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RESEARCH ARTICLE

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Blue carbon benefits from global saltmarsh restoration

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Abstract

Coastal saltmarshes are found globally, yet are 25%–50% reduced compared with 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 431 studies to quantify the benefits of saltmarsh restoration to carbon accumulation and greenhouse gas uptake. The results showed global marshes store approximately 1.41–2.44 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} year^{-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 coasts of the USA and Australia particular hotspots for carbon storage. While 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.

KEYWORDS
climate change, coastal wetland, greenhouse gas, marsh creation, organic matter, sequestration

1 | 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 & 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 $year^{-1}$ (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).

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 (Adams et al., 2021; de la Barra et al., 2022; Fairchild et al., 2021; Sharps et al., 2017). In the United States, coastal wetlands were valued at US$23.2 billion $year^{-1}$ for storm protection services alone (Costanza et al., 2008), and saltmarsh services globally are worth Int$1.07 trillion $year^{-1}$ (Davidson et al., 2019, using 2007 'International' $). Historically, saltmarshes were primarily viewed as valuable for land reclamation to accommodate agriculture and urban sprawl (Bu et al., 2015; Gedan et al., 2009). As a result, global marsh areas decreased by 25%–50% (Crooks et al., 2011; Duarte et al., 2008), 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 (Campbell et al., 2022; Lovelock et al., 2017; Macreadie et al., 2013).

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. Shiau et al., 2019; Soileau et al., 2018).

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 (Burden et al., 2019; Garbutt & Wolters, 2008). 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 United Kingdom: carbon accumulation, which was 1.04 t C ha^{-1} $year^{-1}$ in the first 20 years, slowed to 0.65 t C ha^{-1} $year^{-1}$ in later years (Burden et al., 2019). Models resulting from these values suggested approximately 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

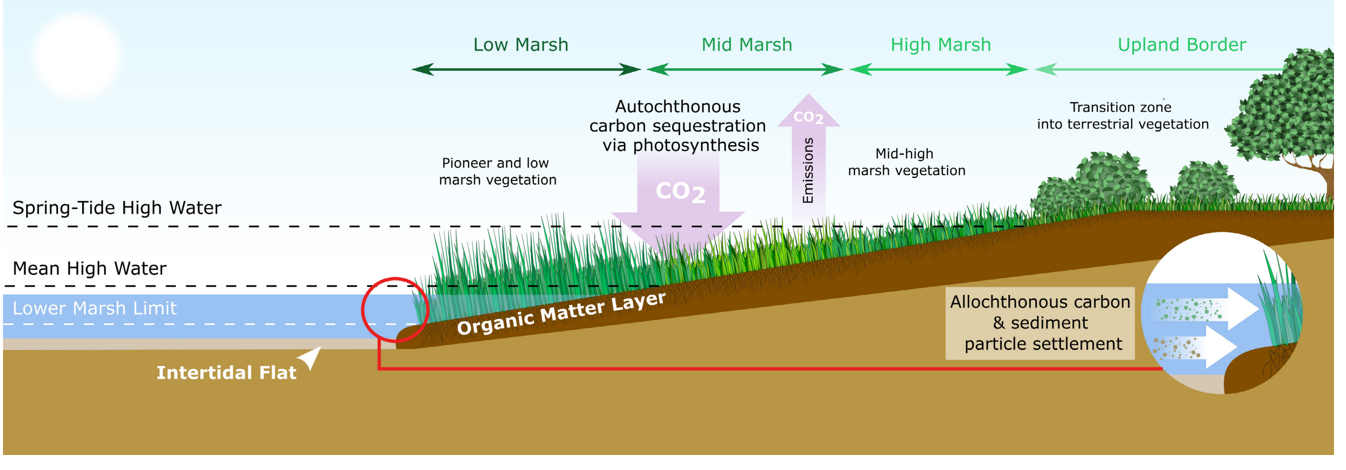

FIGURE 1 Saltmarsh carbon can be generated by the system itself (autochthonous C) or can originate from outside the system (allochthonous C), entering the marsh through passing water and settling out as particulate matter when the vegetation slows down the currents and waves. Carbon sequestration arises 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).

