UK Centre for Ecology & Hydrology

Saltmarsh Blue Carbon in UK and NW Europe - evidence synthesis for a UK Saltmarsh Carbon Code

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Table of Contents

Executive summary

This Initial Report describes the findings of a systematic literature review to synthesise data for developing the metrics of a United Kingdom (UK) Saltmarsh Carbon Code. The review targeted published data on the key drivers of variation in carbon stock, sequestration and greenhouse gas (CO_2, CH_4 and N_2O) fluxes for natural as well as restored saltmarsh systems in the UK.

Saltmarshes, mangrove forests and seagrass beds make up the three ecosystems largely responsible for 'blue' carbon sequestration, or carbon stored by the marine environment. In the UK, saltmarshes have been identified as showing widespread potential to offset carbon emissions. A recent CEFAS paper (Parker *et al.* 2020) reported an average carbon sequestration rate of 118.5 g C m^{-2} y^{-1} (or 4.34 t CO_2e ha^{-1} y^{-1}) for natural marshes in the UK, indicating that conservation and restoration of saltmarsh habitats may be an effective route for increasing carbon storage. There is increasing interest in a voluntary carbon market for carbon sequestered as a result of restoration of UK saltmarshes. A project to investigate the feasibility of developing a UK Saltmarsh Code was launched in 2021 to look into the applicability of existing standards for tidal wetland restoration to the UK and evaluate evidence that could be used to facilitate measurement, reporting and verification of climate change mitigation benefits from saltmarsh restoration.

The systematic review aimed to identify the key environmental and biological variables that best predicted carbon sequestration rates at UK saltmarsh sites. Carbon and greenhouse gas fluxes of restored marshes were compared to those of natural marshes, taking into consideration also the age of restoration. A geographical constraint, centred on the British Isles and extending onto the most adjacent European coast, was set for the distribution of studies from which data was to be extracted. This was to ensure the bio-environmental context was relevant to UK marsh settings. A literature search was conducted on the 3rd November 2021 to compile studies with data relevant to the above criteria. A total of 3844 potential studies were screened for relevance, eventually yielding a list of 35 papers, from which data were extracted and analysed.

A limited amount of data was available, particularly with regards to understanding which environmental characteristics best explain the spatial variation in rates of carbon sequestration and greenhouse gas fluxes. An average carbon sequestration rate of 8.2 ± 5.94 t CO2e ha^{-1} y^{-1} was found for natural marshes. This compared to 13.3 ± 15.0 t CO_2e ha^{-1} y^{-1} for restored marshes. Since most restored marshes were relatively newly restored (< 20 years since restoration), the higher rate of carbon capture by restored marshes is likely due to rapid sediment accumulation, which is expected to slow over time. The only flux that differed statistically between natural and restored saltmarsh was nitrous oxide (N_2O) flux; it was higher in restored (0.6 ± 0.7 t CO_2e ha-

^{1} y^{-1}) than natural marshes (-0.1 ± 0.3 t CO_2e ha^{-1} y^{-1}). N_2O has a 298 times greater global warming potential (GWP) than CO_2. Thus, the N_2O flux observations illustrate the importance of considering both intake of carbon and emission of greenhouse gases when calculating net carbon sequestration of restored marsh area.

Few studies quantified carbon stock to 1m soil depth in line with the IPCC; most had observations to less than 0.3m. Our analyses explored carbon stock responses both with and without extrapolating original estimates to 1m depth. Of the environmental variables tested (salinity, pH, elevation, marsh type and latitude), only pH showed a significant relationship with carbon or greenhouse gas flux variables. Saltmarsh carbon stock was significantly positively correlated with sediment pH ($F_{1,32}$=4.74; P=0.037; R^2=0.13), although the relationship was reversed when saltmarsh carbon stock was extrapolated to a depth of 1m. More variables than pH are expected to influence carbon or greenhouse gas flux and the lack of statistically significant relationships with other contextual drivers is undoubtedly due to insufficient data on the physical characteristics of studied saltmarshes for any substantial analysis.

Data gathering and reporting was very inconsistent across studies. This inconsistency in combination with scarcity of data shows that a standard methodology is required for monitoring saltmarshes and newly restored marshes in particular. Standards should incorporate sampling carbon stock to the IPCC recommended depth of 1m and reporting carbon and greenhouse gas flux in standardised units (t CO_2e ha^{-1} y^{-1}) to ensure comparability between reported results.

Starting in early 2022, we will extend the present study into a global systematic review, to yield a more substantial dataset and larger gradients in key environmental variables that will facilitate more sophisticated analyses. As part of that, we will address an additional question for which the present systematic review revealed no data: how much of the sequestered carbon in restored saltmarshes is ‘additional’?

1. Introduction

This report describes the results of a systematic review and evidence synthesis conducted for Task 1.1 of the UK Saltmarsh Carbon Code:

Task 1.1: Conduct Rapid Evidence Syntheses (including meta-analysis where possible) of effects of restoration methods on carbon sequestration, drawing on peer-reviewed and grey literature, and existing projects in the UK and comparable countries.

Data were compiled to address the need to identify the key environmental and biological variables that best predict carbon sequestration rates at UK saltmarsh sites. In order to compare carbon processes between natural and restored saltmarshes, we investigated how much carbon is captured and/or released by restored saltmarsh and how this changed with marsh typology and over time. Four primary research questions were addressed:

1. What factors control carbon and greenhouse gas fluxes in natural and restored saltmarshes?
2. How much of the carbon in the site 'counts' in terms of additionality?
3. How does the C sequestration rate of a restored marsh compare over time to a natural marsh?
4. What are the current standardised methods for monitoring saltmarsh carbon and greenhouse gas fluxes?

Saltmarshes, alongside seagrass meadows and mangrove forests, have been identified as key areas for carbon sequestration, with 50% all marine sediment carbon burial accounted for by coastal ecosystems (IUCN, 2017). Despite this, 50% of global saltmarsh areas have already been lost or degraded (Barbier *et al.* 2011). Restoration of saltmarsh ecosystems provides a significant potential for increasing coastal carbon sequestration and developing a voluntary carbon trading scheme.

Alongside the potential for sequestering carbon, saltmarshes also exhibit dynamic greenhouse gas fluxes, the balance of which could impinge on the greenhouse gas warming benefit of the ecosystem (McTigue *et al.* 2021). Quantifying the fluxes of greenhouse gases such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) alongside observations of carbon stocks and sequestration rates is therefore important in considering the role of saltmarshes in climate change mitigation.

The present review was geographically constrained to saltmarshes within the British Isles, as well as parts of Northern Europe that fall within the same saltmarsh biogeographical zones as those encountered in the UK (northern 2d, 2bs and 2bn in Figure 1). This geographical constraint ensured the collected metadata had relevance to a UK context and concerned sites with similar characteristic and natural communities, and thus, comparable carbon storage behaviour. Tropical marshes and temperate marshes from outside of this geographic region were regarded as incomparable marsh typologies and were not included. Within the UK (including northern zone 2d), zone 2bs and zone 2bn, restored marshes were contrasted to natural marshes, and the influence of environmental contextual setting on carbon sequestration and greenhouse gas fluxes were assessed (example contextual variables: salinity, sediment type, marsh elevation and vegetation community).

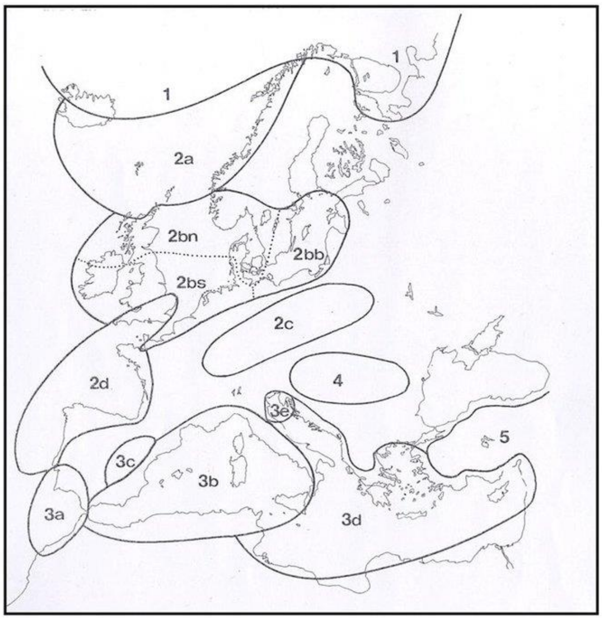

Figure 1. *Biogeographic regions of European salt marshes (Gehu and Rivas-Martinez 1983)*

The methods and geographical distribution of studies included in the systematic review are summarised in Sections 2.0 and 3.0. Carbon and greenhouse gas flux (CGHGF) of restored marshes are compared to those of natural marshes in Sections 3.0, while section 4.0 considers the influence of restored site age on carbon responses. The report used insight from an analysis of key contextual indicators of rates of CGHGF (Section 6.0) to recommend best practices for monitoring of restored marshes, focussing on standardised sampling techniques and units. Finally, we discuss study limitations and caveats to our findings, and highlight data and knowledge-gaps in the literature, in particular those pertaining to a shortfall of environmental data for restored marshes.

