SALTMARSH CODE

Monitoring, Reporting, and Verification

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Contents

Note: The MRV will be incorporated into the main Code document.

1 Introduction

Monitoring, reporting, and verification (MRV) is a multi-step process to measure, report and verify the carbon gains (or losses) from restoration projects entering the Saltmarsh Code. This document provides guidance for the design, implementation and reporting of the monitoring needed in order to quantify the carbon stored at these sites. The guidance is restricted to those measures relevant to restoration via managed realignment only, in line with the focus of the Saltmarsh Code.

It is expected that emission factors (EFs - average emission rate of a given source, relative to units of activity, or common environmental and physical characteristics) will be developed to estimate carbon gains using proxy measures (a parameter that is monitored or measured to determine the value of a strongly correlated parameter that is not monitored or measured) as this reduces the cost of monitoring and verification considerably. However, the current knowledge base is not yet developed enough to allow for development of EFs. This MRV guidance therefore focuses on site-specific, project-based primary data collection to quantify carbon abatement (pools) associated with the restoration activity, whilst also adding to the published knowledge to further inform the development of EFs in the future. An 'ex-ante' approach for predicting the likely carbon gains from the restoration activity is also included. This is needed pre-restoration for two reasons, 1) to determine the financial viability of entering the Saltmarsh Code. It will give an indication of the proportion of funding carbon credits would likely provide to the total needed for the restoration project, and 2) for the Validation stage of the project. A prediction of likely carbon gains to review at each Verification cycle.

The carbon pools that are required to be quantified are listed in Table 1, alongside our approach for their estimation, as well as carbon pools that are optional to monitor. This version of the MRV (v0.1) focuses on the direct measurement of actual carbon pools. Proxies for the determination of carbon pools are being developed (see accompanying MRV justifications and next steps document) and will be included in later versions of the MRV.

We identify three core areas of monitoring: 1) the amount of sediment accumulating, 2) the density of carbon in that sediment and 3) the vegetation zones and their distribution. These are identified as the key areas for monitoring because managed realignment sites are often at low elevations in the tidal frame compared to surrounding saltmarsh and may accumulate sediment rapidly; other sites at higher elevations, or those that have a limited sediment supply, accumulate sediment at much lower rates. The variation in sediment accumulation is a major driver of the variation in carbon accumulation rate. Sediment grain size and vegetation community composition are also important drivers that contribute to variability in the amount of carbon in saltmarsh sediment. The plants that establish on the new saltmarsh contribute root, leaf and other organic matter to the sediment carbon. Annual plants, usually occurring at lower elevations and at the early stages of site establishment, tend to contribute less to the carbon pool than the longer living perennial plants. The sediments of unvegetated mudflat contain microalgae that contribute to the carbon pool, although mudflat is usually less carbon dense than vegetated saltmarsh. Monitoring the changes in the vegetation composition as it develops on a site will therefore provide knowledge on the amount and source of the carbon, as well as the biodiversity.

The carbon found in saltmarsh sediment can take a number of forms, some more easily broken down (reactive) and returned to the atmosphere than others, and arise from a number of sources, which determine whether or not it can be counted under the key principle that for a restoration project to be able to 'count' the carbon it must represent a 'new' removal of CO_2 from the atmosphere into organic matter that is then stored within the saltmarsh sediment pool for the life of the project.

Autochthonous organic carbon is both removed from the atmosphere and stored in the new saltmarsh environment and so can count in principle. However, some of the more reactive carbon will be broken down and returned to the atmosphere in the short term and so does not represent long term storage.

For allochthonous carbon, while the removal of CO_2 from the atmosphere has occurred outside the project site, the site may confer a storage benefit, i.e. if in the absence of the restoration project, the organic carbon would have been returned to the atmosphere, then that carbon is countable. However, some of that allochthonous carbon will be unreactive on project timescales due to its association with mineral sediments. Accumulation of this minerally-associated organic carbon in the saltmarsh does not therefore represent a 'new' sink and should be deducted from the total organic carbon accumulation in the determination of carbon credits.

Table 1. Carbon pools that exist on saltmarshes and should be considered. Carbon pools that are essential to monitor are shown in black, those which are non-essential (but encouraged to monitor) are in grey.

	Sub-category	Measurements of pool or proxy measurements under development	Pools essential to monitor for the Saltmarsh Code
Net carbon stocks from soil and vegetation pools	Soil/sediment carbon	Net volume of sediment accumulation Density of carbon in the sediment	Essential to measure
	Vegetation communities	Percentage cover of vegetation types (unvegetated, annual, perennial, Phragmites) across the whole site.	Essential to measure
	Above-ground biomass	Biomass and carbon content of above-ground plant material.	Biomass and carbon content of plant material is optional. Emissions factors in development.
	Below-ground biomass	Biomass and carbon content of below-ground plant material.	Biomass and carbon content of plant material is optional. Emissions factors in development
	Litter	Importance currently unknown, but "Dead aboveground biomass is usually carried away with the regular tides and can usually be excluded from measurements without compromising the accuracy" (Blue Carbon Handbook). Litter is currently excluded and does not need to be measured but is the subject of research and this guidance will be updated as necessary.	Currently excluded from the code. Measurement not needed.
	Deductions for non-countable carbon	Proportion of carbon that is 'countable' (all carbon minus a deduction for unreactive allochthonous (off-site) carbon that would have been stored in the absence of the site).	Deduction essential. The use of site-specific values is optional but recommended where possible. A default deduction has been proposed.

Net GHG emissions from soil	CO_2 emissions from soil	Net fluxes measured using gas flux towers or chambers. Emissions factors and proxies are in development.	Optional. Emissions factors and proxies are in development.
	CO_2 Emissions from Eroded Soil	**TBC**	**TBC**
	CO_2 Emissions from Soil Exposed to an Aerobic Environment Through Excavation	Most soil excavated, e.g. during creek construction will be reburied in the sea wall. The EA ERIC calculator, which will be used for the quantification of carbon emissions during construction, includes a component of losses through embodied carbon.	**TBC**
	CH_4 emissions from soil	Net fluxes measured using gas flux towers or chambers. It is possible that if the salinity is greater than 18 then CH_4 are negligible. Emissions factors and proxies are in development.	Optional. Emissions factors and proxies are in development.
	N_2O emissions from soil	Potential size of pool currently unknown as there is very limited data. Net fluxes can be measured using gas flux towers or chambers.	Optional. Emissions factors and proxies are in development.

In this document, we provide detailed methodologies for the three core monitoring areas (sediment accumulation, sediment carbon and vegetation zones). For each monitoring area, we provide a range of methods that vary in their cost and need for expertise and equipment. There currently remain many data gaps, and thus uncertainties, with regard to the size and development of carbon pools at managed realignment sites. We therefore highlight those methods that will provide robust data, increasing our understanding of the development of carbon on saltmarsh, and contributing to the development of improved cost-effective and simple indicator measures (EFs and proxy measures). However, these methods may need the input of a research organisation or access to specialist equipment, so we also provide cheaper, simpler alternatives, where possible. For robustness of carbon estimates, regardless of whether EFs or proxy measures have been developed, it is suggested data is sought in the following order: new primary data collection, local published values, proxies, models, and default EFs.

2 Validation stage: Methodology for the estimation of soil carbon accumulation over time (Ex ante)

This methodology describes how to estimate emissions reductions and/or removals over time within a managed realignment site for use in the project Validation stage of the Saltmarsh Code (ex ante approach). This estimation can also be used to determine the financial viability of entering the Saltmarsh Code as it will give an indication of the proportion of funding carbon credits would likely provide to the total needed for the restoration project as a whole, as part of a blended finance approach.

This approach estimates soil carbon accumulation over time. It does not take into account carbon in biomass, or carbon lost through greenhouse gas flux, but is used as an indication of likely carbon gain in the absence of more precise, complete information. There is limited data availability representing the uncertainty and variability in the carbon benefit of saltmarsh restoration sites. With time and more research, emission factors will be able to be developed to determine the expected carbon sequestration rates (as is the approach in the Peatland Code and Woodland Carbon Code).

