Spartina alterniflora	Ecosystems	10.1007/s10021-018-0308-3
6436	Hu et al.	2019	Nitrogen along the hydrological gradient of marsh sediments in a subtropical estuary: Pools, processes, and fluxes	International Journal of Environmental Research and Public Health	10.3390/ijerph16112043

6495	Hu et al.	2019	Effects of nitrogen loading on emission of carbon gases from estuarine tidal marshes with varying salinity	Science of the Total Environment	10.1016/j.scitotenv.2019.02.4
6508	Kaviarasan et al.	2018	Seasonal Species Variation of Sediment Organic Carbon Stocks in Salt Marshes of Tuticorin Area, Southern India	Wetlands	10.1007/s13157-018-1094-6
6819	Ferronato et al.	2019	Effect of waterlogging on soil biochemical properties and organic matter quality in different salt marsh systems	Geoderma	10.1016/j.geoderma.2018.12.
6858	Wang et al.	2019	Tidal regime influences the spatial variation in trait-based responses of Suaeda salsa and edaphic conditions	Ecosphere	10.1002/ecs2.2642
6895	Yao et al.	2019	Bacterial community assembly in a typical estuarine marsh with multiple environmental gradients	Applied and Environmental Microbiology	10.1128/AEM.02602-18
6939	Zhao et al.	2019	Effects of freshwater inputs on soil quality in the Yellow River Delta, China	Ecological Indicators	10.1016/j.ecolind.2018.11.04
6940	Bang and Lee	2019	Differences in crab burrowing and halophyte growth by habitat types in a Korean salt marsh	Ecological Indicators	10.1016/j.ecolind.2018.11.02
6953	Van de Broek and Govers	2019	Quantification of organic carbon concentrations and stocks of tidal marsh sediments via mid-infrared spectroscopy	Geoderma	10.1016/j.geoderma.2018.09.
6955	Yang et al.	2019	Methane dynamics in an estuarine brackish Cyperus malaccensis marsh: Production and porewater concentration in soils, and net emissions to the atmosphere over five years	Geoderma	10.1016/j.geoderma.2018.09.
6957	Steinmuller et al.	2019	Understanding the fate of soil organic matter in submerging coastal wetland soils: A microcosm approach	Geoderma	10.1016/j.geoderma.2018.08.
6971	Lee et al.	2018	Wetland Soil Properties and Resident Bacterial Communities Are Influenced by Changes in Elevation	Wetlands	10.1007/s13157-018-1077-7
6972	Mou et al.	2018	Short-Term Effect of Exogenous Nitrogen on N 2 O Fluxes from Native and Invaded Tidal Marshes in the Min River Estuary, China	Wetlands	10.1007/s13157-018-1060-3
7017	Bu et al.	2019	Spartina alterniflora invasion affects methane emissions in the Yangtze River estuary	Journal of Soils and Sediments	10.1007/s11368-018-2073-5
7034	Gonneea et al.	2019	Salt marsh ecosystem restructuring enhances elevation resilience and carbon storage during accelerating relative sea-level rise	Estuarine, Coastal and Shelf Science	10.1016/j.ecss.2018.11.003

7110	Shiau et al.	2019	Carbon storage potential in a recently created brackish marsh in eastern North Carolina, USA	Ecological Engineering	10.1016/j.ecoleng.2018.09.00
7140	Ford et al.	2019	Large-scale predictions of salt-marsh carbon stock based on simple observations of plant community and soil type	Biogeosciences	10.5194/bg-16-425-2019
7165	Simpson et al.	2018	Wetland Soil Co 2 Efflux Along a Latitudinal Gradient of Spatial and Temporal Complexity	Estuaries and Coasts	10.1007/s12237-018-0442-3
7173	Conrad et al.	2019	Does regional development influence sedimentary blue carbon stocks? A case study from three Australian estuaries	Frontiers in Marine Science	10.3389/fmars.2018.00518
7194	Aalders et al.	2019	Vegetation communities and edaphic relationships along a typical coastal saltmarsh to woodland gradient in eastern tasmania	Papers and Proceedings of the Royal Society of Tasmania	10.26749/rstpp.153.61
7368	Taylor et al.	2019	Sediment dynamics of natural and restored Bolboschoenus maritimus saltmarsh	Frontiers in Ecology and Evolution	10.3389/fevo.2019.00237
7443	Drexler et al.	2019	Carbon accumulation and vertical accretion in a restored versus historic salt marsh in southern Puget Sound, Washington, United States	Restoration Ecology	10.1111/rec.12941
7468	Burden et al.	2019	Effect of restoration on saltmarsh carbon accumulation in Eastern England	Biology Letters	10.1098/rsbl.2018.0773
7469	Mueller et al.	2019	Assessing the long-term carbon-sequestration potential of the semi-natural salt marshes in the European Wadden Sea	Ecosphere	10.1002/ecs2.2556
7599	Tonti et al.	2018	First results of energy and mass exchange in a salt marsh on southeastern South America	Agricultural and Forest Meteorology	10.1016/j.agrformet.2018.08.0
7631	Lalimi et al.	2018	The Spatial Variability of Organic Matter and Decomposition Processes at the Marsh Scale	Biogeosciences	10.1029/2017JG004211
7643	Wilson	2021	Salinity pulses interact with seasonal dry-down to increase ecosystem carbon loss in marshes of the Florida Everglades	Ecological Applications	10.1002/eap.1798
7681	Diefenderfer et al.	2018	High-frequency greenhouse gas flux measurement system detects winter storm surge effects on salt marsh	Global Change Biology	10.1111/gcb.14430