2. Methodology

2.1 Study design

The study employed a systematic review to synthesise published data on saltmarsh carbon stock, sequestration rates and greenhouse gas fluxes, and the environmental and biological contextual variables that best accounted for variation in these. The study set out to document the effect of restoration on carbon and greenhouse gas responses. In the event that publications did not include before-to-after-restoration contrasts to facilitate the direct quantification of restoration effect sizes, we incorporated contrasts of data collected from restored and natural saltmarshes within the study region, to compensate for the omission of before/after observations. To account for the influence of contextual setting on measured responses, literature data on site bio-physical context were collated. These contextual variables were expected to be important predictors of variation in CGHGF. The systematic review was conducted using Web of Science, with no temporal limits to the studies included.

2.2 Literature search and systematic review

The systematic literature search was conducted on the 3rd November 2021, using the standard methodology described by Pullin and Stewart (2006) and O'Dea *et al.* (2021). The search string was scoped for relevance of search hits using 6 pre-identified key studies that we identified as containing particularly relevant data. The final string (below), returned 3844 hits.

Two additional studies were included based on suggestions from the *Saltmarsh Code* consortium: Mossman *et al.* (in press) and ABPmer (2021). Studies were then screened by title, abstract and full-text for relevance. We sought papers with original-research carbon or greenhouse gas observational data from natural or restored saltmarsh sites within our focal geographical region (Figure 1). Studies considering saltmarshes outside our geographic area (zones 2bn and 2bs, plus northern 2d) were excluded, as well as studies considering other wetland ecosystems such as freshwater marshes and peatlands. Studies considering nutrient flux without a gaseous element were excluded. Modelled data were not included, unless based on field measurements of a marsh within the region. Following screening, 35 studies remained, from which data were extracted from the text, tables and figures, using Automeris WebPlotDigitizer Version 4.4 (Rohatgi 2020).

factor* OR variables* OR conditions* OR characteristics* OR drivers* OR restoration OR “managed realignment” OR “managed retreat” OR “regulated tidal exchange” OR RTE* OR temperature* OR sediment* OR vegetation*

AND

carbon OR CO_2 OR nitrous* OR N_2O OR methane OR CH_4 OR “greenhouse gas” OR “GHG*” OR “greenhouse gases” OR gas OR gases OR flux OR fluxes OR storage OR sequestration* OR budget* OR sink* OR removal OR accretion OR accret* OR exchange* OR accumulation OR erosion OR stock* OR burial OR re-created OR “organic matter” OR “organic content” OR DOM OR DOC OR SOM

AND

saltmarsh OR saltmarshes OR marsh OR marshes

AND

UK OR United Kingdom OR England OR Wales OR Welsh OR Scotland OR Scottish OR “Northern Ireland” OR Britain OR British OR Ireland OR Irish OR 2bn OR 2bs OR Germany OR German OR France OR French OR Netherlands OR Dutch OR Denmark OR Danish OR Norway OR Norwegian OR temperate

2.3 Data conversion and standardisation

Standardisation of data was required, given considerable variation in the observational approaches and data summarising of published papers. Following data extraction, response variable data (C stock, C sequestration and greenhouse gas flux) were standardised into common units of t CO_2e ha^{-1} and t CO_2e ha^{-1} y^{-1} based on 100-year global warming potential (GWP) values (IPCC, 2014). Published observations of carbon stock were done to variable depth into the soil. To overcome this issue, we used two approaches: (i) the original stock observations were used regardless of sampling depth (but categorised the observations into soil depth categories by cm depth: 0-25, 25-50, 50-75, 75-100, >100), and (ii) we extrapolated original observations down to 1m depth (for example, values given to a 10cm depth were multiplied by 10). Subsequent analyses considered both of these two datasets. Carbon accumulation, burial and sequestration were grouped together as C sequestration variables for the purpose of analysis but were categorised by which of these the data were originally presented as. Predictor variables including salinity and vegetation type were also standardised into common units or categories (PSU and NVC community, respectively).

A total of 178 sampling sites were analysed across the 35 studies included. Data were explored in terms of geographic distribution and spatial variations in C stock, C sequestration and greenhouse gas flux, as well as changes to restored saltmarsh over time.

2.4 Statistical analyses

We aimed to understand the effects of five potential predictor variables on our six response variables (C stock, C stock 1m, C sequestration, CO_2 flux, CH_4 flux, and N_2O flux). These five predictor variables were marsh type (two categories: natural vs restored marshes), elevation (a categorical variable expressed as 'low', 'mid' or 'high', based on the elevation reported by the authors of each study), salinity (a continuous variable expressed in PSU), pH (a continuous variable expressed on the pH scale) and latitude (a continuous variable expressed in decimal degrees). Our original plan was to start with a global linear model for each response variable, containing all predictor variables, and then using information theoretic-based model selection to identify the predictor variables that best explained the variance in each response variable (Burnham *et al*. 2011). However, initial exploration of the data indicated that the data were too sparse to facilitate such an approach. As an alternative way to understanding the variance in our six response variables, we instead used linear models with Gaussian error structures to independently test the relationships between each of the six response variables and each of the five predictor variables. All models were run using R version 3.6.3 (R Core Team 2020), with statistically significant relationships inferred where $P < 0.05$. Furthermore, R^2 values were used to assess the proportion of the variance in the response variable that was explained by the predictor variable. To ensure that test assumptions were met, model residuals were assessed visually using the *performance* package (Lüdecke *et al*. 2020) and the *plot()* function in base R. To ensure that model assumptions were met, carbon stock and sequestration data were log_{10}-transformed, whilst in each case the flux data for CO_2, CH_4 and N_2O were rescaled between 0 and 1, and square-root-transformed. In addition, data points were removed if overleveraged, i.e. where Cook's distance >1. A linear regression was also conducted to investigate the relationship between time since restoration of restored saltmarsh with C stock. ANOVA tests, followed by post-hoc Tukey tests, were used to test for differences between C stock estimates made for different depth categories.

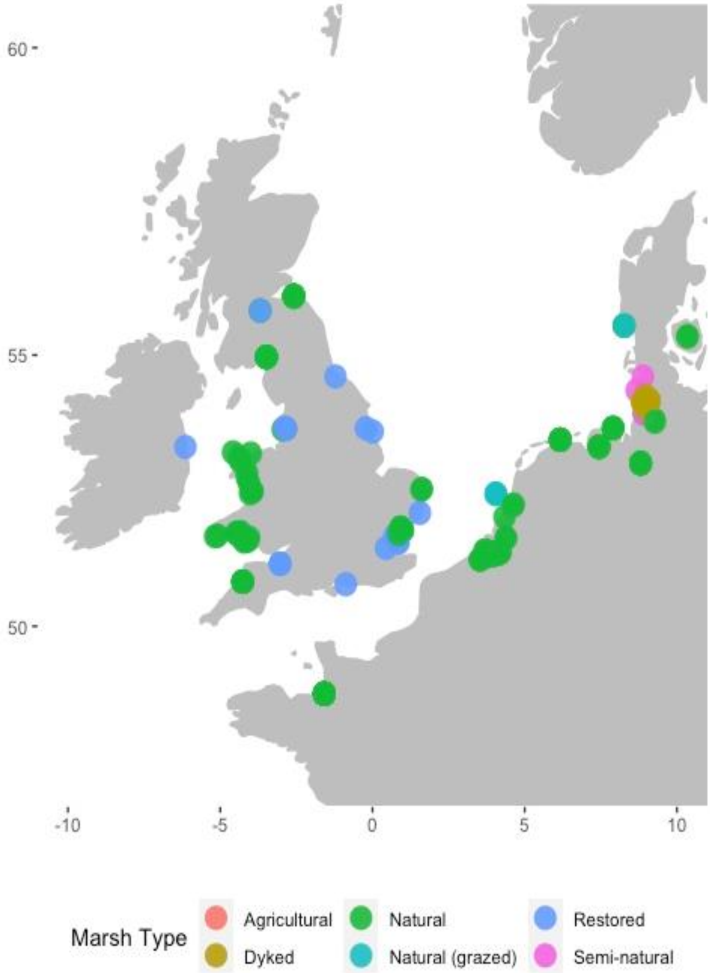

Figure 2. *Observations included in the final dataset (n = 178) mapped by location of the saltmarsh sampling site. Colour represents the type of marsh sampled in terms of human influence or restoration effort*

3. Geographical distribution of observations

Across 35 studies used in the final analysis, 178 study sites were included, with 152 natural marshes and 28 restored marshes sampled (**Error! Reference source not found.**). Restored marshes included semi-natural (partially restored) marsh types, while natural included any marsh where no restoration techniques had been applied.