The typical 'carbon curve' (carbon accumulation over time) for saltmarsh sites includes higher rates of accumulation in the initial post-restoration period, before reducing to a lower, stable rate. This reduction in annual accumulation rate will happen following different time periods depending on site specific conditions.

Estimates of sediment accretion are key to predicting the soil carbon accumulation, alongside bulk density and carbon content data. Soil carbon accumulation is modelled by first fitting a standard curve to sediment accretion estimates, comprised of an exponential component (representing a gradually declining growth rate following sea defence breaching) and a linear component (representing ongoing accretion). This is then extrapolated to give yearly estimates for a 100-year project period.

The expected sediment accretion per year from time of restoration can either be derived from a representative site or local data, or using a long-term data set as a proxy, such as that from the Tollesbury managed realignment site in Essex (Garbutt, 2018). Using initial post-restoration accretion rates from a different site has the potential to introduce error in the soil carbon accumulation estimates. However, this will only make a difference to the immediate and short-term estimated rates, as ongoing accretion (once the initial higher rate has slowed) can easily be based on local data.

<u>Data needed:</u>

- Expected sediment accretion per year from time of restoration for the initial post-restoration period (mm $year^{-1}$) – either derived from a representative site/local data, or using a long-term data set as a proxy, such as that from the Tollesbury managed realignment site in Essex (Garbutt, 2018).
- Accretion rate per year representing long-term accretion (mm $year^{-1}$) – can use RSLR as a proxy
- Area of site (m^2)
- Bulk density of new sediment (t m^3)
- Carbon content of new sediment (%)

Steps taken to estimate soil carbon accumulation rates are:

1) Sediment accretion data is extrapolated into the future by fitting a curve to the data in two parts, then summing together:

a) An exponential curve using the initial post-restoration sediment accretion data, with the main objective of minimising RMSE (root-mean-square-error). This can be performed in Excel, as well as statistical environments such as R.
b) A linear regression representing ongoing accretion rate (can use relative sea level rise as a proxy)
c) Summing these two parts will give an estimation of sedimentation rate (initial + ongoing), and can be extrapolated into the future to fit the timeframe of the expected project.

2) A series of calculations are then made:

a) Sediment volume (m^3) = sedimentation rate (m) from step 1 x site area (m^2)
b) Sediment mass (t) = sediment volume (m^3) x bulk density of new sediment (t m^3)
c) Total carbon accumulation per year = sediment mass (t) x carbon content of new sediment (%)
d) Carbon accumulation rate = total carbon accumulation per year / site area (m^2)

3 Designing the survey

3.1 The Baseline (**in development**)

Pre-restoration land use needs to be assessed so the amount of carbon credits available within the project is additional to carbon that would have been sequestered in the absence of the saltmarsh restoration project.

Mapping of the land prior to application for the project to be part of the Saltmarsh Code, and therefore any restoration works, must be carried out. Each land-use (management, intensity, etc) and land type will need to be marked on the map to allow potential differences in carbon gains or losses to be determined. Information about the site history and how the land-use has changed over time is also useful if available. As well as site specific data, the baseline scenario will need to be assessed for climatic risk, as per the Risk Tool (still in development) to determine what changes may have happened anyway, in the absence of the project.

This information will then be used to determine carbon emissions at the point of baselining, but also how the emissions in the baseline land-use were likely to change over time in the absence of the project. Calculations of predicted emissions for the time period of the restoration project need to be made.

The baselining is still in development. As projects could be planned on various types of land with many different current uses, each baseline scenario – and crucially how to estimate this – is likely to be different. We are currently working on providing default values for different land-uses from a combination of Countryside Survey data, UK Greenhouse Gas Inventory default emission factors, and information from the British Survey of Fertiliser Practise (the latter if the baseline scenario involves land with crops).

Predicted emissions from pre-restoration land use over the time scale of the project must be entered into the Carbon Abatement Calculator[1]

3.2 Quantifying carbon emissions from construction

The carbon emissions from the construction of the site, e.g. new sea defences, creek networks etc., must be quantified using the Environment Agency ERIC tool. Values must be entered into the Carbon Abatement Calculator. [Section in development - more details to follow]

3.3 Site boundary for project monitoring

For the purposes of monitoring the carbon accumulated by the managed realignment, the area exposed to tidal inundation needs to be considered. The area below the current level of Highest Astronomical Tide (HAT) is the most appropriate and straightforward way to capture the area exposed to tidal inundation (see Box 1).

3.3.1 Requirement

- The site boundary should be selected by clipping a map of the site elevations, e.g., a digital terrain model (DTM) derived from LiDAR or a drone survey, by the level of highest astronomical tide (HAT) as measured nearby or at a local port.

3.3.2 Requirement

- Subsequent monitoring must occur within this area.

3.4 Stratifying the site for monitoring

Parts of the site at different pre-restoration starting elevations will develop at different rates, have different sedimentation rates, vegetation communities and sediment carbon. The monitoring strategy should therefore aim to sample areas of different elevation that represent different strata. The method to measure site elevation for stratification is provided in Box 1.

3.4.1 Requirement

- The aerial extent of each of the following strata that occurs within the site boundary must be quantified. These strata will provide the basis for site stratification and scaling up of measurements (Figure, Box 1):

1) The area below mean high water neap (MHWN) tide level.
2) The area between MHWN and mean high water spring (MHWS) tidal levels.
3) The area between MHWS tide level and highest astronomical tide (HAT).

Each stratum is usually associated with different plant communities (Figure, Box 1). However, defining strata based on elevation rather than on the actual plant communities is necessary as the vegetation that develops on a site is not known beforehand.

The basic principle of this monitoring design is to sample carbon pools (e.g. sediment cores) and sediment accretion at sufficient monitoring locations within each of the three strata to estimate the

[1] Carbon Abatement Calculator in development.

strata characteristics, and then use the aerial extent of each stratum within the site to scale up these characteristics to a site-wide estimate.

- Below, we state requirements for the specifics of the sampling and replication:

3.4.2 Requirement

- A minimum of nine monitoring locations must be established at each site with three replicate sampling plots within each well represented strata (e.g., strata that covers >10% of the site).

While a minimum of nine sampling locations must be established per site, the establishment of 15 locations for the monitoring of sediment accretion/ erosion is advised, with five sampling plots per strata for greater accuracy of measurements given the variable nature of sediment accretion/ erosion.

3.4.3 Requirement

- Some strata might not be present or have extremely limited extent, e.g. upper strata confined to the edge of the sea wall.
- Rare strata (<10% of site area) should be sampled less intensively, with additional samples added to more common strata (so the number of monitoring locations must remain nine or more).

It is anticipated that continued monitoring of the same locations will occur over time. However, as the site accretes and develops, sampling points are expected to move between strata, e.g. change from unvegetated mudflat to pioneer saltmarsh.

3.4.4 Requirement

- If all monitoring locations of one strata become another (e.g. no monitoring locations remain in mudflat) but the strata remains frequent on the site, then new monitoring points must be established. i.e. there must be continued monitoring of all strata present within the site boundary.
- Similarly additional strata may be needed as the site develops, i.e. site accretion over time may lead to the presence of higher strata that was not present when monitoring first began.

3.4.5 Requirement

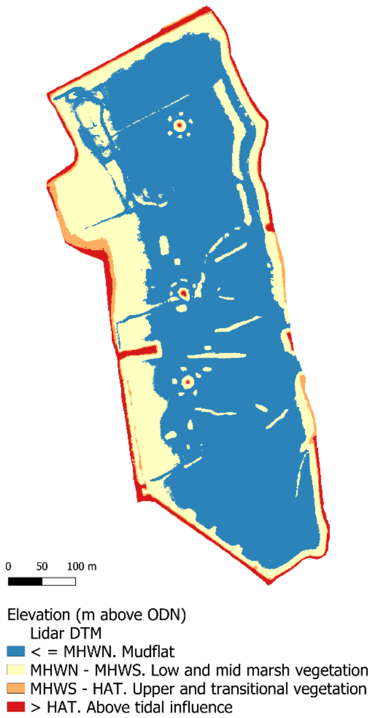
- Monitoring locations within a strata can be located randomly or along transects, but must be representative of the strata present and with no systematic bias (e.g. all along a track or the edge of a creek), acknowledging access and H&S constraints.
- Where possible, there should be a minimum of 20 m between monitoring points.