7888	Chaudhary et al.	2018	Aboveground, belowground biomass and nutrients pool in Salicornia brachiata at coastal area of India: interactive effects of soil characteristics	Ecological Research	10.1007/s11284-018-1634-9
8111	Kauffman et al.	2018	Carbon stocks of mangroves and salt marshes of the Amazon region, Brazil	Biology Letters	10.1098/rsbl.2018.0208
8182	Onorevole et al.	2018	Living shorelines enhance nitrogen removal capacity over time	Ecological Engineering	10.1016/j.ecoleng.2018.05.01
8187	Van Zomeren et al.	2018	Restoring a degraded marsh using thin layer sediment placement: Short term effects on soil physical and biogeochemical properties	Ecological Engineering	10.1016/j.ecoleng.2018.05.01
8255	Leorri et al.	2018	Refractory organic matter in coastal salt marshes-effect on C sequestration calculations	Science of the Total Environment	10.1016/j.scitotenv.2018.03.1
8298	van Ardenne et al.	2018	High resolution carbon stock and soil data for three salt marshes along the northeastern coast of North America	Data in Brief	10.1016/j.dib.2018.07.037
8343	Sun et al.	2018	Short-Term Study on Variations of Carbon Dioxide and Methane Emissions from Intertidal Zone of the Yellow River Estuary during Autumn and Winter	Wetlands	10.1007/s13157-018-1035-4
8345	Chen et al.	2018	Characteristics of CH4 and CO2 emissions and influence of water and salinity in the Yellow River delta wetland, China	Environmental Pollution	10.1016/j.envpol.2018.04.043
8360	Starr et al.	2018	Variation in ecosystem carbon dynamics of saltwater marshes in the northern Gulf of Mexico	Wetlands Ecology and Management	10.1007/s11273-018-9593-z
8391	Cusack et al.	2018	Organic carbon sequestration and storage in vegetated coastal habitats along the western coast of the Arabian Gulf	Environmental Research Letters	10.1088/1748-9326/aac899
8409	Yang and Guo	2018	Exotic Spartina alterniflora Enhances the Soil Functions of a Coastal Ecosystem	Soil Science Society of America Journal	10.2136/sssaj2017.12.0411
8447	Ríos et al.	2018	Soil-geomorphology relationships and landscape evolution in a southwestern Atlantic tidal salt marsh in Patagonia, Argentina	Journal of South American Earth Sciences	10.1016/j.jsames.2018.04.015
8477	Radabaugh et al.	2018	Coastal Blue Carbon Assessment of Mangroves, Salt Marshes, and Salt Barrens in Tampa Bay, Florida, USA	Estuaries and Coasts	10.1007/s12237-017-0362-7

8570	Ellison and Beasy	2018	Sediment carbon accumulation in southern latitude saltmarsh communities of Tasmania, Australia	Biology	10.3390/biology7020027
8590	Li et al.	2018	Effect of reclamation on soil organic carbon pools in coastal areas of eastern China	Frontiers of Earth Science	10.1007/s11707-018-0680-5
8605	Zhang et al.	2018	Soil Organic Carbon Contents and Stocks in Coastal Salt Marshes with Spartina alterniflora Following an Invasion Chronosequence in the Yellow River Delta, China	Chinese Geographical Science	10.1007/s11769-018-0955-5
8613	Van de Broek	2018	Long-term organic carbon sequestration in tidal marsh sediments is dominated by old-aged allochthonous inputs in a macrotidal estuary	Global Change Biology	10.1111/gcb.14089
8622	Yan et al.	2018	Plant litter composition selects different soil microbial structures and in turn drives different litter decomposition pattern and soil carbon sequestration capability	Geoderma	10.1016/j.geoderma.2018.01.
8625	Zhae et al.	2018	Effects of water and salinity regulation measures on soil carbon sequestration in coastal wetlands of the Yellow River Delta	Geoderma	10.1016/j.geoderma.2017.10.
8702	Martin et al.	2018	Long-term nutrient addition increases respiration and nitrous oxide emissions in a New England salt marsh	Ecology and Evolution	10.1002/ece3.3955
8779	Oosterlee et al.	2017	Tidal Marsh Restoration Design Affects Feedbacks Between Inundation and Elevation Change	Estuaries and Coasts	10.1007/s12237-017-0314-2
8817	Li et al.	2018	Role of Scirpus mariqueter on methane emission from an intertidal saltmarsh of Yangtze estuary	Sustainability (Switzerland)	10.3390/su10041139
8836	Roughan et al.	2018	Nitrous oxide emissions could reduce the blue carbon value of marshes on eutrophic estuaries	Environmental Research Letters	10.1088/1748-9326/aab63c
8853	Lu et al.	2018	Spatial and seasonal distribution of carbon, nitrogen, phosphorus, and sulfur and their ecological stoichiometry in wetland soils along a water and salt gradient in the Yellow River Delta, China	Physics and Chemistry of the Earth	10.1016/j.pce.2018.04.001
8858	Mao et al.	2018	Soil-Aggregate-Associated Organic Carbon Along Vegetation Zones in Tidal Salt Marshes in the Liaohe Delta	Clean - Soil, Air, Water	10.1002/clen.201800049
8985	Wang et al.	2018	Species-specific impacts of invasive plant success on vertical profiles of soil carbon accumulation and nutrient retention in the minjiang river tidal estuarine wetlands of China	Soil Systems	10.3390/soils2010005
9001	Forbrich et al.	2018	Constraining Marsh Carbon Budgets Using Long-Term C Burial and Contemporary Atmospheric CO2 Fluxes	Biogeosciences	10.1002/2017JG004336

9011	Wollenberg et al.	2018	Rapid carbon accumulation following managed realignment on the Bay of Fundy	PLoS ONE	10.1371/journal.pone.019393
9075	Wang et al.	2018	Seasonal variations of nitrous oxide fluxes and soil denitrification rates in subtropical freshwater and brackish tidal marshes of the Min River estuary	Science of the Total Environment	10.1016/j.scitotenv.2017.10.1
9076	Carnero-Bravo et al.	2018	Sea level rise sedimentary record and organic carbon fluxes in a low-lying tropical coastal ecosystem	Catena	10.1016/j.catena.2017.09.016
9086	Ewers Lewis et al.	2018	Variability and Vulnerability of Coastal √´Blue Carbon√≠ Stocks: A Case Study from Southeast Australia	Ecosystems	10.1007/s10021-017-0150-z
9122	Chu et al.	2018	Dual effect of precipitation redistribution on net ecosystem CO2 exchange of a coastal wetland in the Yellow River Delta	Agricultural and Forest Meteorology	10.1016/j.agrformet.2017.11.
9402	Xu et al.	2018	Spatial distribution characteristics of soil organic matter and nitrogen under natural conditions in yancheng coastal wetlands	Applied Ecology and Environmental Research	10.15666/aeer/1605_691769
9532	Li et al.	2018	Multi-scale temporal variation of methane flux and its controls in a subtropical tidal salt marsh in eastern China	Biogeochemistry	10.1007/s10533-017-0413-y
9670	Emery et al.	2017	Incomplete tidal restoration may lead to persistent high CH4 emission	Ecosphere	10.1002/ecs2.1968
9735	Simpson et al.	2021	Carbon Storages along a Climate Induced Coastal Wetland Gradient	Wetlands	10.1007/s13157-017-0937-x
9862	Arriola et al.	2017	Variations in carbon burial and sediment accretion along a tidal creek in a Florida salt marsh	Limnology and Oceanography	10.1002/lno.10652
9916	Janouesk et al.	2017	Inundation, Vegetation, and Sediment Effects on Litter Decomposition in Pacific Coast Tidal Marshes	Ecosystems	10.1007/s10021-017-0111-6
9992	Wang et al.	2017	Spartina alterniflora alters ecosystem DMS and CH4 emissions and their relationship along interacting tidal and vegetation gradients within a coastal salt marsh in Eastern China	Atmospheric Environment	10.1016/j.atmosenv.2017.08.
10013	Yuan et al.	2017	Sources and distribution of sedimentary organic matter along the Andong salt marsh, Hangzhou Bay	Journal of Marine Systems	10.1016/j.jmarsys.2017.06.00