There was a total of 69 observations for C stock, which was the most frequently reported variable (Figure 3). Only 2.9% these observations were from restored saltmarshes, in contrast to C sequestration rate (Figure 5a), where 80% observations were reported from restored sites (total number of observations = 25).

The highest C stock estimates were seen in the northwest UK (Figure 3). However, there was a discrepancy with the depth at which carbon stock was recorded, with depths ranging from 0.1m to 1.4m. C stock was found to be statistically different depending on the depth to which the sample was taken (ANOVA, $F_{4,64} = 35.7$, $p < 0.001$). Every depth category had significantly different C stocks, except for between 75-100 and >100, 0-25 and 25-50, and 25-50 and 50-75 (Tukey test, $p = 0.41$, $p = 0.31$ and $p = 0.059$ respectively). This indicated that within the data gathered, C stock was fairly consistent in the first 50cm of sediment. C stock values were also extrapolated to a depth of 1m to reduce the influence of sampling depth on the data and to comply with the IPCC (2014) recommended sampling depth of 1m. Extrapolation does, however, introduce the assumption of constant carbon distribution with depth (up to 1m), which may not be the case in many saltmarshes. Indeed, once extrapolated, the mean C stock to 1m depth for natural saltmarsh was 1693.3 ± 3127.1 t CO_2e ha^{-1}, which is around 7 times higher than estimates in a recent CEFAS review (Parker *et al.* 2020). This suggests that extrapolating to 1m introduced a high degree of uncertainty in the data and that the 1m observations should be considered with caution. It also emphasises the need for C stock cores to be taken to a standard depth of 1m when sampling.

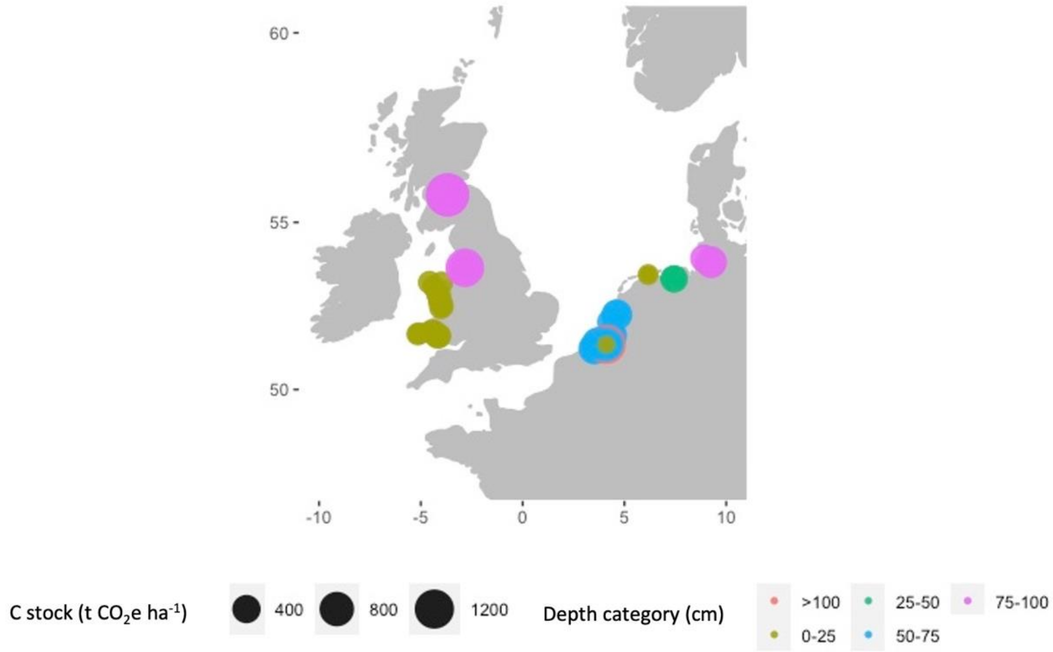

Figure 3. *Map of carbon stock observations (n = 69) in Northern European saltmarshes. Point size corresponds to size of carbon stock (t CO_2e ha^{-1}), colour represents the depth category (cm) of the depth to which carbon stock was estimated.*

For greenhouse gas fluxes (Figure 5b,c,d), CH_4 was the most widely reported, with a total of 26 observations. Eighteen observations were reported for N_2O flux, while there were only 6 observations for CO_2 flux, potentially since CO_2 may have been included in carbon sequestration budgets rather than directly reported.

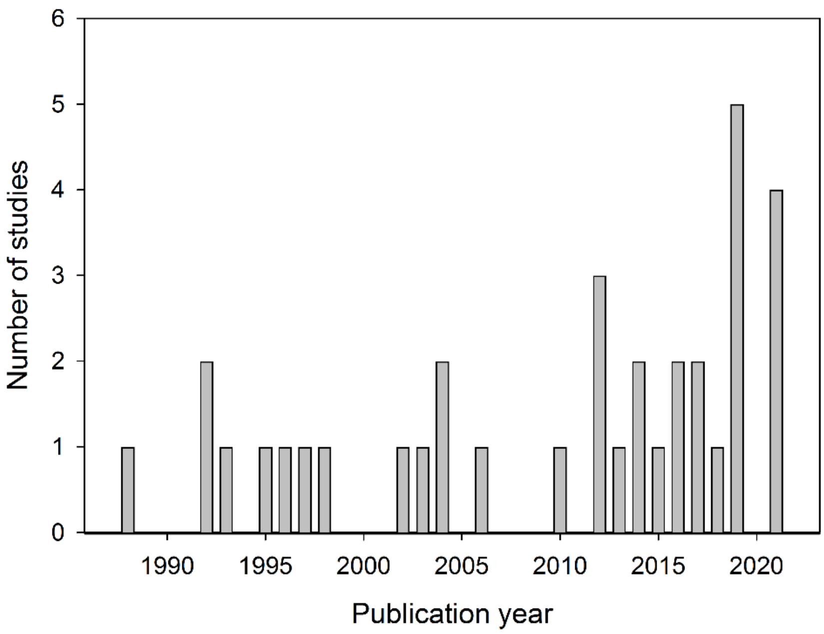

Figure 4. *The number of studies pertaining to carbon stock or sequestration and greenhouse gas flux in saltmarshes published each year, from a total of 35 studies included in the data-analysis.*

Relevant publications reporting CGHGF in saltmarshes within the study region have fluctuated in number since 1988, when the first report used in this analysis was published (Figure 4). Despite these fluctuations, relatively high numbers of studies in 2019 (n = 5) and 2021 (n = 4) suggest that there has been a recent increase in research within this area. Insufficient data were available from the study region to perform an analysis to investigate how much carbon in a saltmarsh site ‘counts’ as additional. A subsequent global-scale systematic review (January to March 2021) is likely to solicit data that might inform on this issue.