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 & Mitsch, 2016; Li et al., 2021; Wang et al., 2021) or CAR (e.g. Burden et al., 2019; Calvo-Cubero et al., 2014; 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 $144 \pm 6\,\text{g}\,\text{C}\,\text{m}^{-2}\,\text{year}^{-1}$ compared with $88.7 \pm 3.5\,\text{g}\,\text{C}\,\text{m}^{-2}\,\text{year}^{-1}$ 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 431 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 hypothesise 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 | 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 character-
istic* OR driver* OR natural OR restored OR res-
toration 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*"
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The search returned 3874 results from Web of Science and 29,253 from Scopus. Duplicate results were removed, and two 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 (431 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 431 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 431 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 coordinates 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 & 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 431 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} year^{-1} using a 100-year timeframe in accordance with IPCC standard approaches (IPCC, 2014). For studies which gave a carbon (C) stock estimate to <1 m, carbon stock observations were extrapolated to 1 m for IPCC comparability (IPCC, 2014), assuming a linear distribution of carbon in the top 1 m sediment. We expressed the mitigative potential of saltmarshes in units of carbon accumulation (t C ha^{-1} year^{-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:

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

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:

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

where 'depth' was the core sampling depth and 10,000 was the conversion factor from m to ha. The resulting carbon stock values were then extrapolated to 1 m 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; five levels), annual rainfall (continuous), salinity type (categorical; six levels), average annual temperature (continuous), simplified marsh geomorphology (categorical; four levels) and vegetation type (categorical; six 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 versus 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 S2) 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 versus 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 S2). One extremely high and outlying observation (10.4 g cm^{-3}) was removed from the bulk density data set, 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), and data are accessible on the repository Dryad (Mason et al., 2023). Statistically significant relationships were inferred where $p < .05$.

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 gas emissions and uptake. From the net values, we determined the potential global and regional carbon benefit (t CO_2e ha^{-1} year^{-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 1452.84 (733.1–2172.07) km^2 between 2000 and 2019 (Campbell et al., 2022).

3 | 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 29.09 new studies per year in 2012–2022, compared to 3.36 studies per year in 1977–2011 (Figure 2). North American and Asian studies made up 41.5% and 33.6% of the 431 papers included, respectively. There were very few studies from South America and Africa (eight and one 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 eight response variables that were derived from the extracted data, 3623 individual data points were taken for further analysis.

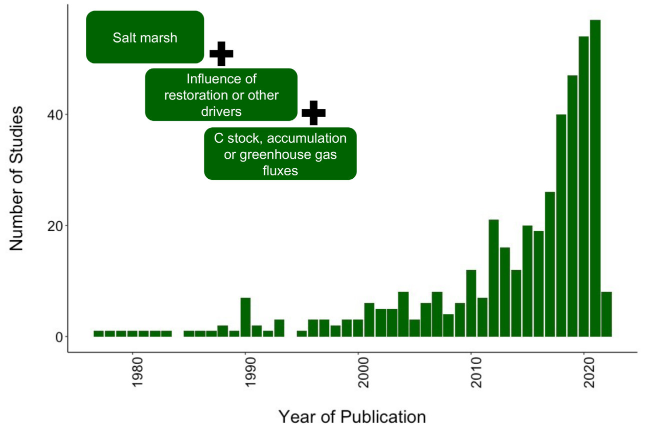

FIGURE 2 Number of relevant studies included in meta-analysis (n = 431) published per year. Text in boxes describes criteria a paper needed to fulfil to be included in the analysis.

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 United Kingdom and the USA (Figure 3b).