10023	Hayes et al.	2017	Dynamics of sediment carbon stocks across intertidal wetland habitats of Moreton Bay, Australia	Global Change Biology	10.1111/gcb.13722
10044	Persico et al.	2017	Feral hog disturbance alters carbon dynamics in southeastern US salt marshes	Marine Ecology Progress Series	10.3354/meps12282
10091	Velinsky et al.	2017	Tidal Marsh Record of Nutrient Loadings in Barnegat Bay, New Jersey	Journal of Coastal Research	10.2112/SI78-008.1
10093	Velinsky et al.	2017	Salt Marsh Denitrification Provides a Significant Nitrogen Sink in Barnegat Bay, New Jersey	Journal of Coastal Research	10.2112/SI78-007.1
10166	Yang et al.	2017	Soil organic carbon and nitrogen dynamics following Spartina alterniflora invasion in a coastal wetland of eastern China	Catena	10.1016/j.catena.2017.03.021
10193	Kelleway et al.	2017	Sediment and carbon deposition vary among vegetation assemblages in a coastal salt marsh	Biogeosciences	10.5194/bg-14-3763-2017
10239	Gao et al.	2017	Effects of environmental conditions and aboveground biomass on CO2 budget in Phragmites australis wetland of Jiaozhou Bay, China	Chinese Geographical Science	10.1007/s11769-017-0886-6
10283	Alexander et al.	2017	Sedimentary processes and products in a mesotidal salt marsh environment: insights from Groves Creek, Georgia	Geo-Marine Letters	10.1007/s00367-017-0499-1
10421	Yang et al.	2017	Diurnal variation of CO2, CH4, and N2O emission fluxes continuously monitored in-situ in three environmental habitats in a subtropical estuarine wetland	Marine Pollution Bulletin	10.1016/j.marpolbul.2017.04.
10444	Spencer et al.	2017	The impact of pre-restoration land-use and disturbance on sediment structure, hydrology and the sediment geochemical environment in restored saltmarshes	Science of the Total Environment	10.1016/j.scitotenv.2016.11.0
10569	Wang et al.	2017	Determining the Spatial Variability of Wetland Soil Bulk Density, Organic Matter, and the Conversion Factor between Organic Matter and Organic Carbon across Coastal Louisiana, U.S.A.	Journal of Coastal Research	10.2112/JCOASTRES-D-16-0
10696	Schile et al.	2017	Limits on carbon sequestration in arid blue carbon ecosystems	Ecological Applications	10.1002/eap.1489

10723	Baustian et al.	2017	Relationships Between Salinity and Short-Term Soil Carbon Accumulation Rates from Marsh Types Across a Landscape in the Mississippi River Delta	Wetlands	10.1007/s13157-016-0871-3
10974	Vizza et al.	2017	Regulators of coastal wetland methane production and responses to simulated global change	Biogeosciences	10.5194/bg-14-431-2017
10975	Sousa et al.	2017	'Blue Carbon' and Nutrient Stocks of Salt Marshes at a Temperate Coastal Lagoon (Ria de Aveiro, Portugal)	Scientific Reports	10.1038/srep41225
11306	Welti et al.	2017	Seasonal nitrous oxide and methane emissions across a subtropical estuarine salinity gradient	Biogeochemistry	10.1007/s10533-016-0287-4
11312	Boyd et al.	2017	Hydrogeomorphic influences on salt marsh sediment accumulation and accretion in two estuaries of the U.S. Mid-Atlantic coast	Marine Geology	10.1016/j.margeo.2016.11.00
11313	Yamochi et al.	2017	Effects of light, temperature and ground water level on the CO2 flux of the sediment in the high water temperature seasons at the artificial north salt marsh of Osaka Nanko bird sanctuary, Japan	Ecological Engineering	10.1016/j.ecoleng.2016.09.01
11361	Hansen et al.	2017	Factors influencing the organic carbon pools in tidal marsh soils of the Elbe estuary (Germany)	Journal of Soils and Sediments	10.1007/s11368-016-1500-8
11379	Van de Broek et al.	2016	Controls on soil organic carbon stocks in tidal marshes along an estuarine salinity gradient	Biogeosciences	10.5194/bg-13-6611-2016
11414	Wang et al.	2016	Effects of spartina alterniflora invasion on soil quality in coastal wetland of beibu gulf of South China	PLoS ONE	10.1371/journal.pone.016895
11451	Yang et al.	2016	The impact of sea embankment reclamation on soil organic carbon and nitrogen pools in invasive Spartina alterniflora and native Suaeda salsa salt marshes in eastern China	Ecological Engineering	10.1016/j.ecoleng.2016.10.06
11474	Shiau et al.	2016	Greenhouse Gas Emissions from a Created Brackish Marsh in Eastern North Carolina	Wetlands	10.1007/s13157-016-0815-y
11531	Moseman-Valtierra et al.	2016	Carbon dioxide fluxes reflect plant zonation and belowground biomass in a coastal Marsh	Ecosphere	10.1002/ecs2.1560
11555	Yang et al.	2016	Response of the soil microbial community composition and biomass to a short-term Spartina alterniflora invasion in a coastal wetland of eastern China	Plant and Soil	10.1007/s11104-016-2941-y