Box 1. Importance of local tidal regime

The frequency and duration of inundation by the tides determines much of the ecology on saltmarshes, from the plants that can survive to the supply of sediment. Elevations within sites that are low relative to the tides will be more frequently inundated. Frequent tidal floods create conditions that few plant species can tolerate, but also brings regular sediment supply. As a general rule, elevations below the level of mean high water neap (MHWN) tides are unvegetated mudflat, with most saltmarsh vegetation occurring between MHWN and mean high water spring (MHWS) tide levels. Above MHWS, upper saltmarsh and transitional communities occur up to the elevation that tides do not reach (highest astronomical tides, HAT).

The elevations of a new saltmarsh site compared to the levels of MHWN, MHWS and HAT can be used to stratify the site for monitoring. However, the same elevation in different geographic locations will experience different numbers of tides due to differences in tidal regimes. For example, saltmarsh in the Severn Estuary occurs around 6 m above ODN (UK measure of mean sea level) but in the Blackwater, Essex its around 2.5 m ODN. This means that it is essential to assess the elevations relative to the local tidal regime.

Measures of elevation (m above ODN) can be derived from LiDAR DTM with an image obtained from www.datagov.uk under Open Government License v3.0. The levels of MHWN, MHWS and HAT in metres (Ordnance Datum) for locations around the country can be obtained from the UK Hydrographic Office. In-situ measurements of tidal regime will be more accurate, but likely unnecessary for the purpose of stratifying a site. By applying elevation to the tidal data, the site can be stratified into three zones for monitoring: 1) below MHWN tidal levels, 2) between MHWN and MHWS tidal levels, and 3) between MHWS and HAT levels (Figure, Box 1).



Box 1 Figure: Elevation (m above ODN) in 2017 of Fingringhoe managed realignment, derived from Lidar DTM. Lidar image obtained from www.data.gov.uk under Open Government Licence v3.0. The three strata recommended for sub-dividing the site for monitoring are highlighted: < MHWN (blue); between MHWN and MHWS (yellow), and between MHWS and HAT (orange). Areas above HAT (red) should not be monitored).

3.5 Key areas for monitoring

This monitoring manual provides guidance on the sampling techniques and how they can be scaled to provide site-wide estimates of carbon storage.

Sites should be stratified into strata, as described in Section 3.4, and measurements made within those strata, which are then averaged and extrapolated to a site-scale by using strata aerial extent (as measured in section 3.4). Figure 1 provides an overview of the monitoring steps and data uses.

The values obtained from the monitoring will be entered into the Carbon Abatement Calculator[2].

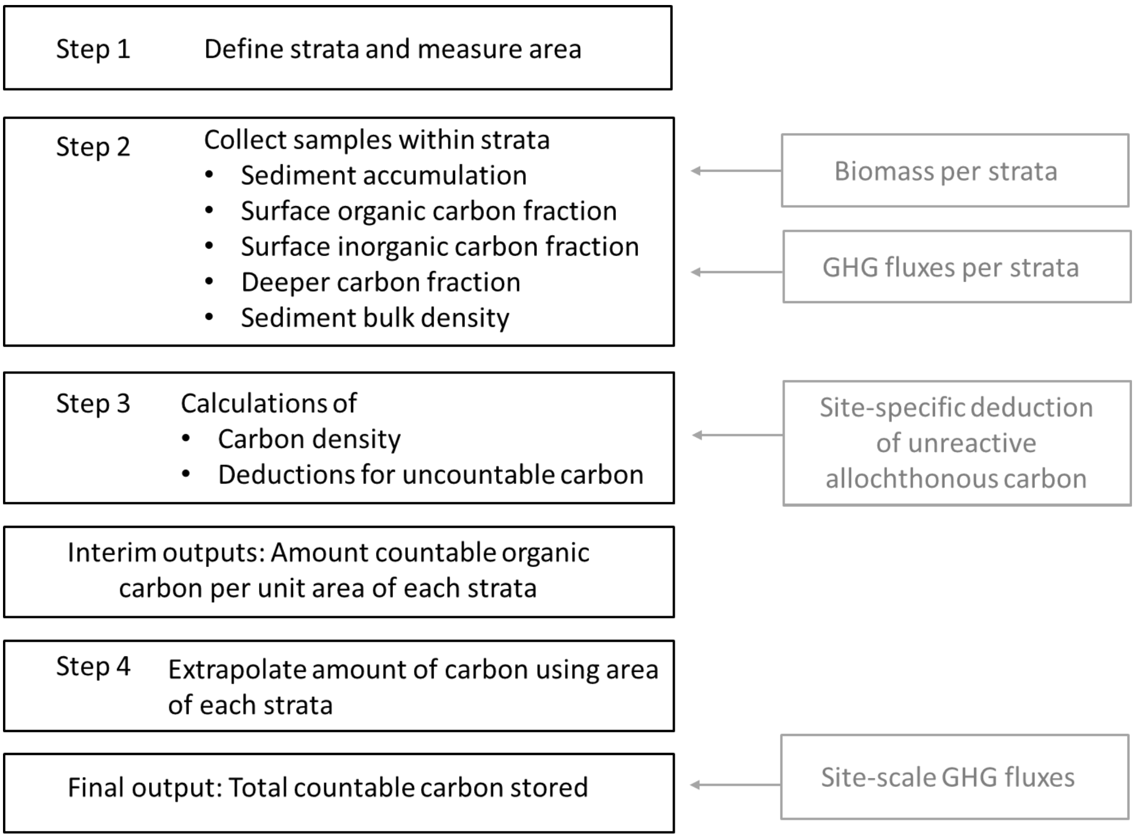


Figure 1. Overview of monitoring regime and data processing suggested in this MRV manual. Elements in grey are those measurements considered optional in this guide.

[2] Carbon Abatement Calculator is in development.

3.6 Regularity of monitoring

In addition to setting a baseline (Section 3.1), the regularity of monitoring is outlined below.

3.6.1 Requirement

- All essential carbon pools (Table 1) must be measured in year 1 following restoration, year 5 and then at a minimum of every 5 years in line with the verification cycle.

3.6.2 Requirement

- Measurements of sediment accretion/ erosion (via sediment pins) and vegetation cover must also take place in year 1 following restoration, year 5 and then in line with the verification cycle.

3.6.3 Requirement

- Monitoring must occur in the summer months to minimise seasonal variation in sediment levels caused by wetting in winter and dewatering in summer and to coincide with peak plant biomass for vegetation cover.

More frequent measurements than those recommended would contribute to data availability and scientific knowledge to ultimately improve EFs and proxies of carbon pools.

3.6.4 Requirement

- If additional measurements of vegetation biomass (above-ground and below-ground biomass) are conducted, these must occur in year 5 and then every 5 years in line with the verification cycle, and in the summer months to coincide with peak plant biomass.

Biomass monitoring could occur in earlier in the restoration cycle if there is very rapid growth in saltmarsh vegetation, but it is anticipated that saltmarsh vegetation will be scant in the first few years following restoration.

3.6.5 Requirement

- Seek specialist advice to establish a reliable GHG flux monitoring programme – these measurements need to be taken at least seasonally. This gives a baseline to work from when setting the monitoring plan for the first phase of code development.

Each methodology outlined in this MRV document provides more specific detail on when the monitoring should occur. Timelines for additional monitoring of the development of restoration sites, such as biodiversity and hydrology, have been presented in the Environment Agency's Saltmarsh Restoration Handbook, in the Restoration Methods chapter (Pontee *et al.,* 2021).