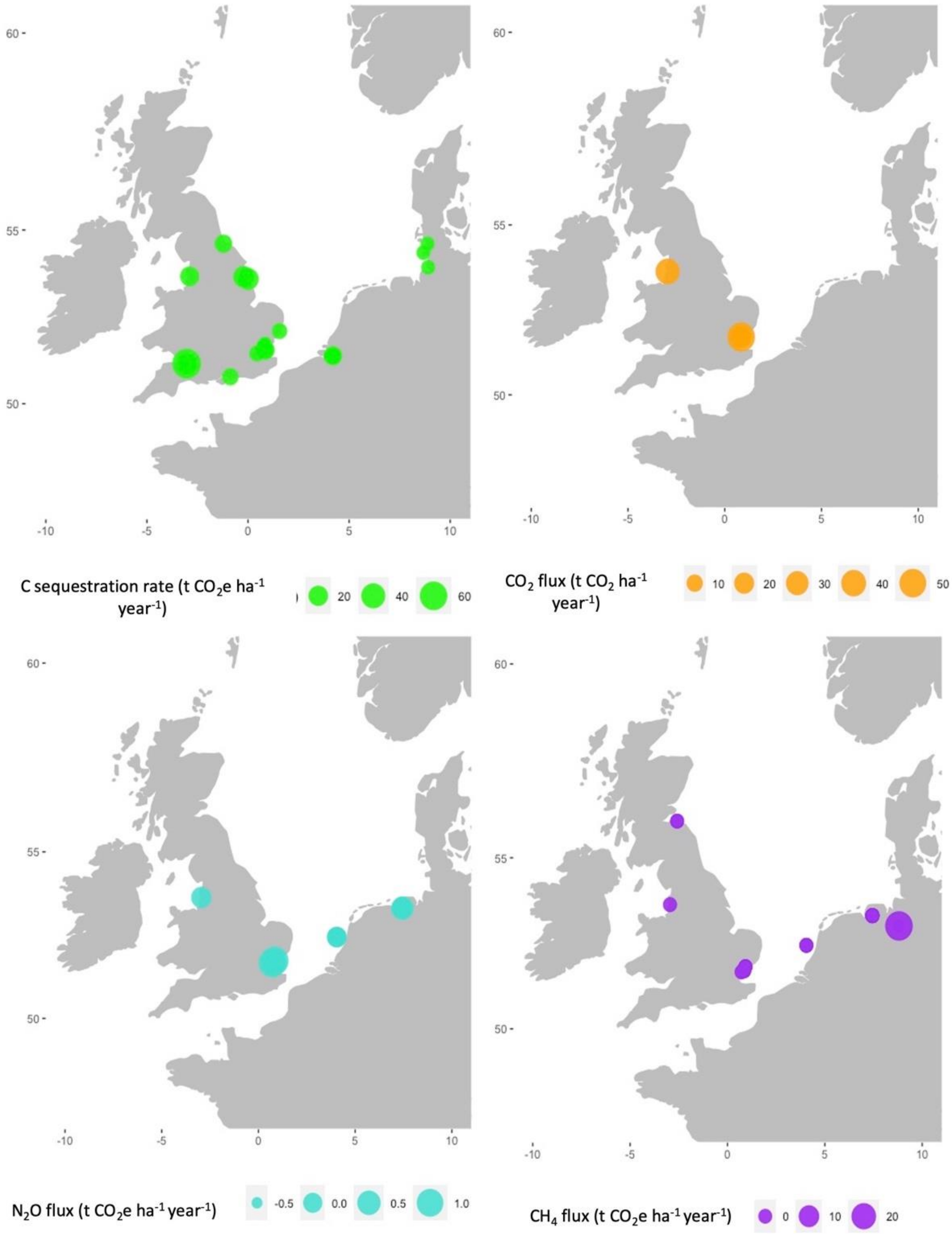

Figure 5. *Map of a) carbon sequestration rate b) CO_2 flux c) N_2O flux and d) CH_4 flux observations in Northern European saltmarshes. Point size corresponds to respective value (t CO_2e ha^{-1} y^{-1}).*

4. Comparison between restored and natural marshes

In contrast with data recently published by CEFAS (Parker *et al.* 2020), C stock was higher in restored than natural saltmarshes (Table 1). However, it should be noted that there were 67 values for C stock in natural marshes compared to 2 for restored marshes, and the difference in C stock was later shown not to be statistically significant (Table 2; Figure 6).

Table 1. *Mean (± SD) values for each response variable (C stock, C stock (1m), C sequestration rate), CO_2 flux, CH_4 flux and N_2O flux) in natural and restored saltmarshes in Northern European saltmarshes.*

Marsh type	Response variable	Mean (± SD)	n	Range of values	Units
Natural	C stock	332.2 (± 339.2)	67	6.59 - 1579.18	t CO_2e ha^{-1}
	C stock (1m)	1693.3 (± 3127.1)	67	65.95 – 22180.26	t CO_2e ha^{-1}
	C sequestration rate	8.2 (± 5.94)	5	3.44 – 14.66	t CO_2e ha^{-1} $year^{-1}$
	CO_2 flux	16.5 (± 16.0)	4	1.64 – 36.93	t CO_2e ha^{-1} $year^{-1}$
	CH_4 flux	1.2 (± 6.3)	22	-2.30-29.28	t CO_2 ha^{-1} $year^{-1}$
	N_2O flux	-0.1 (± 0.3)	14	-0.52 – 0.32	t CO_2e ha^{-1} $year^{-1}$
Restored	C stock	509.1 (± 238.1)	2	340.75 – 677.47	t CO_2e ha^{-1}
	C stock (1m)	1865.4 (± 872.4)	2	1248.51 – 2482.26	t CO_2e ha^{-1}
	C sequestration rate	13.3 (± 15.0)	20	1.23 – 67.74	t CO_2e ha^{-1} $year^{-1}$
	CO_2 flux	29.1 (± 35.1)	2	4.35 – 53.91	t CO_2e ha^{-1} $year^{-1}$
	CH_4 flux	0.1 (± 0.1)	4	-0.02 – 0.17	t CO_2 ha^{-1} $year^{-1}$
	N_2O flux	0.6 (± 0.7)	4	0 – 1.16	t CO_2e ha^{-1} $year^{-1}$

Of our six response variables, only N_2O flux showed a statistically significant difference between natural and restored marshes, being considerably higher in the latter (Table 2; Figure 6).

Table 2. *A summary of the results of the linear models used to test the relationship between each of the response and predictor variables. Statistically significant results are highlighted in bold. I.D. insufficient data were available to perform the test. The subscript numbers given for each F value represent the degrees of freedom associated with that test.*

	Response variable					
Predictor variable	Carbon stock	Carbon stock (1m)	Carbon sequestration	CO_2 flux	CH_4 flux	N_2O flux
Marsh type	$F_{1,67}$=1.04; P=0.311; R^2=0.02	$F_{1,67}$=0.71; P=0.404; R^2=0.01	$F_{1,23}$=0.27; P=0.609; R^2=0.01	$F_{1,4}$=0.25; P=0.645; R^2=0.06	$F_{1,24}$=0.03; P=0.854; R^2<0.01	**$F_{1,16}$=5.06; P=0.039; R^2=0.24**
Elevation	$F_{2,21}$=1.43; P=0.262; R^2=0.12	$F_{2,21}$=0.11; P=0.904; R^2=0.01	*I.D.*	$F_{1,2}$=9.79; P=0.089; R^2=0.83	$F_{2,16}$=0.37; P=0.694; R^2=0.04	$F_{2,11}$=0.72; P=0.507; R^2=0.12
pH	**$F_{1,32}$=4.74; P=0.037; R^2=0.13**	**$F_{1,32}$=17.01; P<0.001; R^2=0.35**	*I.D.*	$F_{1,4}$=3.41; P=0.139; R^2=0.46	$F_{1,10}$=0.38; P=0.549; R^2=0.04	$F_{1,7}$=0.09; P=0.777; R^2=0.01
Salinity	$F_{1,52}$=1.08; P=0.303; R^2=0.02	$F_{1,52}$=3.85; P=0.055; R^2=0.07	*I.D.*	*I.D.*	$F_{1,11}$=0.10; P=0.764; R^2<0.01	$F_{1,8}$=0.20; P=0.670; R^2=0.02
Latitude	$F_{1,67}$=2.08; P=0.154; R^2=0.03	$F_{1,67}$=0.11; P=0.742; R^2<0.01	$F_{1,22}$=0.88; P=0.359; R^2=0.04	$F_{1,4}$=0.86; P=0.406; R^2=0.18	$F_{1,24}$=0.02; P=0.899; R^2<0.01	$F_{1,16}$=0.56; P=0.465; R^2=0.03