11900	Ye et al.	2016	Inter-annual variability of area-scaled gaseous carbon emissions from wetland soils in the Liaohe Delta, China	PLoS ONE	10.1371/journal.pone.016061
11941	Kelleway et al.	2016	Sedimentary Factors are Key Predictors of Carbon Storage in SE Australian Saltmarshes	Ecosystems	10.1007/s10021-016-9972-3
12028	Boyd et al.	2012	Marsh accretion and sediment accumulation in a managed tidal wetland complex of Delaware Bay	Ecological Engineering	10.1016/j.ecoleng.2016.03.04
12041	Zhang et al.	2016	Soil quality assessment of coastal wetlands in the Yellow River Delta of China based on the minimum data set	Ecological Indicators	10.1016/j.ecolind.2016.01.04
12141	Holm et al	2016	Ecosystem Level Methane Fluxes from Tidal Freshwater and Brackish Marshes of the Mississippi River Delta: Implications for Coastal Wetland Carbon Projects	Wetlands	10.1007/s13157-016-0746-7
12143	Li and Mitsch	2016	Methane emissions from created and restored freshwater and brackish marshes in southwest Florida, USA	Ecological Engineering	10.1016/j.ecoleng.2016.01.00
12322	He et al.	2016	Accumulation of soil carbon drives denitrification potential and lab-incubated gas production along a chronosequence of salt marsh development	Estuarine, Coastal and Shelf Science	10.1016/j.ecss.2016.02.002
12473	Kelleway et al.	2016	Seventy years of continuous encroachment substantially increases 'blue carbon' capacity as mangroves replace intertidal salt marshes	Global Change Biology	10.1111/gcb.13158
12484	Song and Liu	2016	Anthropogenic Effects on Fluxes of Ecosystem Respiration and Methane in the Yellow River Estuary, China	Wetlands	10.1007/s13157-014-0587-1
12564	Chmura et al.	2016	Greenhouse gas fluxes from salt marshes exposed to chronic nutrient enrichment	PLoS ONE	10.1371/journal.pone.014993
12590	Witte and Giani	2016	Greenhouse Gas Emission and Balance of Marshes at the Southern North Sea Coast	Wetlands	10.1007/s13157-015-0722-7
12900	Chen et al.	2016	The Role of Salt Marsh Structure in the Distribution of Surface Sedimentary Organic Matter	Estuaries and Coasts	10.1007/s12237-015-9957-z
13118	Tong et al.	2015	Weak Correlation Between Methane Production and Abundance of Methanogens Across Three Brackish Marsh Zones in the Min River Estuary, China	Estuaries and Coasts	10.1007/s12237-014-9930-2
13123	Sheng et al.	2015	Vegetation alters the effects of salinity on greenhouse gas emissions and carbon sequestration in a newly created wetland	Ecological Engineering	10.1016/j.ecoleng.2015.09.04

13340	Forbrich et al.	2015	Marsh-atmosphere CO2 exchange in a New England salt marsh	Journal of Geophysical Research G: Biogeosciences	10.1002/2015JG003044
13372	Hill and Anisfield	2015	Coastal wetland response to sea level rise in Connecticut and New York	Estuarine, Coastal and Shelf Science	10.1016/j.ecss.2015.06.004
13399	Olsson et al.	2015	Factors influencing CO2 and CH4 emissions from coastal wetlands in the Liaohe Delta, Northeast China	Biogeosciences	10.5194/bg-12-4965-2015
13457	Bu et al	2015	Reclamation of coastal salt marshes promoted carbon loss from previously-sequestered soil carbon pool	Ecological Engineering	10.1016/j.ecoleng.2015.04.05
13533	Tong et al.	2015	Small-Scale Spatial Variability of Soil Methane Production Potential and Porewater Characteristics in an Estuarine Phragmites australis Marsh	Journal of Coastal Research	10.2112/JCOASTRES-D-14-0
13554	Xiang et al.	2015	Invasion chronosequence of Spartina alterniflora on methane emission and organic carbon sequestration in a coastal salt marsh	Atmospheric Environment	10.1016/j.atmosenv.2015.04.0
13615	Yang et al.	2015	Labile and Recalcitrant Soil Carbon and Nitrogen Pools in Tidal Salt Marshes of the Eastern Chinese Coast as Affected by Short-Term C4 Plant Spartina alterniflora Invasion	Clean - Soil, Air, Water	10.1002/clen.201300846
13645	Wang et al.	2015	Variations in temperature sensitivity (Q10) of CH4 emission from a subtropical estuarine marsh in southeast China	PLoS ONE	10.1371/journal.pone.012522
13666	Tempest et al.	2015	Modified sediments and subsurface hydrology in natural and recreated salt marshes and implications for delivery of ecosystem services	Hydrological Processes	10.1002/hyp.10368
13707	Jacobo et al.	2015	Tidal Suppression Negatively Affects Soil Properties and Productivity of Spartina densiflora Salt Marsh	Rangeland Ecology and Management	10.1016/j.rama.2015.03.005
13711	Landi and Angiolini	2015	Soil-Plant Relationships in Mediterranean Salt Marshes across Dune-Cultivated Land Gradient	Journal of Coastal Research	10.2112/JCOASTRES-D-13-0
13754	Vivanco et al.	2015	Nonlinear responses in salt marsh functioning to increased nitrogen addition	Ecology	10.1890/13-1983.1