3.2 | Natural versus 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

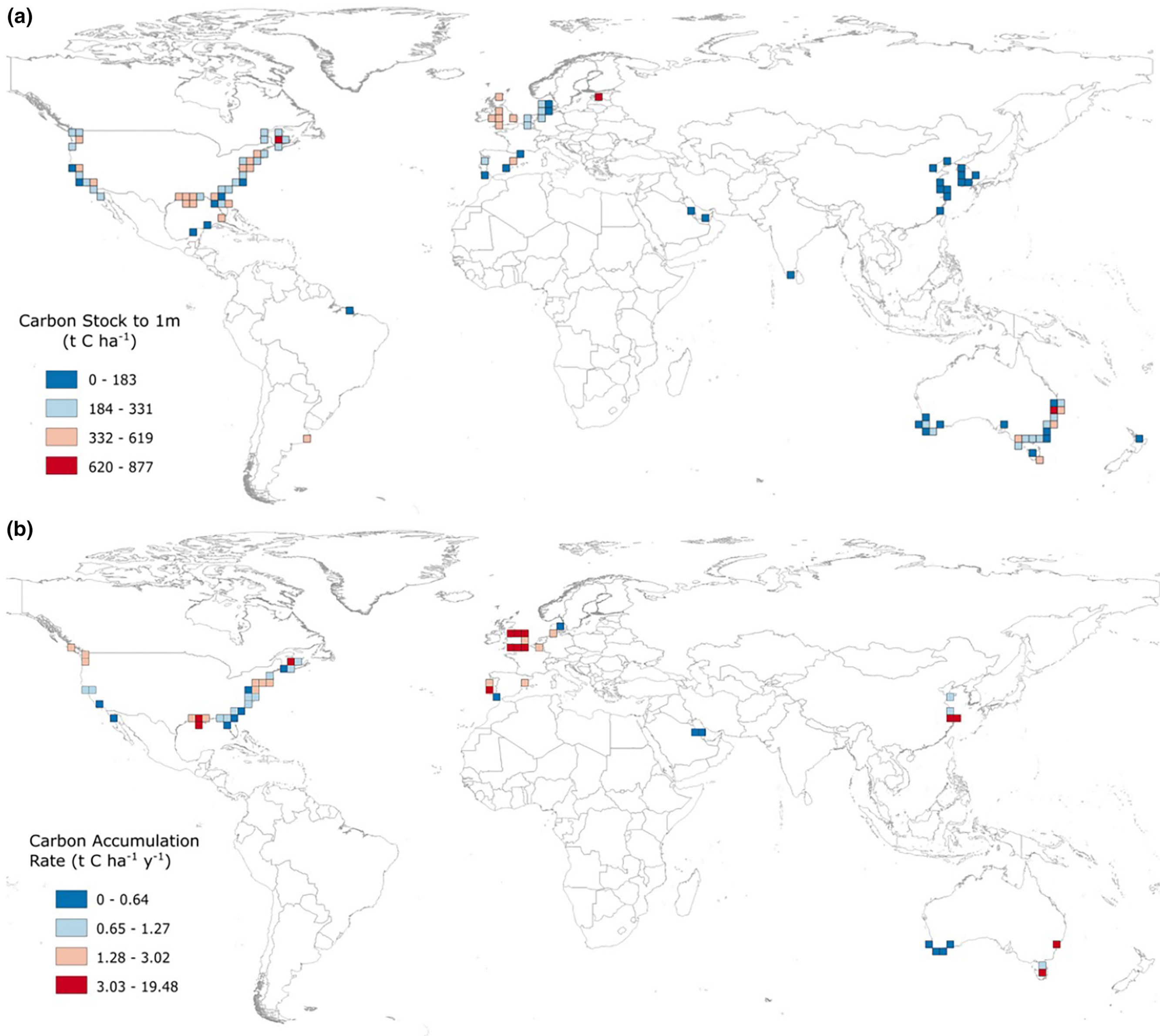

FIGURE 3 Pixel maps of (a) saltmarsh carbon stock to 1 m sediment depth ($t C ha^{-1}$) and (b) saltmarsh carbon accumulation rate ($t C ha^{-1}$ $year^{-1}$) for global regions. Map lines delineate study areas and do not necessarily depict accepted national boundaries.

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).

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 versus 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 ($\chi^2_{18} = 104.22$, $p < .001$). 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: $p < .001$), 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 1 Continental and global mean values (±SD) of carbon and greenhouse gas fluxes for natural and restored marshes.

	% OC	Bulk density ($g\,cm^{-3}$)	C stock ($t\,C\,ha^{-1}$)	C acc. rate ($t\,C\,ha^{-1}\,year^{-1}$)	Net CO_2 flux ($t\,CO_2\,ha^{-1}\,year^{-1}$)	CO_2 respiration ($t\,CO_2\,ha^{-1}\,year^{-1}$)	CH_4 flux ($t\,CO_2e\,ha^{-1}\,year^{-1}$)	N_2O flux ($t\,CO_2e\,ha^{-1}\,year^{-1}$)
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)

Note: Including organic carbon (%OC), bulk density, carbon stock (to 1 m 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 $p < .05$).