4 Techniques for monitoring

This section describes the techniques and methodology that must be used to monitor essential carbon pools:

- Local sediment accumulation (Section 4.1.4).
- Site-wide sediment accumulation (Section 4.1.5).
- In-situ collection of sediment cores (Section 4.2.2).
- Dry bulk density (Section 4.2.3).
- Organic carbon (Sections 4.2.4 and 4.2.5).
- 'Non-countable' carbon deductions (Section 4.2.6 and Section 4.2.7).
- Accounting for carbon loss with depth/ time (Section 4.3.1)
- Carbon accumulation rate and site-wide carbon accumulation (Section 4.3.2).
- Cover of broad vegetation types (Section 4.4.1).

This section also covers the techniques and methodology that must be used to monitor carbon pools that are not essential, but advised:

- Above-ground vegetation biomass (Section 4.5.1.1).
- Below-ground vegetation biomass (Section 4.5.1.2).
- Greenhouse gas emissions measured via static gas chambers (Section 4.5.2.1) and flux towers (Section 4.5.2.2).

4.1 Amount of sediment accumulating

The volume of sediment accumulating is a vital component in calculating the amount of carbon accumulating at a site. Digital terrain models (DTMs) derived from LiDAR plane or UAV surveys can provide a site-wide snapshot of the elevation of the site. Comparing a DTM from around the time of the breaching of the managed realignment to later images will provide the total net volume change in sediment at the site (i.e. account for erosion of creeks in the total net accretion of sediment). However, vertical errors in LiDAR are too large to make them suitable for assessing small changes in surface elevation (< 0.1 m, Tempest, 2017). Localised measurements of sediment accumulation (e.g. using sediment pins or rods) provide a more accurate assessment of elevation change but can only do so on a local scale making whole-site estimates of sediment volume difficult. Nolte *et al.* (2013) provides an overview of methods to measure sedimentation in saltmarsh.

4.1.1 Requirement

- Localised measurements (e.g., sediment pins) must be used where sedimentation rates are low.
- Localised measurements must also be used to calibrate/ validate LiDAR DTMs to allow scaling up of carbon accumulation to the site-wide scale using the aerial extent of the strata.
- The total volume of sediment accumulating on each strata should be calculated[3].

[3] Instructions to do this are in development.

4.1.2 Requirement

- As a minimum, sedimentation/ erosion measurements must take place pre-breach, in year 1 following restoration, and then following the verification cycle.

More frequent measurements will provide more information on sediment accumulation rates.

4.1.3 Monitoring localised sediment accretion/erosion measurement

What. A simple but effective measurement of elevation change (i.e. sediment accretion or erosion) at a local scale.

Why. Quantifying the net volume of sediment accreted is half of the quantification of carbon accumulation.

Where. At all monitoring locations within a site, stratified as indicated above – a minimum of nine monitoring locations to include three replicates within each well-represented strata (e.g. strata that cover >10% of the site). Rarer strata can be sampled less intensively, with additional measurements added to more common strata (so that the number of monitoring locations remains nine or more). While a minimum of nine sampling locations must be established per site, the establishment of 15 locations for the monitoring of sediment accretion/ erosion is advised, with five sampling plots per strata for greater accuracy of measurements given the variable nature of sediment accretion/ erosion.

When. Installation must occur after any major construction or earth works but prior to site breaching to capture the pre-restoration surface. Post-breach monitoring sediment accretion/erosion must occur at the same time of year (ideally in summer) to minimise seasonal variation in sediment levels caused by wetting in winter and dewatering in summer.

How.

1) Drive two rods into the pre-restoration surface to approximately 0.5m deep.
2) Rods must stick out of the marsh by at least 0.5m.
3) Rods must be distanced apart (e.g. 0.5 m) such that an aluminium bar can be placed between them each monitoring visit.
4) Record the distance from the bottom of the bar to the site surface at 20 evenly spaced locations along the bar to the nearest mm.
5) Record vegetation type.
6) Ensure the location (GPS) of the rods are recorded.
7) Return and remeasure the distance between the bar and the surface to assess sediment accretion (smaller distance) or erosion (larger distance).
8) **WARNING.** Be careful not to trample around the two rods or between them, as this will affect your current measurements and could affect future ones.

Cost. Very low cost to install.

Time. Rods are easy to install and quick to check.

Data expectations. The method provides accurate assessment of local scale sediment accretion/erosion. Relationship between changes in elevation from pin measurements and those from the LiDAR pixel around the pins can be made to validate site-scale assessments from LiDAR.

4.1.4 Site-scale sediment accretion/erosion using LiDAR digital terrain models

What. A similar but effective measurement of elevation change (i.e. sediment accretion or erosion) at a site scale.

Why. Quantifying the net volume of sediment accreted is half of the quantification of carbon accumulation.

Where. Whole of restoration site below HAT (see Box 1).

When. 'Pre-restoration' digital terrain models should be obtained after any major construction or earth works but ideally immediately prior to breaching in order to capture the pre-restoration surface. If using publicly available data, then the availability of images close in date to the breach may be limited, so bespoke UAV surveys may be needed. Images taken prior to the breach might capture elevation changes due to construction, e.g. digging of the creeks. Images taken after the breach will not capture all of the sedimentation and/or erosion. Post-restoration DTMs should occur at the same time of year (ideally in summer) to minimises seasonal variation in sediment levels caused by wetting in winter and dewatering in summer.

How.

1) Obtain digital terrain models from publicly available data (if available) or from a specific UAV surveys.
2) Processing of DTMs can be conducted in specialist GIS software (including open access QGIS) or in other open licence software such as R.
3) Ensure where possible that DTMs are the same resolution (e.g. 1m for publicly available LiDAR). If they are not the same resolution, sub-sample images to the same resolution.
4) Clip DTMs by the site outline and by the level of HAT to ensure that only tidally influenced areas are analysed.
5) The difference between the pre- and post- restoration DTMs can be calculated and the total net change provides the total volume of sediment. This can then be expressed as the volume per hectare as calculated by the area of the site pixels analysed, and expressed as a rate if the difference in time between the two images is calculated.
6) The LiDAR changes in sediment can be checked and/or calibrated by comparing to the localised measurements. Extract the pixel from the DTM corresponding to each of the localised measurements, and compare the elevation change between the two measures.

Cost. Low cost if LiDAR tiles are publicly available. More costly if specific UAV flights are needed, especially for a large site.

Time. Very quick if LiDAR tiles are available. More time consuming if specific UAV flights are needed, especially for a large site, but specialist companies will do the basic processing of the images, i.e. will provide one image of the site.

Data expectations. The method provides estimates of the site scale sediment accretion/erosion. Relationship between changes in elevation from localised measurements and those from the LiDAR pixel around the rods can be made to validate site-scale assessments from LiDAR.

Potential issues: Sites where sedimentation rates are low (i.e. below or around the LiDAR error rates) cannot be accurately assessed with this technique. Sites with large amounts of standing water (e.g.

large pools) will also be inaccurately assessed due to the inability of LiDAR to fully penetrate water to the land surface.

4.2 Amount of carbon in the sediment

4.2.1 Requirement

- To accurately quantify the soil carbon pool, soil cores (with relevant subsamples) must be analysed for the following:

1) Dry bulk density
2) Soil organic carbon content (% C_{org})
3) Fraction of 'countable' carbon

Dry bulk density is a measure of soil dry weight (after drying) divided by original soil volume (sample collected in-situ using syringe or sub-sampled in the lab using water displacement). Dry bulk density and soil organic carbon content are used to calculate carbon density.