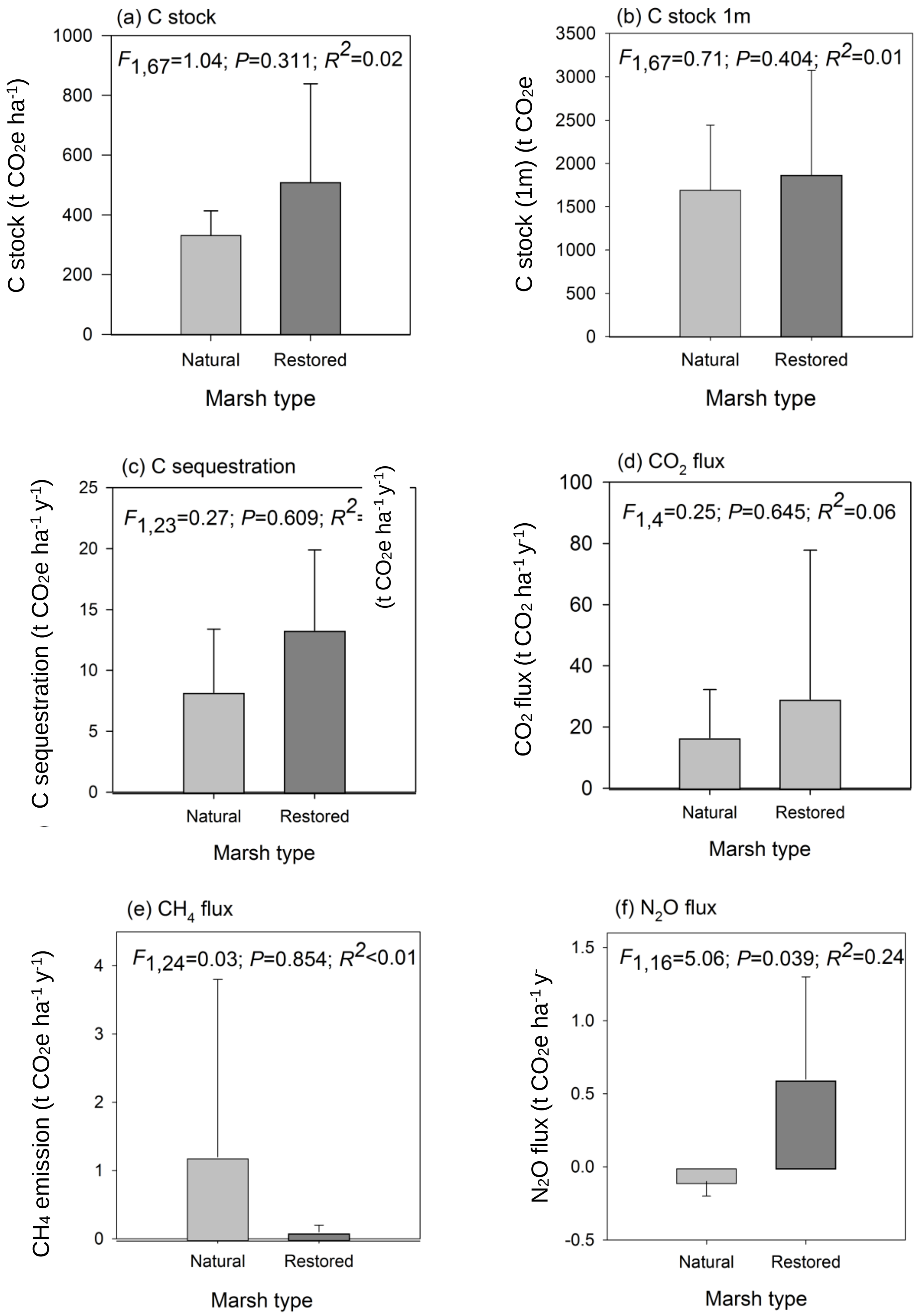

Figure 6. *A comparison of the mean (± 95% CI) values of our six response variables between natural and restored salt marshes.*

5. Influence of time since restoration

Carbon sequestration rate was the only response variable for which there were sufficient observations (20 restored marshes) for an effect of time since restoration to be detected. While it visually appeared that the rate of carbon sequestration decreased with time since restoration (Figure 7), the regression was not statistically significant (R^2 = 0.06, $F_{1,18}$ = 2.12, p = 0.16). The lack of significance may have resulted from limited observations of old restoration sites.

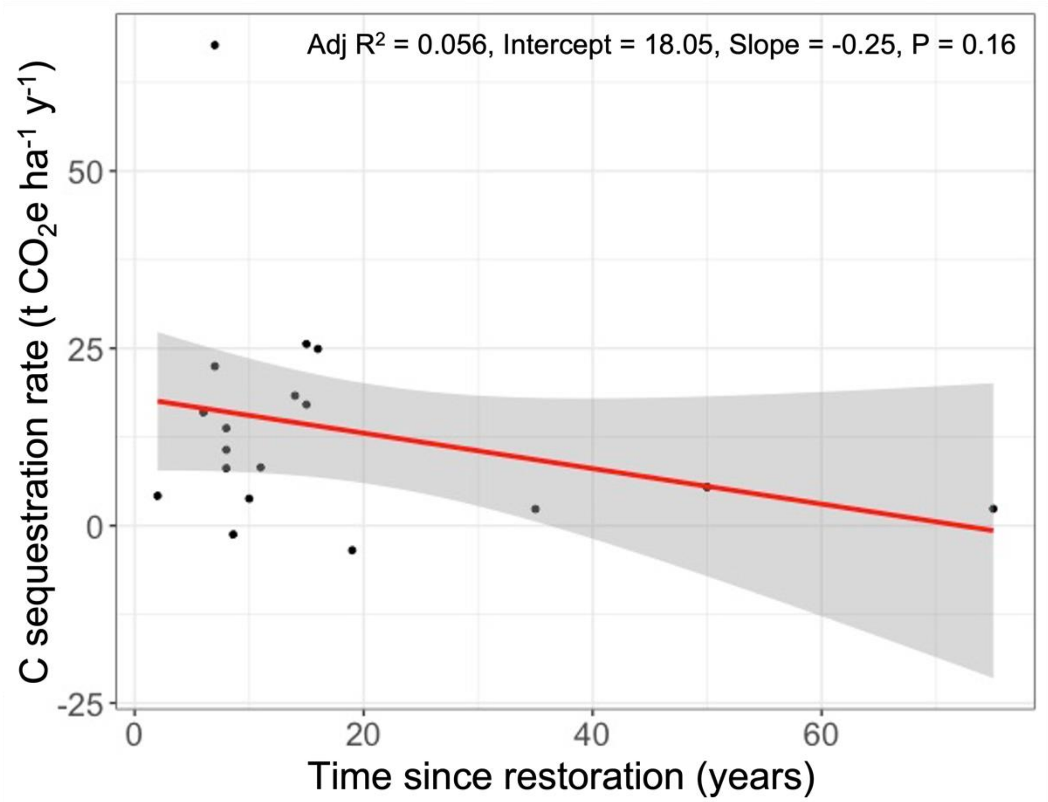

Figure 7. *Linear regression model of carbon sequestration rate (t CO_2e ha^{-1} y^{-1}) with time since restoration (years) of restored saltmarsh (n = 20) in the UK and north-western Europe.*

Rapid C sequestration rates in recently restored marshes are consistent with recent studies. For example, Burden *et al.* (2019) reported C accumulation of 1.04 t C ha^{-1} y^{-1} in the first 20 years following restoration in Eastern England, decreasing to 0.65 t C ha^{-1} y^{-1} thereafter. It is expected that C sequestration rates will slow in restored marshes over time as bed levels rise and sediment accretion rates slow (ABPmer 2021). Net C sequestration should, however, be considered in the context of GHG flux, which reduces the overall C storage potential of the marsh. In common with our findings, Adams *et al.* (2012) found significantly higher N_2O flux in restored saltmarsh compared to natural saltmarsh, which reduced the net C sequestration benefit. In that study, CH_4 emissions were lower in restored compared to natural marshes, resulting in the opposite effect (Adams *et al.* 2012). Although the mean values obtained from our review likewise suggested higher CH_4 emissions in natural marshes (Figure 6e), our analyses detected no statistically significant difference. It should therefore be a priority to obtain more data on changes in greenhouse gas flux, as well as gross C accumulation or sequestration, in restored marshes of different ages, to be able to develop a timescale over which net C sequestration is changing (Mitsch *et al.* 2013).

6. Contextual predictors of marsh carbon and GHG processes

Our linear models indicated that the elevation of a salt marsh did not affect the magnitude of any of our response variables (Table 2; Figure 8); however, there was insufficient data to allow us to test the effect of elevation on carbon sequestration rates (Table 2).

We found statistically significant relationships of carbon stock with soil pH. The relationship was negative when stock observations were extrapolated to 1m depth (Table 2; Figure 9b), but positive when not extrapolated (Table 2; Figure 9a). No statistically significant relationships were detected with any other environmental predictor variables (Table 2; Figure 9). Sampling of saltmarshes in Wales has shown the influence of marsh variables such as sediment type and vegetation community on C stock (Ford *et al.* 2019). Additionally, Hansen *et al.* (2017) reported that salinity and elevation were major drivers of variation in soil organic C pools in northern Germany. It is therefore likely that environmental characteristics do influence C stock in natural and restored marshes, despite statistically significant relationships not being shown in this study.

Carbon and flux variables had no apparent associations with sediment salinity (Table 2; Figure 10) and there were insufficient data to allow us to test the effect of elevation on carbon sequestration rates (Table 2). Finally, no statistically significant relationships were detected between salt marsh latitude and any of the six response variables (Table 2; Figure 11). Similarly to C stock, previous studies have shown that various environmental drivers, such as temperature, sulphate concentrations and vegetation community, can contribute to variation in saltmarsh greenhouse gas flux (Heyer and Berger 2000, Ford et al. 2012, Witte and Giani 2015). We therefore suggest that the lack of statistically significant relationships found here was the result of the limited available data.