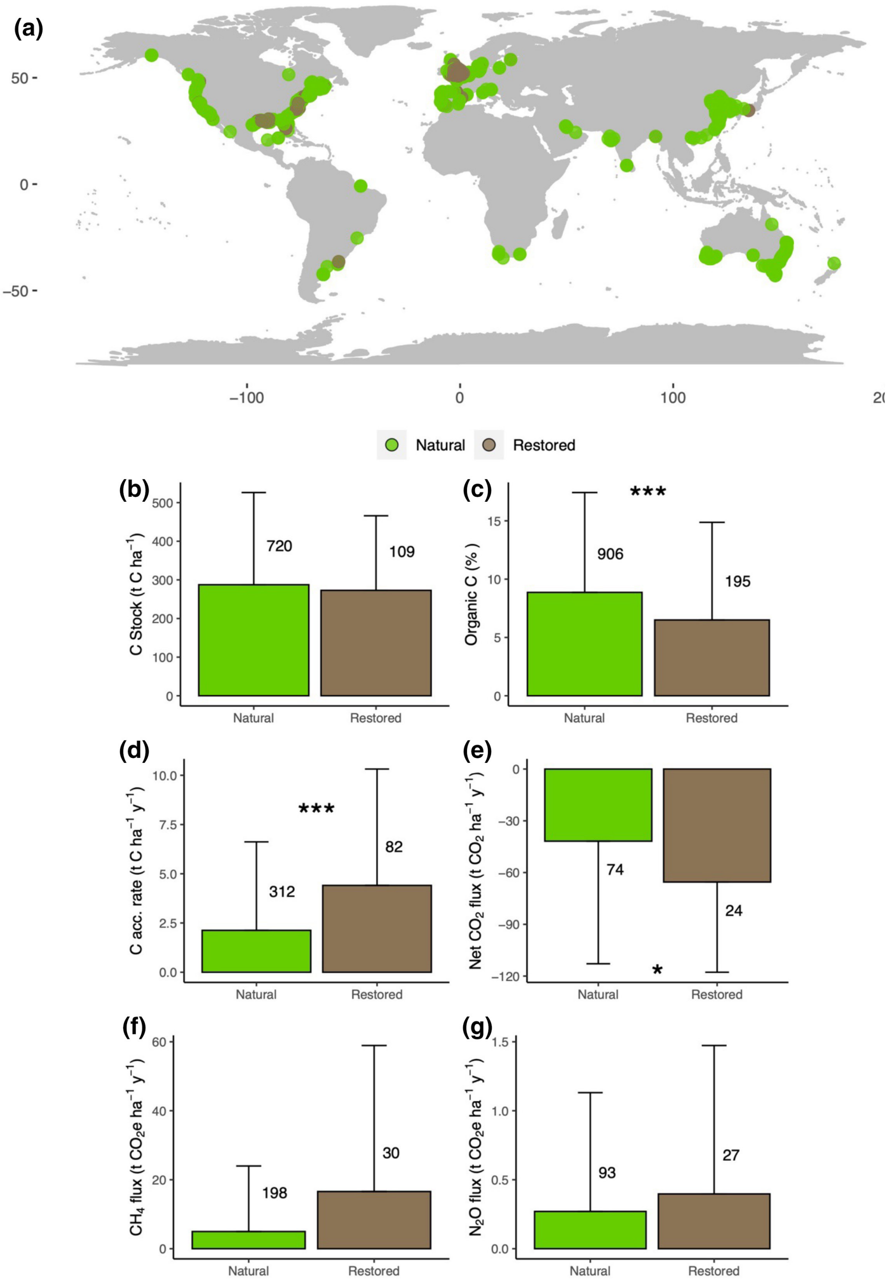

FIGURE 4 (a) Distribution of samples across natural and restored saltmarshes (total $n = 2055$). Global mean values (±SD) of (b) carbon stock, (c) organic carbon (%OC), (d) carbon accumulation rate, (e) net CO_2 flux, (f) CH_4 flux and (g) N_2O flux. Numbers above bars indicate number of samples per mean. * denotes $p < .05$ and *** denotes $p < .001$ (Mann–Whitney *U*-test).