13796	Yuan et al.	2015	Exotic Spartina alterniflora invasion alters ecosystem-atmosphere exchange of CH4 and N2O and carbon sequestration in a coastal salt marsh in China	Global Change Biology	10.1111/gcb.12797
13815	Bu et al	2015	Effects of spartina alterniflora invasion on soil respiration in the Yangtze River Estuary, China	PLoS ONE	10.1371/journal.pone.012157
13850	Butzeck et al.	2015	Sediment Deposition and Accretion Rates in Tidal Marshes Are Highly Variable Along Estuarine Salinity and Flooding Gradients	Estuaries and Coasts	10.1007/s12237-014-9848-8
13950	Qin et al.	2015	Seasonal changes in soil TN and SOC in a seawall-reclaimed marsh in the Yellow River Delta, China	Journal of Coastal Conservation	10.1007/s11852-014-0362-8
13967	Zhou et al.	2015	The Invasion of Spartina alterniflora Alters Carbon Dynamics in China&apos;s Yancheng Natural Reserve	Clean - Soil, Air, Water	10.1002/clen.201300839
14174	Brooks et al.	2015	Limited Vegetation Development on a Created Salt Marsh Associated with Over-Consolidated Sediments and Lack of Topographic Heterogeneity	Estuaries and Coasts	10.1007/s12237-014-9824-3
14415	Sheng et al.	2014	Greenhouse gas emissions following an invasive plant eradication program	Ecological Engineering	10.1016/j.ecoleng.2014.09.03
14822	Wang et al.	2014	Long-term effect of agricultural reclamation on soil chemical properties of a coastal saline marsh in Bohai Rim, Northern China	PLoS ONE	10.1371/journal.pone.009372
14841	Morrissey et al.	2014	Salinity affects microbial activity and soil organic matter content in tidal wetlands	Global Change Biology	10.1111/gcb.12431
14892	Yu et al.	2013	Spatiotemporal distribution characteristics of soil organic carbon in newborn coastal wetlands of the Yellow River Delta estuary	Clean - Soil, Air, Water	10.1002/clen.201100511
14933	Lewis et al.	2014	Effects of flooding and warming on soil organic matter mineralization in Avicennia germinans mangrove forests and Juncus roemerianus salt marshes	Estuarine, Coastal and Shelf Science	10.1016/j.ecss.2013.12.032
14961	Yuan et al.	2014	Methane production potential and methanogenic archaea community dynamics along the Spartina alterniflora invasion chronosequence in a coastal salt marsh	Applied Microbiology and Biotechnology	10.1007/s00253-013-5104-6
15211	Curado et al.	2014	Effectiveness of the aquatic halophyte Sarcocornia perennis spp. perennis as a biotool for ecological restoration of salt marshes	Water, Air, and Soil Pollution	10.1007/s11270-014-2108-5

15219	Calvo-Cubero et al.	2014	Changes in nutrient concentration and carbon accumulation in a mediterranean restored marsh (Ebro Delta, Spain)	Ecological Engineering	10.1016/j.ecoleng.2014.07.0
15250	Weston et al.	2014	Net ecosystem carbon exchange and the greenhouse gas balance of tidal marshes along an estuarine salinity gradient	Biogeochemistry	10.1007/s10533-014-9989-7
15274	Duarte et al.	2014	Abiotic control modelling of salt marsh sediments respiratory CO 2 fluxes: Application to increasing temperature scenarios	Ecological Indicators	10.1016/j.ecolind.2014.06.01
15287	Wigand et al.	2014	Below the disappearing marshes of an urban Estuary: Historic nitrogen trends and soil structure	Ecological Applications	10.1890/13-0594.1
15389	Hansen and Nestlerode	2014	Carbon sequestration in wetland soils of the northern Gulf of Mexico coastal region	Wetlands Ecology and Management	10.1007/s11273-013-9330-6
15658	Hulisz et al.	2013	Chronosequential alterations in soil organic matter during initial development of coastal salt marsh soils at the southern North Sea	Zeitschrift fur Geomorphologie	10.1127/0372-8854/2013/01
15692	Yang et al.	2013	Consequences of short-term C4 plant Spartina alterniflora invasions for soil organic carbon dynamics in a coastal wetland of Eastern China	Ecological Engineering	10.1016/j.ecoleng.2013.09.0
15735	Kiehn et al.	2013	Biogeochemical recovery of oligohaline wetland soils experiencing a salinity pulse	Soil Science Society of America Journal	10.2136/sssaj2013.05.0202
15763	Chen et al.	2013	Characteristics of greenhouse gas emission in the Yellow River Delta wetland	International Biodeterioration and Biodegradation	10.1016/j.ibiod.2013.04.009
15848	Curado et al.	2013	Native plant restoration combats environmental change: Development of carbon and nitrogen sequestration capacity using small cordgrass in European salt marshes	Environmental Monitoring and Assessment	10.1007/s10661-013-3185-4
16028	Sun et al.	2013	Seasonal and spatial variations of methane emissions from coastal marshes in the northern Yellow River estuary, China	Plant and Soil	10.1007/s11104-012-1564-1
16059	DeLaune et al.	2013	Freshwater diversions as an ecosystem management tool for maintaining soil organic matter accretion in coastal marshes	Catena	10.1016/j.catena.2013.02.01
16083	Macreadie et al.	2013	Loss of 'Blue Carbon' from Coastal Salt Marshes Following Habitat Disturbance	PLoS ONE	10.1371/journal.pone.006924

16230	Vincent et al.	2013	Ditching and Ditch-Plugging in New England Salt Marshes: Effects on Hydrology, Elevation, and Soil Characteristics	Estuaries and Coasts	10.1007/s12237-012-9583-y
16231	Tong et al.	2013	Diurnal Variations of Carbon Dioxide, Methane, and Nitrous Oxide Vertical Fluxes in a Subtropical Estuarine Marsh on Neap and Spring Tide Days	Estuaries and Coasts	10.1007/s12237-013-9596-1
16379	Burden et al.	2013	Carbon sequestration and biogeochemical cycling in a saltmarsh subject to coastal managed realignment	Estuarine, Coastal and Shelf Science	10.1016/j.ecss.2013.01.014
16401	Lin et al.	2013	Sources and preservation of organic matter in soils of the wetlands in the Liaohe (Liao River) Delta, North China	Marine Pollution Bulletin	10.1016/j.marpolbul.2013.01.
16448	Zhang et al.	2013	Soil microbiological variability under different successional stages of the Chongming Dongtan wetland and its effect on soil organic carbon storage	Ecological Engineering	10.1016/j.ecoleng.2012.10.00
16643	Reid et al.	2013	Tidal marsh methane dynamics: Difference in seasonal lags in emissions driven by storage in vegetated versus unvegetated sediments	Biogeosciences	10.1002/2013JG002438
16805	Sun et al.	2013	Fluxes of nitrous oxide and methane in different coastal Suaeda salsa marshes of the Yellow River estuary, China	Chemosphere	10.1016/j.chemosphere.2012
16924	Ford et al.	2012	Methane, carbon dioxide and nitrous oxide fluxes from a temperate salt marsh: Grazing management does not alter Global Warming Potential	Estuarine, Coastal and Shelf Science	10.1016/j.ecss.2012.08.002
16942	Tong et al.	2012	Invasive alien plants increase CH4 emissions from a subtropical tidal estuarine wetland	Biogeochemistry	10.1007/s10533-012-9712-5
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17042	Liu et al.	2012	Effects of exotic cordgrass Spartina alterniflora on soil physical and chemical characteristics in the Haihe River estuary, China	RSETE 2012 - Proceedings	10.1109/RSETE.2012.62605
17045	He et al.	2012	Spatial-temporal distribution characteristics of soil organic matter and total nitrogen in the Jiuduansha wetlands of the Yangtze estuary	iCBEB 2012	10.1109/iCBEB.2012.359