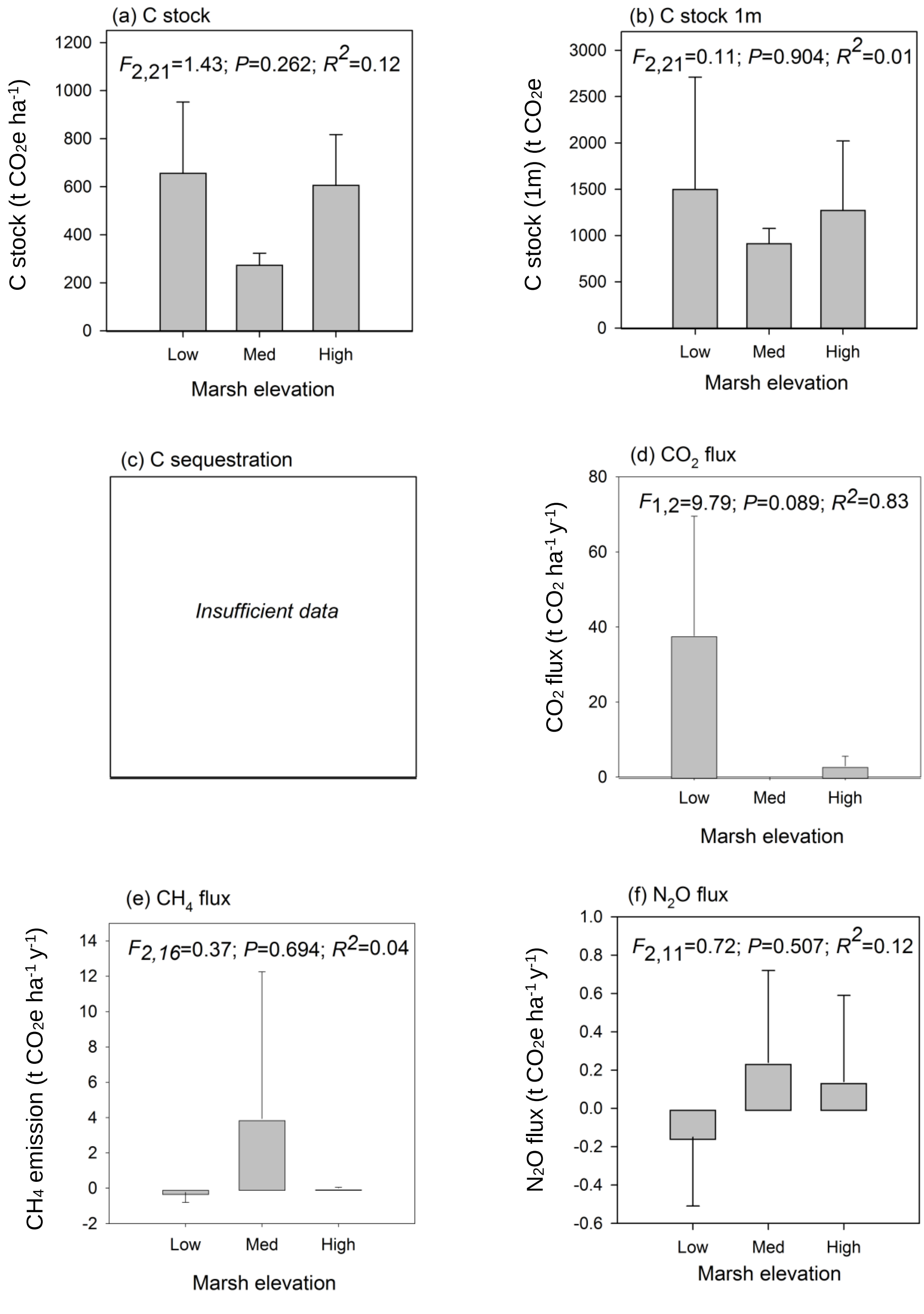

Figure 8. *The mean (± 95% CI) values of our six response variables at three different marsh elevations. N.B., no data were available for CO_2 fluxes at the medium marsh elevation.*

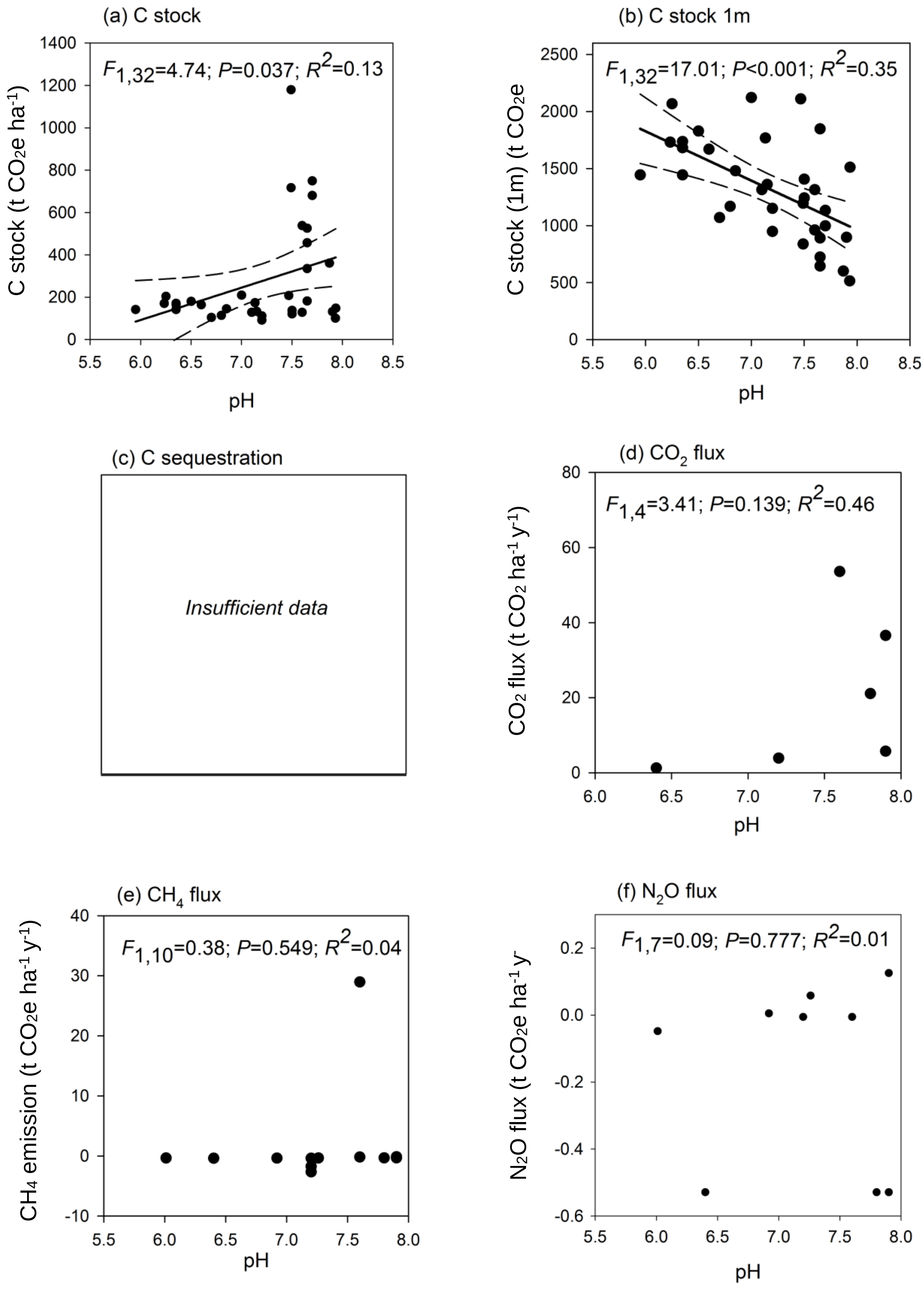

Figure 9. *The relationships between our six response variables and salt marsh pH values. The solid and dashed lines indicate the mean and 95% CI regression lines associated with statistically significant relationships (see Table 2).*