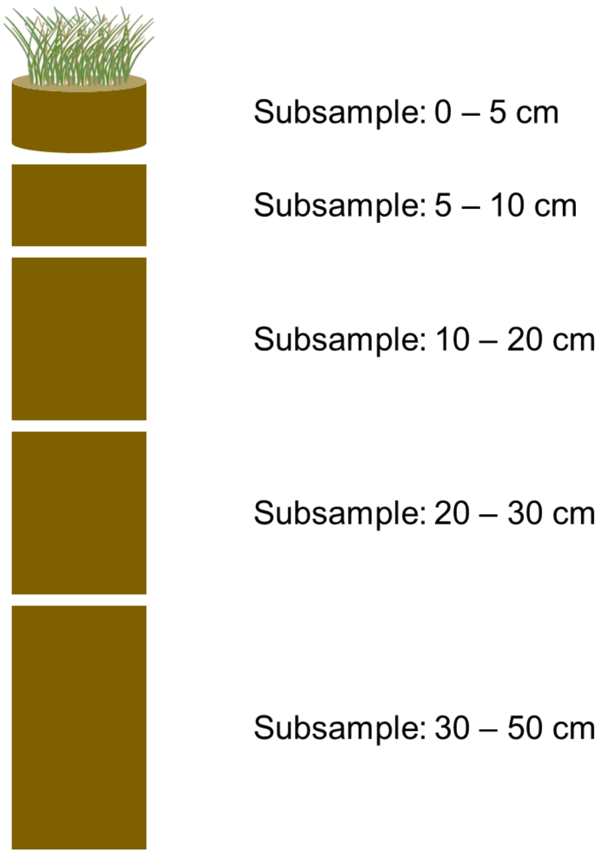
Ideally, core sampling would only sample the new sediment, i.e. not the underlying pre-restoration soils. However, it can be very difficult to identify the horizon between the two layers, and at high elevations, in early years of restoration or where sedimentation is slow, it can be difficult to effectively sample the thin layer of sediment laid down after restoration. The sampling depth of the sediment profile should be guided by site-specific sediment accumulation measured from in-situ measurements (Section 4.1.4; see Box 2).

Box 2. Sediment core depth

Due to a higher proportion of labile carbon (reactive carbon that is more quickly returned to the atmosphere) in upper layers of sediment, the sampling of just surficial sediments may lead to an overestimation of carbon accumulation rates. Conversely, sampling of deeper sediments may underestimate carbon accumulation rates by capturing mostly agricultural soil that existed prior to managed realignment, while presenting greater issues with core compaction.

For the most accurate measure of sediment carbon in a managed realignment scheme, sampling should strive to only capture the new sediment that has accumulated post-restoration. However, it is often challenging to locate the horizon between new sediment and the underlying agricultural soil. The sediment sampling depth at each monitoring location should be derived from the location specific sediment accretion (see Section 4.1.4), i.e. if 20 cm of sediment accretion has been measured at a given location, then you should core down to 20 cm.

The subsamples (or divisions) of a sediment core will depend upon the total depth of the core. The figure below shows the minimum number of subsamples required for a given depth, but higher resolution sampling is encouraged if possible.



Box 2 Figure. Sediment core subsamples. Variations in sediment carbon are greatest in the upper portions and require higher resolution sampling.

4.2.2 Taking cores

What. Coring device used to collect sediment cores and determine soil depth.

Why. Soil depth, dry bulk density and organic carbon content can be measured from sediment cores to inform organic carbon density and accumulation rates.

Where. At all monitoring locations within a site, stratified as indicated above – a minimum of 9 monitoring locations to include three replicates within each well-represented strata (e.g. strata that cover >10% of the site). Rarer strata can be sampled less intensively, with additional samples added to more common strata (so that the number of monitoring locations remains nine or more).

When. Refer to regularity of monitoring section above.

How. Detailed information on coring technique and soil coring devices can be seen in the Blue Carbon Handbook (pp. 44 - 45). Gouge augers or Russian corers are recommended. PVC tubes can also be cut to size and hammered gently into the sediment.

1) At the monitoring location, remove plant litter from sediment surface before inserting core.
2) Steadily insert the coring device vertically into the sediment until the top of the coring device is level with the soil surface. Slowly descend the core to avoid compaction.
3) Once at depth, twist the coring device to cut through any remaining fine roots. Gently pull the coring device from the sediment while continuing to twist.
4) Once the core has been removed, sub-sample the required depth, guided by measured sediment accumulation, and divide into sections at the resolution recommended (see Box 2), and discard the remainder of the core.
5) Record the vegetation community at the sampling point.
6) Following retrieval, core samples should be transported to the laboratory for analysis. To minimise decomposition of organic matter, samples should be kept in cold stores (4 °C) and either frozen or dried as soon after retrieval as achievable.

Note: for measurements of bulk density, a separate sample of known volume can be collected from surficial sediments using a syringe. However, we recommend using a sub-sampled section of the core (see bulk density methods below).

Cost. Relatively low cost although labour intensive.

Time. Highly dependent upon site area and number of sampling locations.

Data expectations. Direct measures of soil depth and material for laboratory analysis on dry bulk density and organic carbon content.

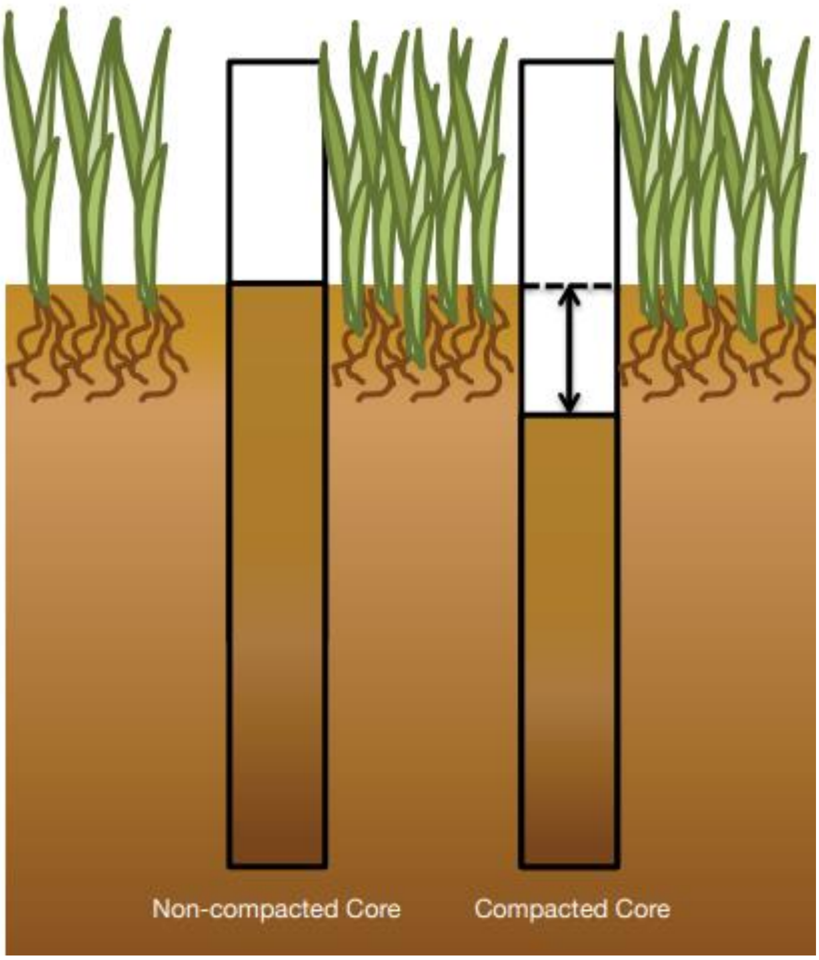
Potential issues. Care should be taken to limit core compaction; however, it can be unavoidable, and corrections will need to be made when it does occur (Box 3). Sediment volume is needed to calculate bulk density and can only be determined from intact cores, which are not always possible to retrieve. Alternative methods to measure sediment sample volume are provided below (section 4.2.3).

Box 3. Sediment core compaction

Information obtained from the Coastal Blue Carbon Manual (pp. 46 – 49).

Extracting sediment cores can lead to sediment compression which causes depth-variable changes in bulk density and may in turn affect the estimation of carbon stocks. Where possible, core compaction needs to be avoided and where it is significant, another sediment core should be retrieved nearby. However, where core compaction is minimal, and unavoidable, correction factors can be calculated by dividing the length of sample recovery by length of core penetration.