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 S3). Bulk density reduced with marsh age, although the rate of change was very low (Table S3: slope). Bulk density was highest in Asia and Oceania, and low at sites restored by freshwater introduction (Table S3), which was a restoration approach used only in North America and reported by just two 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 S3). The optimal model for net CO_2 flux included continent and rainfall ($R^2c = 0.626$, $\chi^2 = 11.54$, $p = .009$), 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 S3), 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).

TABLE 2 Contextual drivers of spatial variation in soil physical and chemical variables across all saltmarsh sites, as indicated by GLMM models.

								Natural versus 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	<.001	3.25	0.653	1035	4.978	<.001
Bulk density ($g\,cm^{-3}$)	1 + C + Re + (1 | SI)	871.77	0.586	0.258	105.63	6	<.001	−0.346	0.059	688	−5.896	<.001
C stock ($t\,ha^{-1}$)	1 + C + Re + (1 | SI)	−1468.92	0.756	0.232	71.99	5	<.001	9.56	7.82	765	2.821	.005
C accumulation ($t\,ha^{-1}\,year^{-1}$)	1 + C + Re + (1 | SI)	2219.66	0.719	0.110	37.70	9	<.001	−1.21	0.855	370	−1.420	.156
Net CO_2 flux ($t\,CO_2\,ha^{-1}\,year^{-1}$)	1 + Re + S + V + (1 | SI)	−265.77	0.979	0.076	25.85	9	.002	28.74	28.72	55	0.612	.543
CO_2 respiration ($t\,CO_2\,ha^{-1}\,year^{-1}$)	1 + Re + (1 | SI)	1392.56	0.842	0.001	0.130	1	.719	−2.75	7.46	140	−0.368	.713
CH_4 flux ($t\,CO_2e\,ha^{-1}\,year^{-1}$)	1 + R + Re + (1 | SI)	2057.14	0.479	0.029	4.26	2	.119	−4.56	5.14	215	−0.887	.376
N_2O flux ($t\,CO_2e\,ha^{-1}\,year^{-1}$)	1 + Re + T + V + (1 | SI)	308.88	0.599	0.215	17.61	6	.007	−0.438	0.25	108	−1.752	.08

Note: Differences (±SE) in pairwise estimated marginalised means (EMMs) are given between natural and restored saltmarshes.

Abbreviations: C, continent; R, annual rainfall (mm); Re, natural or restored; S, salinity (categorical); SI, study ID; T, average annual temperature (°C); V, vegetation type. Carbon stock was to 1 m soil depth.

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 1.41–2.44 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 1452 km^2 (733–2172 km^2) between 2000 and 2019 (Campbell et al., 2022) 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} $year^{-1}$, 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).

4 | 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} $year^{-1}$. Incorporating greenhouse gas fluxes into global-scale estimates of net carbon accumulation, we show that saltmarsh restoration provides the 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 1.3–1.0 (Alvis & Avison, 2021). Our study provides an up-to-date blue carbon estimate of 1.41–2.44 Pg stored in the top 1 m of saltmarsh sediment globally, a higher quantity than recent estimates of 1.35 Pg (Macreadie et al., 2021) and 1.37 Pg (Temmink

TABLE 3 Contextual drivers of spatial variation in the % organic carbon (%OC), bulk density, carbon stock (to 1 m), carbon accumulation rate and net CO_2 flux of restored marshes, as indicated by GLMM models.

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	.039
Bulk density (g cm^{-3})	1 + RA + A + C + (1 | SI)	−9.62	0.883	0.631	47.20	9	<.001
C stock (t C ha^{-1})	1 + A + T + V + (1 | SI)	1337.40	0.895	0.360	26.66	6	<.001
C accumulation (t C ha^{-1} year^{-1})	1 + (1 | SI)	480.08	0.866	0.000	NA	NA	NA
Net CO_2 flux (t CO_2e ha^{-1} year^{-1})	1 + C + R + (1 | SI)	252.97	0.626	0.566	11.54	3	.009

Note: Significant model fit was found for all response variables except for accumulation.

Abbreviations: A, marsh age; C, continent; R, annual rainfall (mm); RA, restoration approach; S, salinity (categorical); SI, study ID; T, average annual temperature (°C); V, vegetation type.