17088	Adams et al.	2012	Nitrous oxide and methane fluxes vs. carbon, nitrogen and phosphorous burial in new intertidal and saltmarsh sediments	Science of the Total Environment	10.1016/j.scitotenv.2011.11.0
17121	Callaway et al.	2012	Carbon Sequestration and Sediment Accretion in San Francisco Bay Tidal Wetlands	Estuaries and Coasts	10.1007/s12237-012-9508-9
17146	González-Alcaraz et al.	2012	Storage of organic carbon, nitrogen and phosphorus in the soil-plant system of Phragmites australis stands from a eutrophicated Mediterranean salt marsh	Geoderma	10.1016/j.geoderma.2012.03.
17229	Spohn and Giani	2012	Carbohydrates, carbon and nitrogen in soils of a marine and a brackish marsh as influenced by inundation frequency	Estuarine, Coastal and Shelf Science	10.1016/j.ecss.2012.05.006
17262	Huang et al.	2012	Two-decade wetland cultivation and its effects on soil properties in salt marshes in the Yellow River Delta, China	Ecological Informatics	10.1016/j.ecoinf.2011.11.001
17312	Hu et al.	2012	Variability of soil organic carbon reservation capability between coastal salt marsh and riverside freshwater wetland in Chongming Dongtan and its microbial mechanism	Journal of Environmental Sciences (China)	10.1016/S1001-0742(11)6087
17318	Yu et al.	2012	Effect of Scirpus mariqueter on nitrous oxide emissions from a subtropical monsoon estuarine wetland	Biogeosciences	10.1029/2011JG001850
17413	Madrid et al.	2012	Marsh construction techniques influence net plant carbon capture by emergent and submerged vegetation in a brackish marsh in the northwestern Gulf of Mexico	Ecological Engineering	10.1016/j.ecoleng.2012.02.00
17472	Sammul et al.	2012	Biomass accumulation during reed encroachment reduces efficiency of restoration of Baltic coastal grasslands	Applied Vegetation Science	10.1111/j.1654-109X.2011.01
17492	Dausse et al.	2012	Biogeochemical functioning of grazed estuarine tidal marshes along a salinity gradient	Estuarine, Coastal and Shelf Science	10.1016/j.ecss.2011.12.037
17492	Dausse et al.	2012	Biogeochemical functioning of grazed estuarine tidal marshes along a salinity gradient	Estuarine, Coastal and Shelf Science	10.1016/j.ecss.2011.12.037

17553	Gao et al.	2012	Influence of spartina colonization on the supply and accumulation of organic carbon in tidal salt marshes of Northern Jiangsu Province, China	Journal of Coastal Research	10.2112/JCOASTRES-D-11-
17697	Hulisz et al.	2012	Characteristics of sedimentary environments in brackish marsh soils in relation to organic matter properties (Puck Lagoon, Northern Poland)	Ecological Questions	10.2478/v10090-012-0009-z
17764	Irvine et al.	2012	The effect of nitrogen enrichment on C1-cycling microorganisms and methane flux in salt marsh sediments	Frontiers in Microbiology	10.3389/fmicb.2012.00090
17832	Anisfeld et al.	2012	Fertilization Effects on Elevation Change and Belowground Carbon Balance in a Long Island Sound Tidal Marsh	Estuaries and Coasts	10.1007/s12237-011-9440-4
18019	Twohig and Stolt	2011	Soils-based rapid assessment for quantifying changes in salt marsh condition as a result of hydrologic alteration	Wetlands	10.1007/s13157-011-0210-7
18102	O'Driscoll et al.	2011	Mercury speciation and distribution in coastal wetlands and tidal mudflats: Relationships with sulphur speciation and organic carbon	Water, Air, and Soil Pollution	10.1007/s11270-011-0756-2
18135	Kadiri et al.	2011	Sediment characteristics of a restored saltmarsh and mudflat in a managed realignment scheme in Southeast England	Hydrobiologia	10.1007/s10750-011-0755-8
18187	Moseman-Valtierra et al.	2011	Short-term nitrogen additions can shift a coastal wetland from a sink to a source of N2O	Atmospheric Environment	10.1016/j.atmosenv.2011.05.
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Table S3 – Description of different approaches currently used to restore degraded or previously reclaimed saltmarshes, as categorised for our analysis. Based on information from Hudson et al. (2021)

Restoration Approach	Description
Artificial structures	May include use of structures such as sluices or tide gates, to alter tidal flow onto the marsh or to affect sedimentary processes, e.g. enhancing sediment deposition.
Freshwater reintroduction	Diversion of river flow to reintroduce freshwater to a marsh from which freshwater input was previously restricted.
Marsh creation	Creation of saltmarsh habitat, usually on previously reclaimed marsh area, often using multiple techniques such as vegetation planting, addition of dredged sediment and fertilisation.
Sediment alteration	Altering sediment properties of the saltmarsh, such as adding sediment or levelling marsh surface to achieve a desirable elevation.
Tidal reintroduction	Reintroduction of tidal flow to a saltmarsh on which this was previously restricted. Often done by managed realignment, involving a breaching of an existing sea defense or regulated tidal exchange, where tidal flow is reintroduced to the marsh under a controlled mechanism.

Table S4. Fixed factors included in optimal (best supported) models for % organic carbon (%OC), bulk density, carbon stock (to 1m), carbon accumulation rate and net CO_2 flux for restored marshes. Estimated marginalised means (EMMs) are shown for categorical fixed effects and slope estimates are given for continuous fixed effects, each with standard error (SE). Age of marsh refers to years since restoration. Net CO_2 uptake by restored marshes is indicated by negative net CO_2 flux values.