Sediment compaction is measured upon core retrieval as the difference between the length of core penetration and length of sample recovery. For example, sediment compaction is 3 cm when a recovered sample is 47 cm long and the depth reached by the corer was 50 cm. Compaction can also be measured between the sediment surface and the top of the sediment in the core sample using a ruler. A compaction correction factor can be applied by dividing the length of the recovered sample by the core depth (47 cm / 50 cm = 0.94).



Box 3 Figure. The top of a non-compacted core will be level with the surrounding ground (left). A compaction correction factor from a compacted core (left) is calculated by dividing the length of the recovered sample by the core depth [Source: Coastal Blue Carbon Manual).

4.2.3 Laboratory analysis of dry bulk density

What. Measures dry weight of a known volume of sediment.

Why. Quantifying the dry bulk density of sediment is half of the quantification of carbon density.

Where. Either on all sediment core subsamples collected across the site or on separate samples of known volume collected during sampling (e.g., via a syringe), depending on the chosen method.

When. Following sediment core collection and storage.

How.

1) Determine the volume of sediment samples by one of the following methods:
    a. Collecting a sample separate to the core sample using a syringe from which the volume can be measured directly.
    b. Using water displacement on a sub-sampled section of the core.
    c. An equation using the internal diameter of the coring device and sample thickness for intact cores only:
    $$[\pi \times (radius\ of\ coring\ device)^2] \times sample\ thickness$$
2) Sediment samples of a known volume are oven-dried until a constant weight is reached (60 °C, minimum 24 hours). After the initial 24 hours, samples should be removed from the oven and cooled to room temperature in a desiccator for at least an hour before weighing. The sample should then be weighed before returning to the oven to dry for at least another 12 hours and re-weighed. The drying cycle should be repeated until there is no difference in successive weight. Drying at 60 °C is recommended to avoid potential oxidisation of organic matter at higher temperatures.
3) Calculate dry bulk density (g cm^3) by dividing the sample dry weight (g) by the known sample volume (cm^3).

Cost. Low-cost and simple technology (oven).

Time. Relatively quick depending on the time taken for samples to dry to a constant weight. Time may increase depending on number of samples and capacity of ovens.

Data expectations. This method provides an accurate measure of the dry bulk density of a sample. This information is required to calculate carbon stock.

Potential issues. Oven-dried samples left in the open air for a long time prior to the measurement of dry weight may acquire moisture from the air. This can affect the accuracy of the measured dry weight of the sample.

4.2.4 Laboratory analysis of carbon from cores: Method One Elemental Analysis (**preferred method**)

What. A high temperature induction furnace detects the carbon and nitrogen (and potentially other elements) content of the sample using either infrared spectroscopy or gas chromatographic separation of gases and thermal conductivity.

Why. Quantifying the organic carbon content of sediment is half of the quantification of carbon density.

Where. On all sediment core subsamples collected across the site.

When. Once sediment samples have been oven-dried and homogenised using a pestle and mortar or ball mill.

How. Detailed methods on measuring organic carbon content (%), including methods to correct for inorganic carbon, can be seen in the Blue Carbon Handbook (pp. 54 – 63). Where instrumentation and expertise are available, thermogravimetric analysis can be used to determine the organic and inorganic carbon composition of samples.

1) Sediment samples are oven-dried (60 C, minimum 24 hours) to a constant weight (see step 2 under laboratory analysis of dry bulk density above) and homogenised to a fine powder using a pestle and mortar or ball mill.
2) Dried and ground core samples are weighed accurately to determine the mass of the sediment (**M_{SED}**)
3) Sediment sub-samples (10 – 15 mg), and standards with a known elemental composition, are weighed into foil boats.
4) Sub-samples are run through the elemental analyser where the total carbon content (organic and inorganic carbon) is measured. This can be corrected to organic carbon content by determining the inorganic carbon content. Note: some instruments (e.g., Elementar Soli TOC) use a temperature gradient method to quantify organic and inorganic fractions from a single untreated sediment sample.
5) Additional sub-samples from the dried and ground core samples are heated in a furnace to combustion (see Method Two: Loss on Ignition) to remove organic carbon leaving only inorganic carbon in the ash. The carbon content of the decarbonated sample re-run through the elemental analyser can then be subtracted from total carbon to provide the organic carbon content.

Note: Samples can also be treated with acid to remove carbonates and inorganic carbon. Methods for the removal of inorganic carbon via acidification include variations in acid type, strength, volume, time and temperature. Samples are weighed before and after acidification. Elemental analysis of the decarbonated samples ($\%OC_{decarb}$) provides a measurement of the %OC of the remaining material, which is then corrected to the %OC original sample mass ($\%OC_{corrected}$):

$$\%OC_{corrected} = \%OC_{decarb} \cdot \left(\frac{mass\ after\ decarb}{mass\ before\ decarb}\right)$$

If you have used the acid decarbonation method, you will need to separately combust the samples (see Method 2: Loss on Ignition) to calculate the proportion of the carbon that is countable.

Cost. Costly – requires specialist equipment and technical expertise.

Time. Relatively quick depending on availability of equipment and expertise.

Data expectations. This method provides accurate measurements of carbon content (%). Accurate measurements of organic carbon content (%) can be achieved via corrections for inorganic carbon detailed above. Organic carbon density can be calculated as the product of organic carbon content and dry bulk density.

Potential issues. Instrumental drifts can occur during the sequence which may skew results. However, such drifts can be corrected for. The precision of the elemental analyser measurements must be monitored using standards of a known carbon content and where possible, using an internal standard with an elemental composition similar to that of the samples.

4.2.5 Laboratory analysis of carbon from cores: Method Two Loss on Ignition (LOI) (not preferred)

This method is not the preferred method and if you choose to use this method, please contact a member of the Code team to discuss.

What. Measures mass of sample lost when heated to moderate temperature, thus giving an indication of the organic matter content.

Why. Measuring organic matter via combustion is a cheap and simple method which can be used as a proxy for organic carbon content.

Where. On all sediment core subsamples collected across the site.

When. Once sediment samples have been oven-dried and homogenised using a pestle and mortar or ball mill.

How.

1. Weigh sample into ceramic crucible.
2. Heat in a furnace to 105 °C (4 hrs) to remove water.
3. Re-weigh to determine water content.
4. Heat in a furnace to combust organic matter (e.g. 500 °C for 12 hrs, see footnote[4]). This temperature ensures organic matter is oxidised without carbonate mineral decomposition.
5. Re-weigh sample following combustion.
6. Sample mass loss on ignition can be used to calculate organic matter content:
$$Organic\ matter\ content\ (\%LOI)\ = \frac{Mass\ after\ 105\ °C\ -\ Mass\ after\ 500\ °C}{Mass\ after\ 105\ °C}$$
7. Convert the organic matter content into an estimate of organic carbon content using an appropriate equation.

Cost. Low-cost and simple technology (furnace & crucibles)

Time. Quick. Throughput is limited by availability of crucibles and oven space. One batch of samples can be analysed per day.

[4] Furnace temperature between 450 and 500 °C should be used. Temperatures above 600 °C result in the loss of carbonates and inorganic carbon (Wang & Wang, 2011), leading to an overestimate of organic carbon content. Temperatures close to 550 °C are not recommended because many ovens may not be well calibrated, and the temperature ramp rate could potentially take it over 600 °C.

Data expectations. This method provides accurate and precise measurements of organic matter. From this, conversion factors can provide estimates of organic carbon content.

Potential issues. Conversion equations are required to estimate organic carbon content from organic matter and this method can only provide an estimate of the organic carbon.

Best practice would involve generating a bespoke conversion equation[5] for each site using another method, for example elemental analysis (see Method One above). This requires funds, instrumentation, and technical expertise. In the absence of a site-specific equation, a series of general-use equations have been defined.