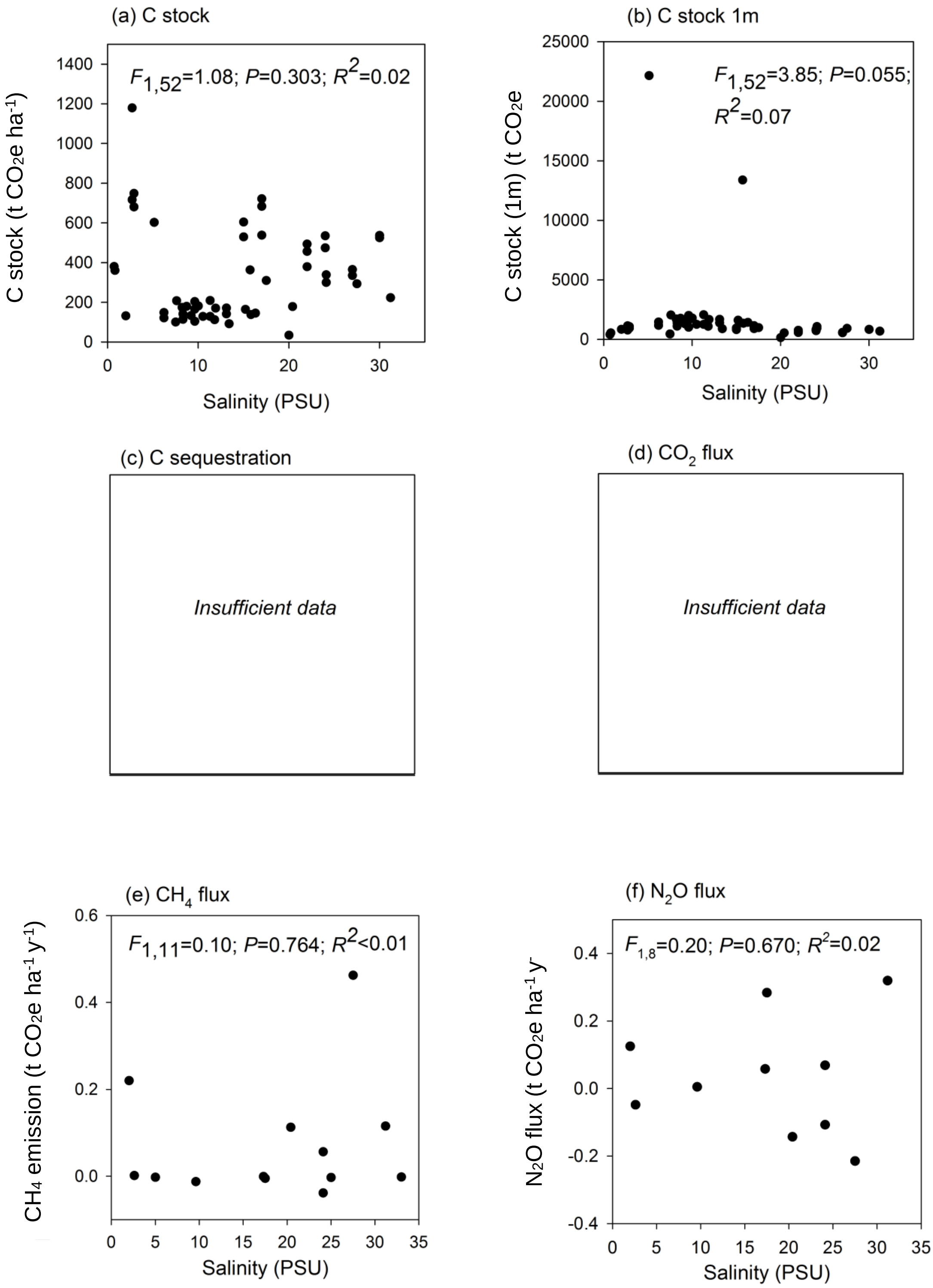

Figure 10. *The relationships between our six response variables and salt marsh salinity values.*

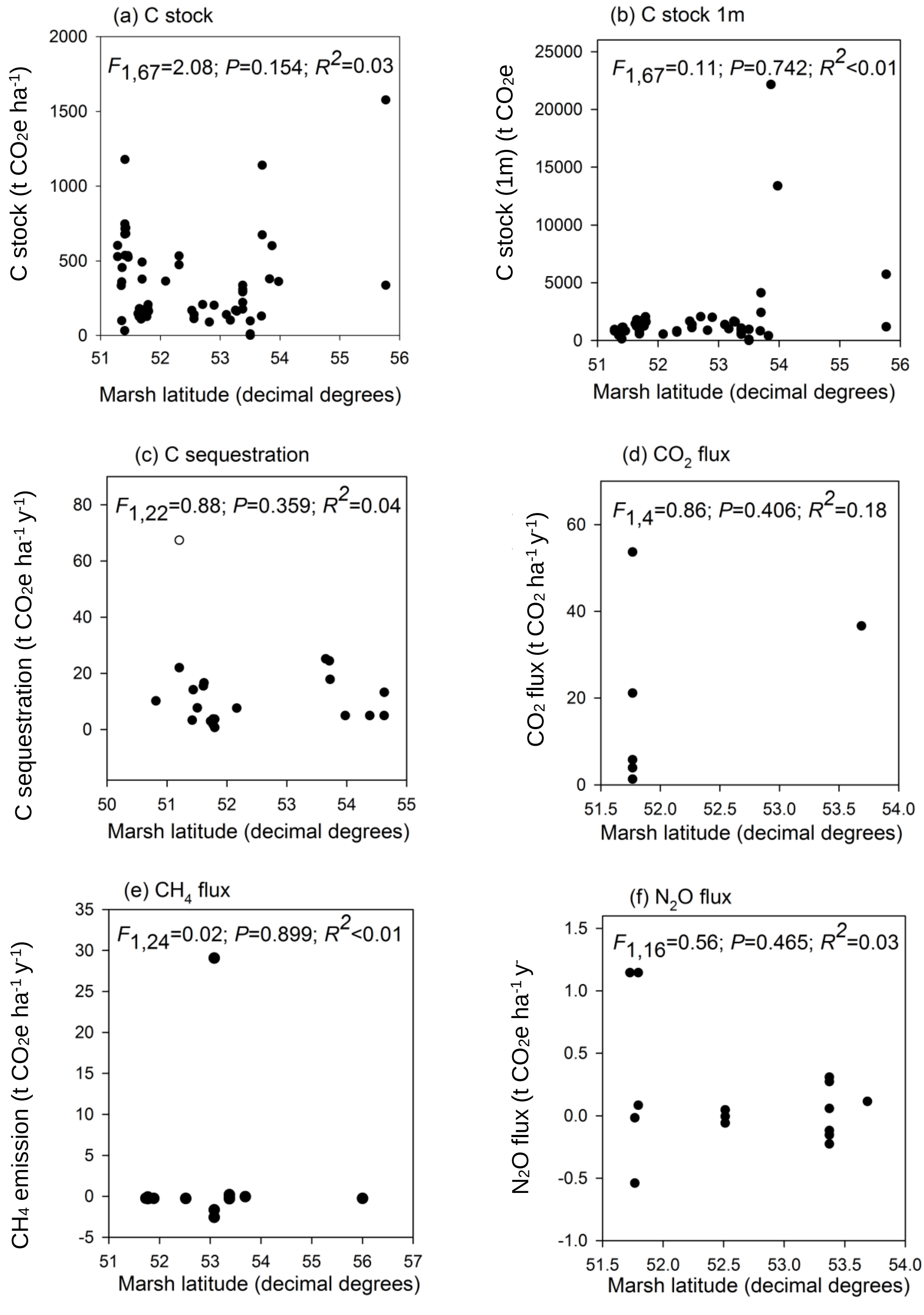

Figure 11. *The relationships between our six response variables and salt marsh latitude. N.B. the white circle in c indicates an over-leveraged data point that was removed from the regression analysis.*

7. Study limitations and caveats

Throughout the course of this review, we identified several limitations which restricted the addressing of our four primary research questions. Most of these issues resulted from three themes: insufficient data, inconsistency in the sampling methodologies engaged by studies, and a range of reporting units.

Data scarcity within our geographical region (zones 2bn, 2bs and northern 2d, Figure 1), such as very little data on potential contextual drivers of CGHGF (marsh elevation, salinity, sediment type, etc), limited the analyses we could do. This reduced the statistical power of our tests and, arguably, the detection of real relationships of CGHGF with contextual predictors. It also meant that more subtle interactive effects between environmental variables could not be tested for and so may have been missed. Additionally, we had observations from only a few restored sites (n = 26) compared to natural marshes (n = 152), and thus a strong skew towards natural marsh types in our dataset. Analyses would have benefitted from more data on restored marshes, particularly observations of the same marsh before and after restoration.

With regards to sampling methodologies, C stock estimates in particular were made to a range of soil depths, with 48.7% of values estimating C stock in the top 10cm of saltmarsh sediment. In order to make these values comparable, we extrapolated C stock values to a depth of 1m, which also brought estimates in line with IPCC (2014) recommendations. Extrapolations assumed a constant C density with depth. We acknowledge this assumption may not be valid for many marshes, and we consider that extrapolation introduced a high degree of uncertainty in the findings. We suggest considering the non-extrapolated values for C stock over those extrapolated to 1m, while realising the caveat that non-extrapolated C stock estimates were to a range of depths.

Finally, response variables of CGHGF were reported in a range of units, which made it difficult to compare values. Most were standardised into t CO_2e ha^{-1} or t CO_2e ha^{-1} y^{-1}, however values which could not be standardised into these units (for example, % values) were excluded from the analysis of that variable. This exclusion of data restricted the statistical power of some of our analyses through limiting sample size.

It is anticipated that extending the systematic review into a global scale, by early 2022, will yield a larger dataset and greater gradients in key environmental variables, as it can draw on the rich salt marsh blue carbon literatures available from global regions such as Australia and the USA. Enlarging the study to a global scale will help mitigate some of the above-mentioned shortcomings to the dataset and identify key predictor variables of saltmarsh CGHGF. It should also make it possible to answer the question we had insufficient data here to address: how much C sequestration is ‘additional’ in restored saltmarshes?

8. Suggestions best practices for monitoring

The difficulties encountered when comparing and synthesising relevant data for the production of this report highlight the need for standardised methodologies and consistent data reporting in studies assessing CGHGF for saltmarsh habitats. Such standard practices would reduce the uncertainty introduced when comparing carbon values obtained using different methodologies and facilitate more robust investigations of spatiotemporal patterns in saltmarsh carbon stocks and burial rates. A selection of published methodologies pertaining to blue carbon stock assessments are already publicly available and have been widely adopted among conservation practitioners overseas. These include the IUCN's *Manual for the Creation of Blue Carbon Projects in Europe and the Mediterranean* (IUCN 2021) and the Blue Carbon Initiative's *Manual for Measuring, Assessing, and Analysing Blue Carbon* (Howard *et al.* 2014). These methodologies could be used as the basis for a future best practice guide for scientific research, bridging the gap between academia and restoration practitioners. A guide of this nature was produced by the European Commission for research on ocean acidification (Reibesell *et al.* 2011), which (like blue carbon) is a relatively young field and addresses complex chemical processes and feedback mechanisms. We recommend the following as priorities for standardisation:

- **Coring depth**:
  The IPCC has recommended 1m depth as a standard. If resources are low or cores cannot be taken to 1m, carbon measurements from a consecutive series of shorter cores (0-30 cm) can be used to develop log-linear equations to predict soil organic carbon density down to 1m (Young et al. 2018) instead of linear extrapolation, which can lead to an overestimation of the carbon pool.