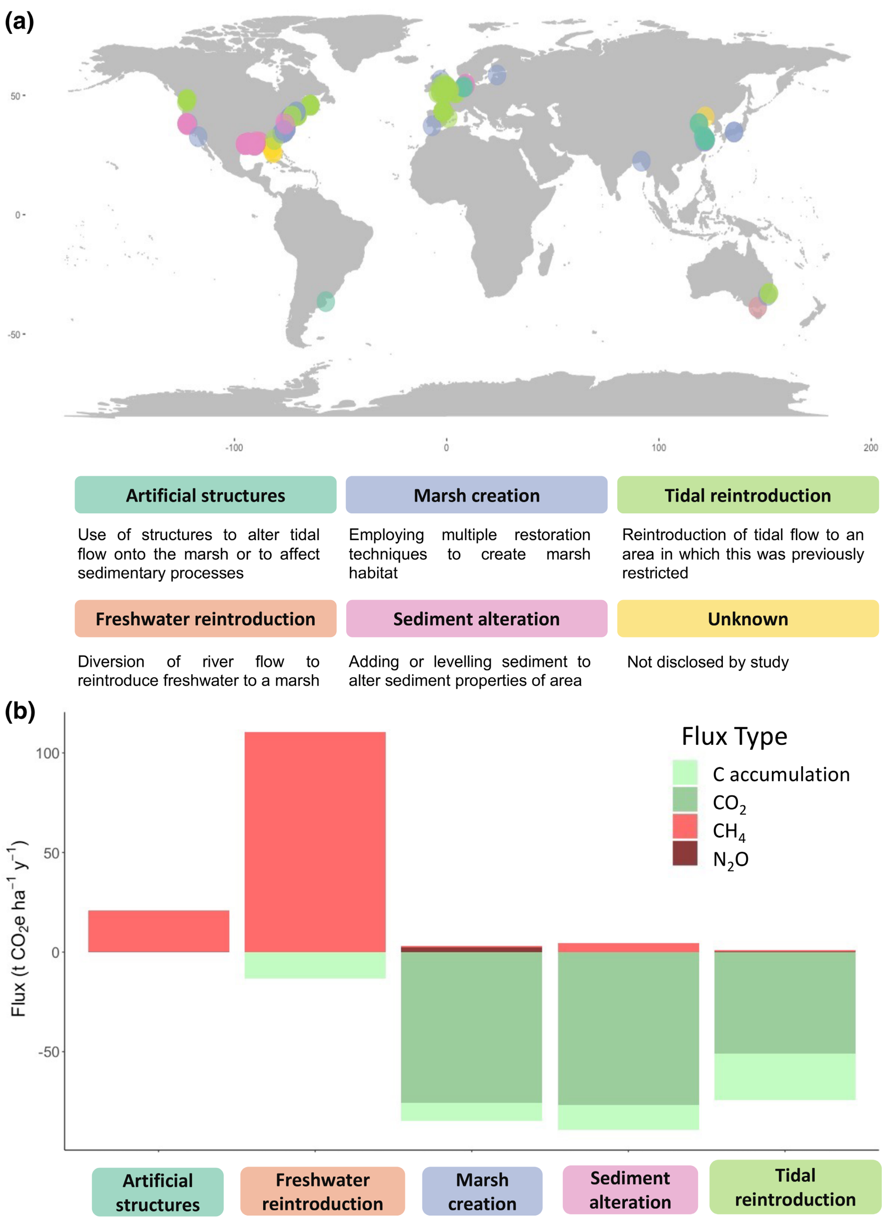

FIGURE 5 (a) Distribution of marsh restoration approaches used by studies (total *n* = 298). (b) Means of soil and flux variables per restoration approach, t CO_2e ha^{-1} year^{-1}. Values above 0 represent emissions (red), values below 0 show uptake (green). Note a lack of carbon accumulation data for artificial structure sites. More detailed descriptions of restoration approach can be found in Table S2.

et al., 2022), but still lower than recent estimates of total carbon stock for mangroves (7.13 Pg) and seagrasses (3.58 Pg) (Lovelock & Reef, 2020). For IPCC comparability (IPCC, 2014), the present study extrapolated original observations of carbon stock to 1 m 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