Smeaton *et al.* (2002) defined a conversion for GB natural marshes:

$$OC\ (wt\%)\ =\ 0.377\ \times OM\ (wt\%)\ +\ 1.452$$

Craft *et al.* (1991) has the calculated the conversion for young saltmarsh in the USA:

$$OC\ (wt\%)\ =\ 0.4\ \times OM\ (wt\%)\ +\ 0.0025$$

Given the very small intercept value (0.0025) and the reasonable assumption that all OC will be associated with OM, this simplifies to:

$$OC\ (wt\%)\ =\ 0.4\ \times OM\ (wt\%)$$

4.2.6 Assessing 'countable' carbon using the default equation: Method One using loss on ignition coupled with elemental analysis.

If the combustion version of Method One (Section 4.2.4) is used, then no further laboratory analysis is needed. We recommend this approach.

1) Dried and ground core samples is weighed accurately to determine the mass of the sediment (**M_{SED}**)
2) Organic matter is removed through loss on ignition as described above
3) The mineral mass of the sediment (**$M_{MIN\text{-}I}$**) is calculated from loss on ignition.
4) The amount of carbon that needs to be deducted (**OC_{deduct}**) is calculated from using the equation $OC_{deduct} = 0.01612 \times M_{MIN\text{-}I}$[6].
5) The total C content of the sediment **(TC_{SED})** is determined from elemental analysis of the dried and ground bulk sample (Section 4.2.4).
6) The mineral (inorganic) C content of the sediment **$IC_{MIN\text{-}I}$** is determined from elemental analysis of the combusted sample, expressed as wt% of the bulk sediment (**$IC_{MIN\text{-}I}$** = **$IC_{measured}$*****f_{MIN}-I**, where **f_{MIN}-I** = **$M_{MIN\text{-}I}/M_{SED}$**)

[5] A controlled test using certified reference materials demonstrated that no published conversion equation could accurately report organic carbon from a variety of starting sediments, with errors significantly different from the expected value in many samples (Sparkes *et al., in review*). The discrepancy is particularly high at low organic carbon concentrations, as may be found in managed realigned saltmarsh sediments. Therefore, a site-specific link between organic carbon (combustion-elemental analysis) and organic matter (loss on ignition) datasets is recommended.

[6] The equation for the deductible carbon is presented in Dunk et al. (2024) Countable Carbon Study: Literature Review Summary Report. MMU/Jacobs. Report to the Environment Agency. It is derived unreactive mineral-bound organic carbon from UK-wide continental shelf sediments.

7) The total organic C content of the sediment $\mathbf{OC_{SED}}$ is determined by difference, $\mathbf{OC_{SED}} = \mathbf{TC_{SED}} - \mathbf{IC_{MIN\text{-}I}}$
8) $\mathbf{OC_{count}}$ is calculated from $\mathbf{OC_{SED}} - \mathbf{OC_{deduct}}$
9) The Carbon Abatement Calculator will provide equations to calculate the deductions[7]

4.2.7 Assessing 'countable' carbon using the default equation: Method Two using loss on ignition only

1) Dried and ground sample is weighed accurately to determine $\mathbf{M_{SED}}$
2) Organic matter is removed through loss on ignition (furnace: 500 °C, 12 hours)
3) Sample is reweighed to determine $\mathbf{M_{MIN\text{-}I}}$
4) $\mathbf{OC_{deduct}}$ is calculated from $\mathbf{M_{MIN\text{-}I}}$ using equation $OC_{deduct} = -0.01612 \times LOI + 1.61248$
5) $\mathbf{OM_{LOI}}$ is calculated from the mass loss $\mathbf{M_{SED}} - \mathbf{M_{MIN\text{-}I}}$
6) $\mathbf{OM_{LOI}}$ is converted to $\mathbf{OC_{LOI}}$ using a conversion factor (see above)
7) $\mathbf{OC_{count}}$ is calculated from $\mathbf{OC_{LOI}} - \mathbf{OC_{deduct}}$
8) The Carbon Abatement Calculator will provide equations to calculate the deductions[8]

4.3 Processing carbon and sediment data

4.3.1 Accounting for labile carbon loss with time/depth

Sediment bulk density and organic carbon contents vary with depth and location. As such, there is not always a consistent pattern of carbon density with depth. Some labile carbon will be degraded over time, observed by lower carbon densities with depth.

4.3.1.1

- The changes in carbon in the down-core subsamples must be used to identify the loss of carbon with depth[9].

4.3.2 Upscaling carbon accumulation rates

What. Carbon density measures from each sediment core used to upscale carbon accumulation rate to a site-wide value.

Why. Following deduction of 'uncountable carbon' (Section 4.2.5/ 4.2.6), carbon accumulation rates are used in the determination of carbon credits for a project.

Where. On all sediment cores collected across the site.

When. Following measurements of sediment accretion and laboratory analysis of dry bulk density and organic carbon.

How[10].

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[7] Carbon Abatement Calculator in development
[8] Carbon Abatement Calculator in development
[9] The Carbon Abatement Calculator (in development) will provide details to analyse this, and a worked example will be provided here.
[10] A worked example of calculations with formulas will be included and provided in the Carbon Abatement Calculator (in development).

1) Multiply dry bulk density by organic carbon (%) to generate carbon density for each core.
2) To obtain carbon density per strata, multiply the average carbon density obtained for each core by the area of the corresponding stratum, as determined by LiDAR. Repeat for each stratum.
3) Sum average carbon density from each stratum to generate total carbon density in the project area.
4) To obtain a site-wide value for carbon accumulation rate, multiply total carbon density in the project area by site-scale sediment accretion rate.

Cost. No cost associated with calculation and upscaling but see previous sections for costs associated with data collection.

Time. Relatively quick depending on availability of data.

Data expectations. An estimate of average carbon density for each stratum and an extrapolated rate of carbon accumulation at the site-scale.

Potential issues. Units of measurements must be standardised[11].

4.4 Assessment of vegetation communities

An assessment of broad vegetation communities (mudflat, annuals, perennials, and phragmites; see footnote[12]) in a project area may be useful for determining site eligibility and inclusion criteria. At this stage, an assessment of vegetation communities does not inform carbon or sedimentation rates but will be most useful when used alongside proxies that are being developed and will be included in later versions of the MRV document.

4.4.1 Percentage cover of vegetation types

What. Measure of vegetation cover at a local (plot level) and site-wide scale across each broad vegetation category (mudflat, annual, perennial, and phragmites).

Why. Broad vegetation communities contribute different amounts to the carbon pool via structural differences. Monitoring the changes in the vegetation composition as it develops on a site will therefore provide knowledge on the amount and source of the carbon and the biodiversity.

Where. At all sampling locations where sediment cores are collected – a minimum of 9 monitoring locations to include three replicates within each well-represented strata (e.g. strata that cover >10%

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[11] Specific units of measurements for standardisation will be recommended.

[12] Differences in carbon storage potential among saltmarsh vegetation communities is well researched, particularly in relation to vegetation zones. It is therefore recommended that monitoring captures the variation in vegetation communities within a site, which will likely be achieved through site stratification. The categorisation of vegetation communities into four broad types (mudflat, annual, perennial, and phragmites) is recommended to aid identification among non-specialists and to avoid issues within classification schemes (e.g., National Vegetation Classification (NVC) system, which does not effectively characterise communities from restored saltmarshes). Variation in carbon stocks and accumulation rates among species in a broad category (e.g., annual *Salicornia spp.* vs annual *Suaeda maritima*) is likely much smaller than the variation between broad categories (e.g., annuals vs perennials). Alternative categories of the vegetation communities, especially with regard to biomass, are currently being investigated.

of the site). Rarer strata can be sampled less intensively, with additional samples added to more common strata (so that the number of monitoring locations remains nine or more).

When. Refer to regularity of monitoring section above.

How. At each sampling location in a site:

1) Survey the presence/ absence of each vegetation community (mudflat, annuals, perennials, phragmites) in a 1 m^2 area.
2) Assign each present vegetation community in the survey area a percentage cover. Note: using a 1 m^2 quadrat divided into smaller frames can aid in the estimation of percentage cover (e.g., each 25 square frames in a quadrat would represent 4 %).
3) To assess the percentage cover of vegetation communities at the site-scale, the cover of each community needs to be averaged across each stratum, multiplied by stratum area, and summed across each stratum in the site.