Variable	Fixed factors	Level	EMM	Slope	SE
% OC	Restoration approach (RA)	Artificial structures	4.37		3.31
		Freshwater introduction	33.54		8.65
		Marsh creation	7.90		2.35
		Sediment alteration	5.48		1.89
		Tidal reintroduction	7.90		1.85
		Unknown	1.24		8.73
Bulk density (g cm^{-3})	Age of marsh (A)			-	0.00094
	Restoration approach (RA)	Artificial structures	1.02	0.00016	0.18
		Freshwater introduction	0.49		0.18
		Marsh creation	1.22		0.11
		Sediment alteration	1.15		0.12
		Tidal reintroduction	1.09		0.11
		Unknown	1.44		0.21
	Continent (C)	Asia	1.31		0.17
		Europe	0.89		0.11
		North America	0.64		0.07

		Oceania	1.43		0.30
C Stock (t C ha^{-1})	Vegetation (V)	Phragmites	398		92.3
		Spartina	187		38.1
		Suaeda	119		89.8
		Other	175		44.0
		Unknown	379		62.0
	Age of marsh (A)			-0.75	0.43
	Air temp (T)			-18.73	6.59
C accumulation (t C ha^{-1} y^{-1})	None	NA	NA	NA	NA
Net CO_2 flux (t CO_2e ha^{-1} y^{-1})	Annual rainfall (R)		-9.54	-0.08	0.03
	Continent (C)	Asia	-		25.30
		North America	77.47		13.30
		Oceania	-4.11		32.00

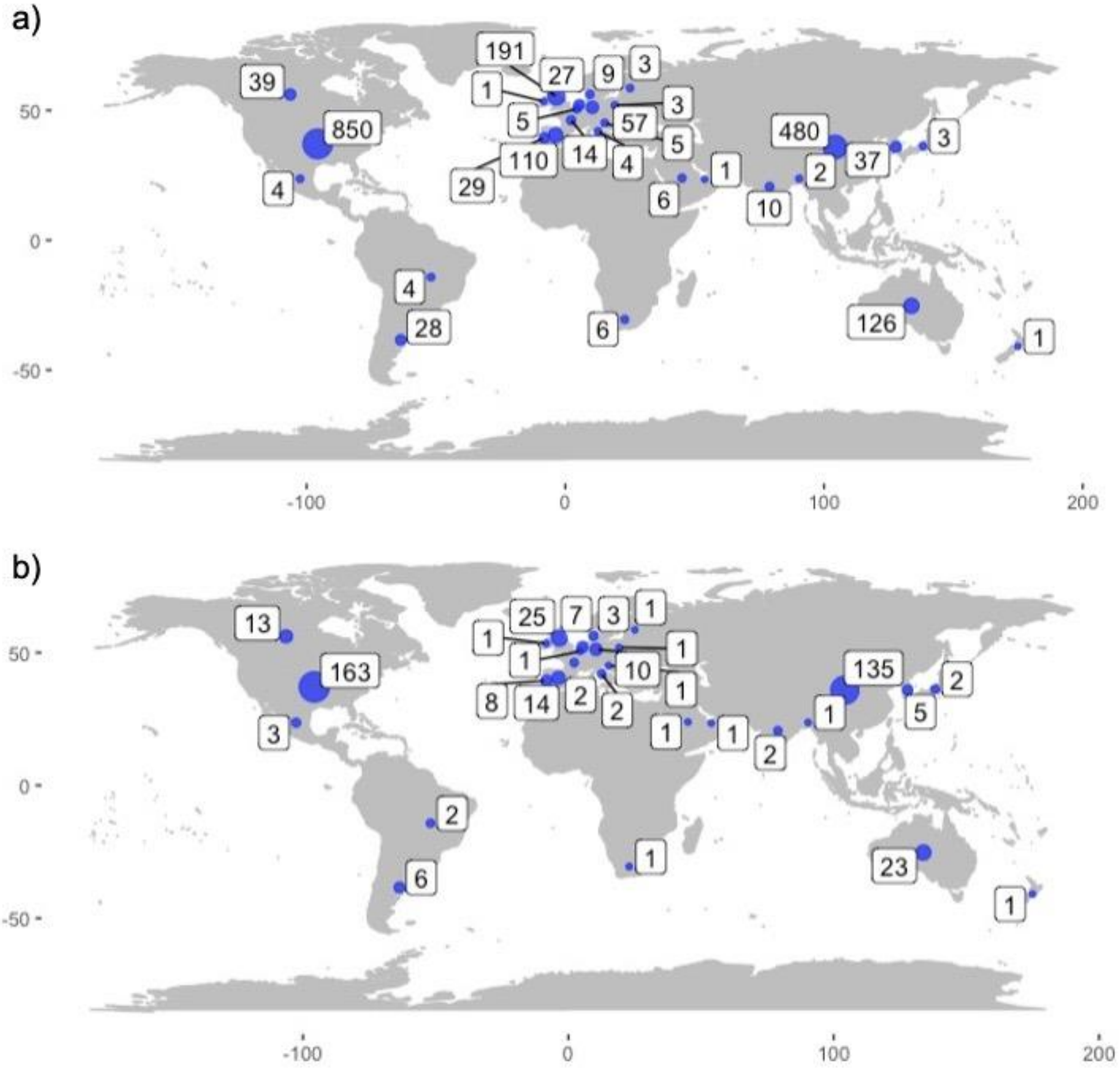

Figure S1 – The number of studies and individual samples extracted from the systematic review indicated by the country of origin. (a) The number of samples collated from each country (n = 2055). A “sample” refers to a distinct condition or contextual settings investigated within a study. (b) The number of relevant studies in each country (n = 435).