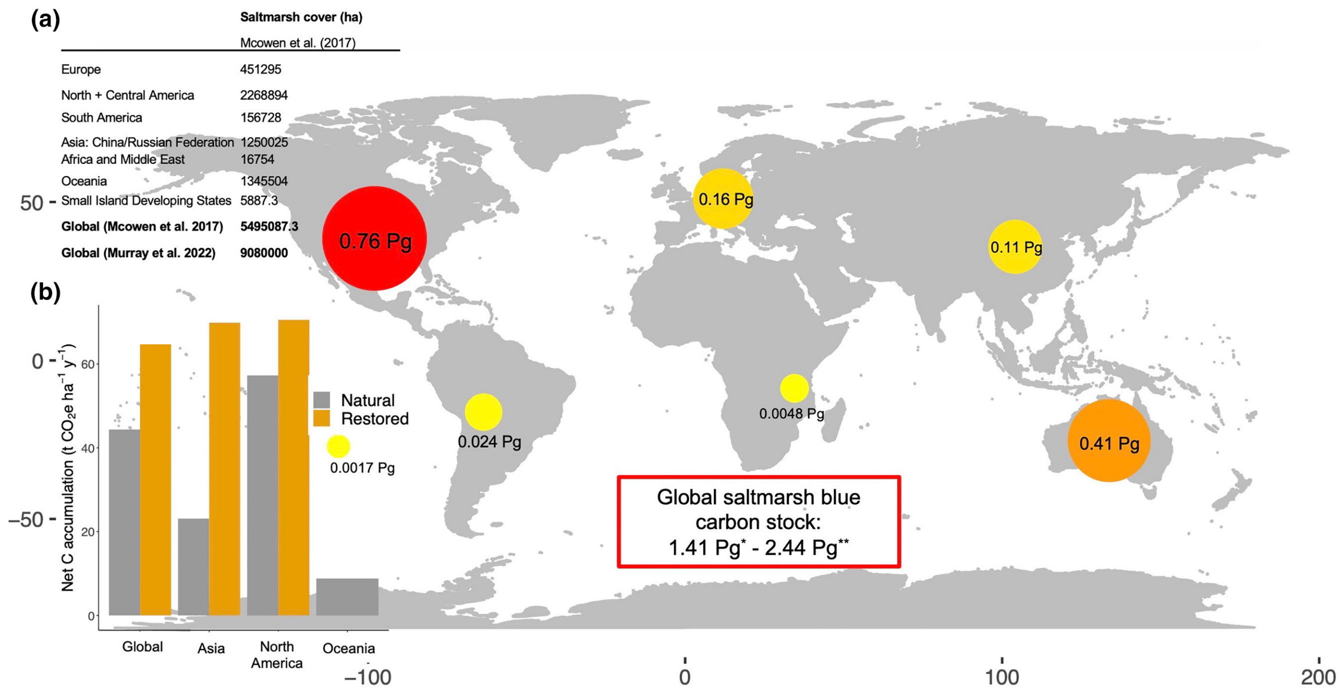

FIGURE 6 Estimated total saltmarsh blue carbon stock per continent to 1 m depth. Estimates were based on the marsh area coverage of Mcowen et al. (2017), Murray et al. (2022) and Worthington et al. (2023) listed in table (a) (units: ha). (b) The average net carbon accumulation rates (accounting for greenhouse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

of studies. Our estimate is based on a substantially higher number of published studies compared with previous studies (e.g. Ouyang & Lee, 2014; Temmink et al., 2022) and used the most recent saltmarsh coverage estimates (Mcowen et al., 2017; Murray et al., 2022; Worthington et al., 2023). 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 (Gulliver et al., 2020; Macreadie et al., 2017). 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 2015; 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 six mid-USA states could be lost with 1.2 m 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 year^{-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 & 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 & 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 this was 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 (Needelman et al., 2018; Poffenbarger et al., 2011)—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 & 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 (Adams et al., 2021; Barbier et al., 2011).