Cost. Minimal.

Time. Variable depending upon site area and number of sampling locations.

Data expectations. An average estimate of percentage cover of vegetation communities for each stratum and across the site. This information may be necessary for the eligibility criteria of a site [in development]. Remote sensing techniques can be developed to assess site-wide vegetation communities.

Potential issues. Monitoring of vegetation percentage cover is most useful alongside proxies for biomass and carbon content for the broad vegetation types. Such proxies are under development and will be included in later versions of the MRV document.

4.5 Additional monitoring

The following monitoring is optional and in addition to those explained in Section 4.1 – 4.4 above. It is recommended that these methodologies are only used if a research project is running alongside the restoration project, or as a development activity to improve the knowledgebase for development of proxy measures.

4.5.1 Assessing the vegetation and its carbon

Carbon conversion factors for saltmarsh vegetation communities are currently in development using data collected from managed realignment sites across England.

4.5.1.1 Aboveground living biomass

What. Measures above-ground biomass across plant communities.

Why. The living above-ground biomass is a carbon pool in saltmarshes.

Where. At all sampling locations where sediment cores are collected – a minimum of 9 monitoring locations to include three replicates within each well-represented strata (e.g. strata that cover >10% of the site). Rarer strata can be sampled less intensively, with additional samples added to more common strata (so that the number of monitoring locations remains nine or more).

When. Refer to regularity of monitoring section above.

How. Sampling should take place when biomass is at its peak growth in the summer months. Drying of vegetation cuttings should take place shortly after collection to avoid decomposition.

1) Vegetation clippings should be removed a 25 cm^2 or 30 cm^2 quadrat and stored in a cold environment (4 °C).
2) To determine above-ground biomass, clippings are oven-dried (60 °C, minimum 72 hours) to a constant weight.
3) Carbon content in biomass can be measured using an elemental analyser or using a carbon conversion factor from the peer-reviewed literature if available.

Cost. Low-cost.

Time. Quick depending on amount of sample and oven capacity.

Data expectations. This method provides an accurate measure of biomass from which the carbon content of vegetation pools can be estimated.

Potential issues. Carbon conversion factors for saltmarsh plant species in the UK are limited and/or not available.

4.5.1.2 Belowground living biomass (roots and rhizomes)

What. Measures below-ground biomass across plant communities.

Why. The living below-ground biomass (dominated by roots and rhizomes) contains most of the carbon of the overall vegetative biomass.

Where. At all sampling locations where sediment cores are collected – a minimum of 9 monitoring locations to include three replicates within each well-represented strata (e.g. strata that cover >10% of the site). Rarer strata can be sampled less intensively, with additional samples added to more common strata (so that the number of monitoring locations remains nine or more).

When. Refer to regularity of monitoring section above.

How. Samples are collected by extracting a core (see details above).

1) Narrower cores with a diameter between 2.5 and 5 cm are recommended.
2) Sediment cores are then washed over a 1 mm sieve. Dead material is removed.
3) Living below-ground roots and rhizomes are oven-dried (60 °C, minimum 72 hours) to a constant weight.
4) Below-ground biomass is calculated by dividing the dry mass of the sample by the wet mass.
5) Carbon content in biomass can be measured using an elemental analyser or using a carbon conversion factor from the peer-reviewed literature if available.

Cost. Low-cost.

Time. Quick depending on amount of sample and oven capacity.

Data expectations. This method provides an accurate measure of biomass from which the carbon content of vegetation pools can be estimated.

Potential issues. Carbon conversion factors for saltmarsh plant species in the UK are limited and/or not available.

4.5.2 Greenhouse Gas emissions

Measuring greenhouse gas (GHG) flux directly is vital to furthering our understanding of the full carbon balance of restoration sites. Many carbon gain estimates of restoration are based on stock change assessments only, but GHG uptake or release could have a large impact on whether these sites are deemed sinks or sources of carbon. Furthermore, building up a dataset of new direct empirical GHG measurements alongside contextual variables will also allow for development of proxy measures, reducing the cost and expertise needed to estimate the GHG flux. However, measurement of GHG fluxes involves substantial technical expertise and specialist equipment, and we therefore only recommend these measurements where it is possible to work alongside a research team. Here, we briefly describe methods for measurement only. There is additional data management, processing, and analysis tasks not included here as they require specialist expertise.

4.5.2.1 Static chamber method

What. Measures gas exchange between the land-air interface at localised scales.

Why. Greenhouse gas flux is a key component of the overall carbon balance of a site.

Where. We recommend using a subset of three of five replicates per strata used for the other monitoring.

When. Monthly, or at least bimonthly to cover all seasonal changes.

How.

- To take these measurements, the following equipment is needed:
  - a flux chamber
  - Permanent collars in the ground for the chamber to sit on
  - A lid for the chamber
  - A way to measure and log auxillary measurements such as PAR, air, and soil temperature
  - A portable greenhouse gas analyser
- The chamber is placed on top of the permanent collar and the lid is placed on the chamber. Both are sealed in place to create a closed loop system with the analyser.
- Gas samples are drawn from the chamber, through the analyser, and back to the chamber. The analyser measures and logs the changes in gas flux in near to real time.
- Light and dark chambers are used to estimate net ecosystem exchange (NEE) and ecosystem respiration (R_{eco}). A series of measurements with various shading between fully light and dark are also recommended to develop light response curves.

Cost. High

Time. High due to repeat visits, and the time needed for data management and analysis

Data expectations. High quality, detailed flux data targeted to specific areas and/or vegetation types.

Potential issues. Provides 'snap shot' fluxes, and due to logistically difficulties is often only taken in the day and good weather conditions. It is not advised to use portable greenhouse gas analysers whilst it's raining, or at very high or low temperatures, which may also limit data collection.

4.5.2.2 Flux Towers

What. Measures gas exchange between the land-air interface in three dimensions over large areas.

Why. Greenhouse gas flux is a key component of the overall carbon balance of a site.

Where. Flux towers measure a large area (called a footprint). They need to be located downwind of the prevailing wind direction.

When. Ideally before restoration occurs to obtain baseline data and to catch all fluxes from the moment restoration occurs. However, they can be installed at any time and will still contribute valuable data

How.

- Installing a flux tower needs a specialist team due to the complexity of the equipment, and the site-level planning needed. Every install will be different due to local conditions.
- Additionally, once a flux tower is installed it will need maintenance, the regularity of which will again depend on site conditions (mostly exposure) and which GHGs are being measured. Equipment measuring CH4 as well as CO2 will need more regular maintenance than CO2 only.
- The power source (most likely a solar array with battery storge, but can sometimes be mains power) and signal strength for telemetry both need to be considered in detail prior to installation as having reliable power and automated data streaming will make maintenance much easier and time efficient.
- Choosing a locating for a Flux tower: The size of the fetch is dependent on the height of the flux tower, which is in turn dependent on the highest expected water level at the specific location (to always keep equipment out of the water). There is a roughly 1:100 ratio of height to fetch, meaning a 3m tower needs a 300m unobstructed view (the fetch) of saltmarsh upwind of its location.

Cost. High.

Time. Initial high time investment. If power and telemetry are optimised, maintenance of CO2 only systems can be reactive, and the systems are able to work for months without intervention.

Data expectations. High quality, continuous, and detailed flux data representative of a large area. Data streams need to be managed with a trackable QA and QC procedure.

Potential issues. Financially expensive and can be time intensive. The data is representative of a large area which, although also a strength, means smaller-scale (by area) differences in GHG flux will not be represented. If a finer resolution is needed, flux tower operation can be combined with chamber measurements of GHGs, which combined with a vegetation survey of the flux tower footprint would allow for the overall flux to be attributed to differing vegetation types. A similar approach could be used for saltmarsh zone, or any other environmental or physical characteristic thought to explain spatial variation of GHG flux.

4.5.3 In situ values for countable carbon

This section is in development.

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