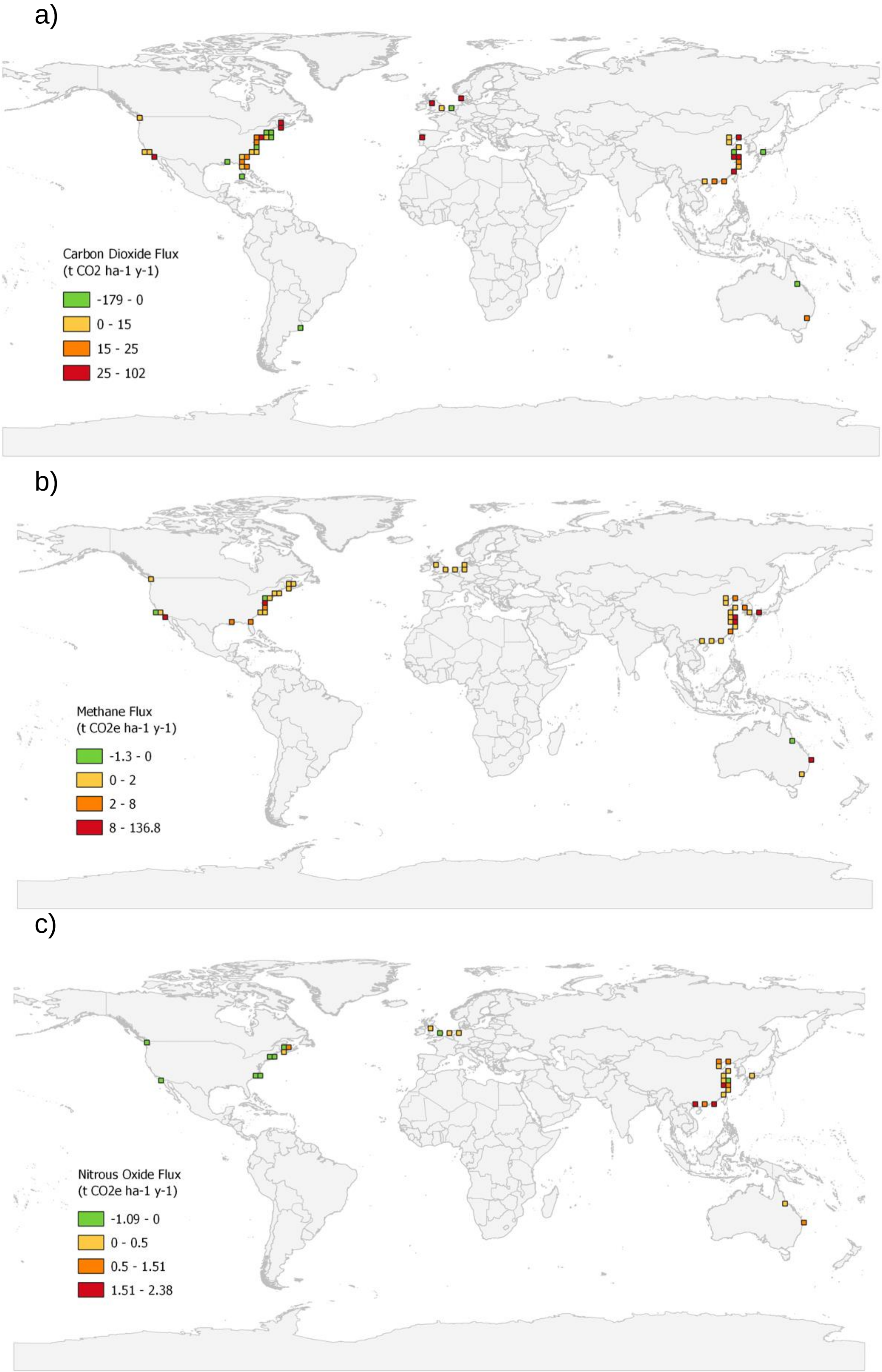

Figure S2 – Pixel maps showing saltmarsh greenhouse gas fluxes of a) carbon dioxide (t CO$_2$ ha^{-1} y^{-1}) b) methane (t CO$_2$e ha^{-1} y^{-1}) and c) nitrous oxide (t CO$_2$e ha^{-1}

y^{-1}). **Map lines delineate study areas and do not necessarily depict accepted national boundaries.**

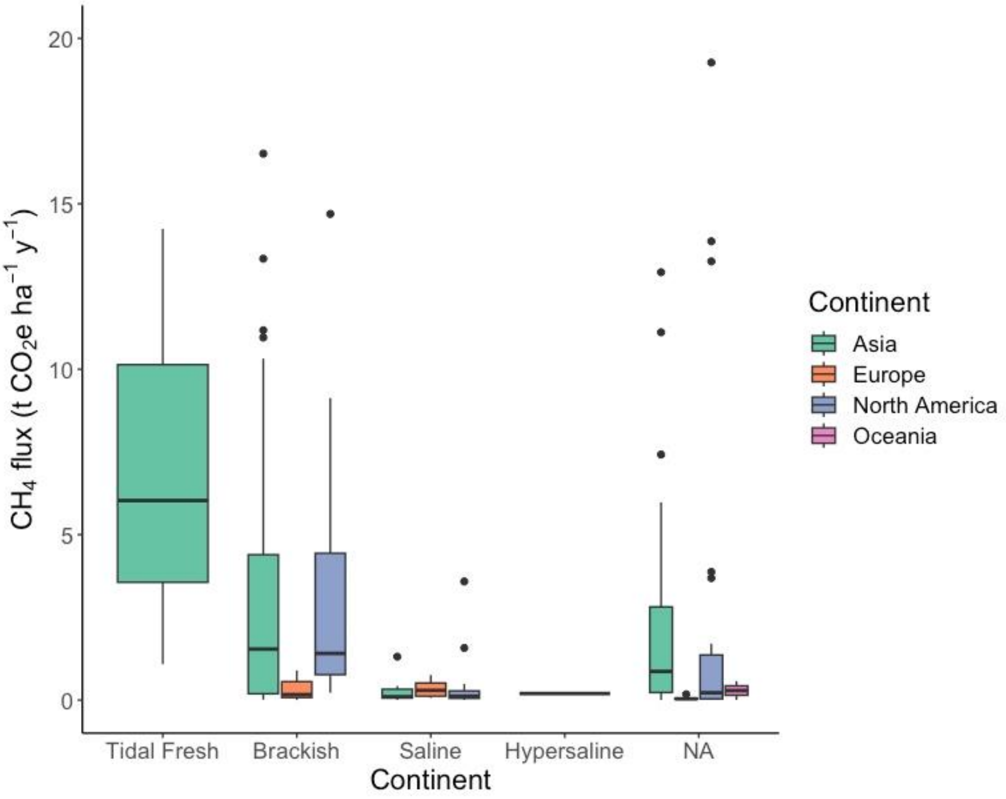

Figure S3 – Distribution of methane flux (t CO_2e ha^{-1} y^{-1}) data by salinity category across 4 different continents (Asia, Europe, North America and Oceania). Central line shows median values, box limits are lower and upper quartile ranges.

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