Bundled socio-ecological gains through ecosystem-service provisioning are generally ensured by marsh restoration (Barbier et al., 2011; Sánchez-Arcilla et al., 2022; Stewart-Sinclair et al., 2020), although the choice of restoration can drive trade-offs between benefits. For instance, while 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 & 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. Barbier et al., 2011; Mossman et al., 2022), but it can also result in trade-offs of other ecosystem services, depending on design (Auerswald et al., 2019; Loon-Steensma and Vellinga 2013). While trade-offs from flood protection projects are relatively well-studied (see e.g. van Loon-Steensma & Vellinga, 2013), insight into trade-offs resulting from projects targeting saltmarsh carbon accumulation 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 synthesised 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 United Kingdom were successfully restored, an additional 0.14 Mt C year^{-1} would be accumulated, 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 & 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

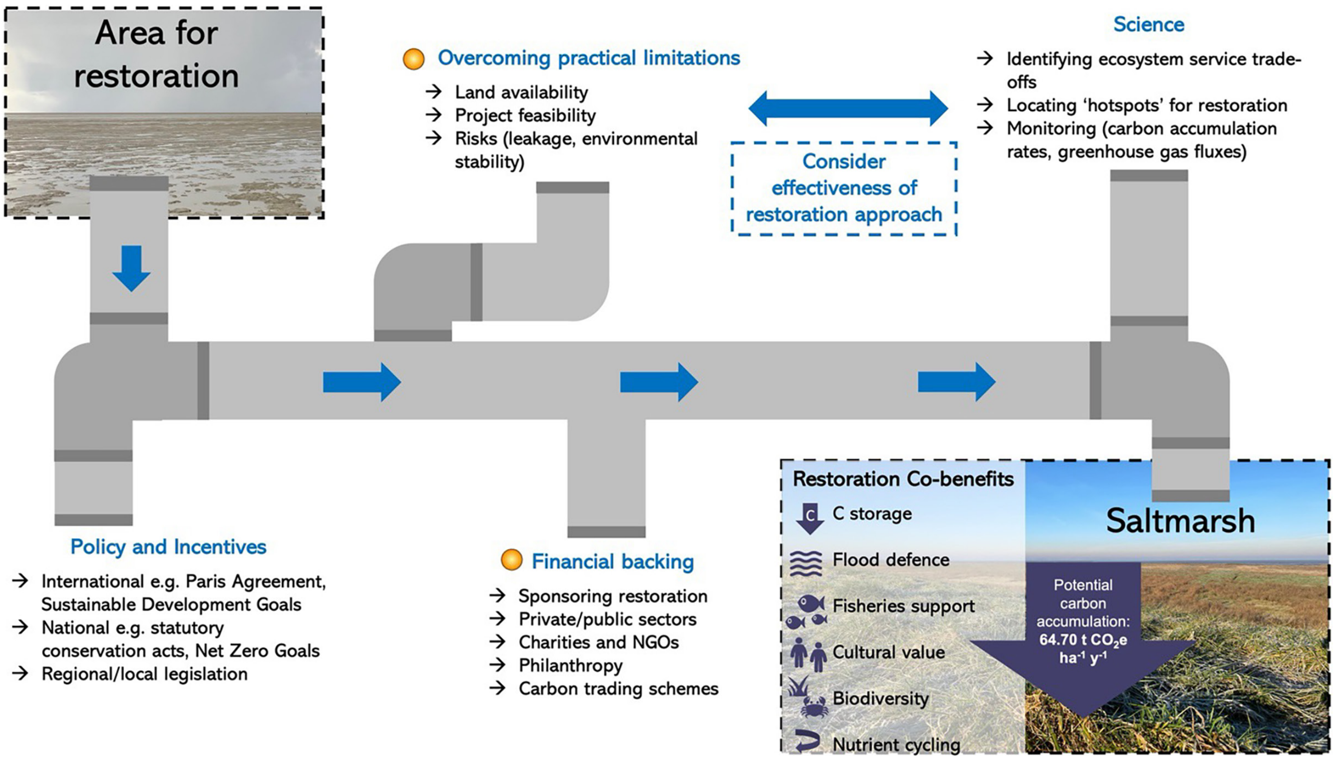

FIGURE 7 Key processes underpinning the transformation of restorable areas into saltmarshes, with multiple societal co-benefits, including carbon storage. Major current challenges which may limit the upscaling of marsh restoration are highlighted in yellow.

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. Sánchez-Arcilla et al., 2022; Stewart-Sinclair et al., 2020; 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 generally 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 & 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 5–30 years, for 20%–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 (Adams et al., 2021; Lillebø et al., 2010; Wang et al., 2022).

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.

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CONFLICT OF INTEREST STATEMENT

The authors declare no competing financial interests.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in Dryad at https://doi.org/10.5061/dryad.pc866t1vp.

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SUPPORTING INFORMATION

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