- **Sub-sampling core strata**:
  To obtain more accurate estimates for the total carbon stock of whole saltmarsh systems, subsamples should be taken from different strata within each core and carbon content measured. This will account for depth-specific variation in organic carbon concentration in sediments. Every 5 cm for the first 50 cm has been suggested, with greater intervals thereafter (Fourqurean *et al.* 2014). Combining this data with elevation and soil depth will yield more robust estimates of the total amount carbon stored below-ground in saltmarshes. This data will also help in estimating changes in carbon burial through time.

- **Response variables**:
  In order to obtain a more complete picture of the Sustained Global Warming Potential (SGWP) of wetland habitats, diurnal fluxes of greenhouse gases including carbon dioxide, methane, nitrous oxide and Dimethylsulfoniopropionate (DMSP) should be measured wherever possible.

- **Reporting units**:
  To allow for greater ease when comparing and evaluating the SGWP of wetland habitats, carbon sequestration and gas flux data should be reported in tons of carbon dioxide equivalent (t CO_2e ha^{-1} y^{-1}) to ensure comparability between different greenhouse gases.

- **Metadata**:
  To improve our capacity to understand drivers of variance in saltmarsh carbon burial rates, future studies assessing carbon stock, sequestration or greenhouse gas flux should, where possible, record relevant metadata including temperature, salinity, pH, vegetation community, sediment type, elevation and tidal range. Any human activity, presently or prior to restoration, should be recorded. Our analysis indicated that pH and restoration status of a marsh may have been drivers of variation in these processes, so environmental characteristics should be prioritised for monitoring.

9. Areas requiring additional data

We have identified three key areas which require additional data in order to improve our understanding of CGHGF drivers in saltmarshes within the UK and our geographical region. Suggested areas for further research to target include:

- Estimating carbon stocks **to a depth of 1m** so that accurate C stock estimates to 1m can be produced for UK saltmarshes, also making these values comparable with each other
- Recording environmental variables such as salinity, sediment type and elevation for both natural and restored marshes where CGHGF are being measured so that major drivers of variation in these processes can be identified
- Obtaining before and after data for natural and restored marshes (where possible) and increased data on restored marshes generally and over time, in order to fully compare the responses of restored marshes with their natural 'equivalents'.

Definitions

Additionality: The additional carbon which is likely to be sequestered (see below) as a result of marsh restoration, not including carbon which would have been sequestered by the same area in the absence of a restoration project.

Biogeographical zone: Geographical areas within which ecosystems (in this case, saltmarshes) exhibit similar biological communities and processes and thus can be regarded as comparable.

Blue carbon: Carbon taken up and sequestered (see below) by marine ecosystems including the open sea but particularly focused on coastal ecosystems, particularly saltmarshes, mangroves and seagrasses.

Flux: Processes of intake or emission of carbon or gases.

Greenhouse gas: A gas which traps heat in the atmosphere and thus contributes to climate change via atmospheric warming. In this report, the greenhouse gases considered are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O).

Metadata: Data providing information about the data extracted from a study, for example, the sampling location.

Restoration: The process of restoring a marsh (usually where the land had previously been reclaimed e.g. for agriculture) via controlled flooding methods such as managed realignment or regulated tidal exchange.

Sediment accretion: Growth of saltmarsh via the deposition of sediment during tidal flooding of the marsh area.

Carbon Sequestration: The removal and subsequent burial of carbon from the atmosphere, in this case, into saltmarsh sediments.

Carbon Stock: carbon stored as organic matter within saltmarsh sediments.

Abbreviations

C: carbon

CGHGF: carbon and greenhouse gas flux

CO_2e: equivalent value in CO_2 flux

DMSP: Dimethylsulfoniopropionate

GHG: greenhouse gas(es)

GWP: global warming potential

IPCC: Intergovernmental Panel on Climate Change

NVC: National Vegetation Classification

PSU: Practical Salinity Unit

SGWP: sustained global warming potential

SOC: soil organic carbon

UK: United Kingdom

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Studies from which data were extracted for systematic review

Ref No	Article Title	Authors	Year
1	Nitrous oxide and methane fluxes vs. carbon, nitrogen and phosphorous burial in new intertidal and saltmarsh sediments	Adams *et al.*	2012
2	Carbon sequestration and biogeochemical cycling in a saltmarsh Subject to coastal managed realignment	Burden *et al.*	2013
4	Effect of restoration on saltmarsh carbon accumulation in Eastern England	Burden *et al.*	2019
8	Greenhouse Gas Emission and Balance of Marshes at the Southern North Sea Coast	Witte and Giani	2016
9	Methane, carbon dioxide and nitrous oxide fluxes from a temperate salt marsh: Grazing management does not alter Global Warming Potential	Ford *et al.*	2012
16	Biogeochemical functioning of grazed estuarine tidal marshes along a salinity gradient	Dausse *et al.*	2012
48	Organic carbon isotope systematics of coastal marshes	Middelburg *et al.*	1997
95	Factors influencing the atmospheric flux of reduced sulfur-compounds from North-Sea intertidal areas	Harrison *et al.*	1992
164	Long-term organic carbon sequestration in tidal marsh sediments is dominated by old-aged allochthonous inputs in a macrotidal estuary	Van de Broek *et al.*	2018
206	Factors influencing the organic carbon pools in tidal marsh soils of the Elbe estuary (Germany)	Hansen *et al.*	2017
220	Large-scale predictions of salt-marsh carbon stock based on simple observations of plant community and soil type	Ford *et al.*	2019
229	On autochthonous organic production and its implication for the consolidation of temperate salt marshes	Bartholdy *et al.*	2014

253	Assessing the long-term carbon-sequestration potential of the semi-natural salt marshes in the European Wadden Sea	Mueller *et al.*	2019
283	Methanogenesis in saltmarsh soils of the North Sea coast of Germany	Giani *et al.*	1996
285	Organic sulfur forms in mineral top soils of the Marsh in Schleswig-Holstein, Northern Germany	Mansfeldt and Blume	2002
286	Long-term CH3Br and CH3Cl flux measurements in temperate salt marshes	Blei *et al.*	2010
288	Benefits of coastal managed realignment for society: Evidence from ecosystem service assessments in two UK regions	MacDonald *et al.*	2020
332	Controls on soil organic carbon stocks in tidal marshes along an estuarine salinity gradient	Van de Broek *et al.*	2016
398	The carbon balance of grazed and non-grazed Spartina anglica saltmarshes at Skallingen, Denmark	Morris and Jensen	1998
401	Impact of the invasive native species Elymus athericus on carbon pools in a salt marsh	Valery *et al.*	2004
408	Ecosystem engineering by large grazers enhances carbon stocks in a tidal salt marsh	Elschot *et al.*	2015
453	Soil organic carbon stocks in a tidal marsh landscape are dominated by human marsh embankment and subsequent marsh progradation	Van de Broek *et al.*	2019
499	Temporal and spatial variation in methyl bromide flux from a salt marsh	Drewer *et al.*	2006
574	Factors controlling denitrification rates of tidal mudflats and fringing salt marshes in South-West England	Koch *et al.*	1992
633	Quantification of organic carbon concentrations and stocks of tidal marsh sediments via mid-infrared spectroscopy	Van de Broek and Govers	2019
714	Benthic metabolism and sulfur cycling along an inundation gradient in a tidal Spartina anglica salt marsh	Gribsholt and Kristensen	2003
845	A study to explain the emission of nitric-oxide from a marsh soil	Remde *et al.*	1993

1006	Geochemical mapping of a blue carbon zone: Investigation of the influence of riverine input on tidal affected zones in Bull Island	Grey *et al.*	2021
1041	Accretion rates in salt marshes in the Eastern Scheldt, Southwest Netherlands	Oenema and Delaune	1988
1313	Hydrodynamics affect plant traits in estuarine ecotones with impact on carbon sequestration potentials	Ostermann *et al.*	2021
1503	Sulphate reduction, methanogenesis and phylogenetics of the sulphate reducing bacterial communities along an estuarine gradient	Nedwell *et al.*	2004
1510	Coastal Zone Ecosystem Services: From science to values and decision making; a case study	Luisetti *et al.*	2014
1769	Decay of plant detritus in organic-poor marine sediment – production-rates and stoichiometry of dissolved C-compound and N-compound	Kristensen and Hansen	1995
3845	Rapid carbon accumulation at a saltmarsh restored by managed realignment far exceeds carbon emitted in site construction	Mossman *et al.*	2021 (in press)
3846	Blue carbon in Managed Realignment sites: An overview with a comparative analysis and valuation of 10 different UK sites	ABPmer	2021

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