Ecological Indicators 178 (2025) 113867

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Monitoring UK saltmarsh restoration using earth observation for national greenhouse gas accounting

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ARTICLE INFO

Keywords:
Saltmarsh
Managed realignment
Greenhouse gas inventory
Earth observation
Normalised difference vegetation index

ABSTRACT

Saltmarsh habitats are recognised for their role in long-term sequestration and storage of 'blue carbon'. Historically, saltmarshes have been subject to high levels of drainage and land-use change, resulting in past CO_2 emissions. However, reversing these management practices through rewetting and revegetation of saltmarsh at coastal realignment sites presents opportunities to sequester carbon as part of a nature-based mitigation against climate change. We used Google Earth Engine to develop a model based on satellite data that can monitor annual saltmarsh vegetation cover changes following restoration across five UK test sites. Classification of saltmarsh communities was ultimately based on monthly 75th centile Normalized Difference Vegetation Index (NDVI) values, which represents "greenness" of the land surface, to minimise the effect of tidal phases. Model results demonstrate a useful method for historic and continued monitoring of saltmarsh habitat condition, with initial accuracy of 62% for the NDVI classification. However, when classification was simplified into vegetated versus bare soils (i.e. the criteria for inclusion into national GHG inventory reporting) accuracy of over 90% was reported. This method provides a living picture of colonised saltmarsh that could be upscaled for tracking the carbon removals associated with saltmarsh restoration and management in GHG inventories.

1. Introduction

Blue carbon (BC) habitats, such as saltmarshes have been subject to high levels of historic modification by drainage and land-use change, with ~ 85 % of saltmarsh area lost from estuaries in England (ECSA 2016). Recent global estimates suggest that saltmarsh loss is continuing to be a global problem with nearly 1,500 km^2 of saltmarsh lost globally between 2000 and 2019, equivalent to a loss rate of 0.28 % $year^{-1}$ (Campbell et al. 2022). Due to the high rate of carbon (C) accumulation in saltmarshes, associated with their high productivity and efficiency for trapping sediment, and their importance for long-term storage of C in sediments, there is gathering momentum for their preservation and restoration as a nature-based solution to mitigate against climate change (Mcleod et al. 2011, Hudson et al. 2021, Mason et al. 2023). Additionally saltmarshes exemplify a wide range of adaptation co-benefits to climate change including improved flood water storage, shoreline protection from storms, habitat provision and improvements to biodiversity (Jones et al. 2012, Temmerman et al. 2013). Managed realignment of coastal areas, via the deliberate breaching of a seawall, reinstates land to sea connectivity, enhancing the exchange of water, sediment and nutrients to encourage the creation of coastal habitats, which can play an important role in driving habitat heterogeneity for fish and bird species, plant regeneration, providing natural buffers of wave energy for flood defence, soil carbon sequestration and avoided emissions from degraded land (Dausse et al. 2012, Burden et al. 2013a, Rosentreter et al. 2023). Management actions that aim to rewet and recreate saltmarsh habitats, through the removal or breaching of hard engineered sea defences, now present opportunities to sequester CO_2, which could be included in Nationally Determined Contributions (NDCs) to reduce greenhouse gas emissions (GHG) (Crooks et al. 2018).

1.1. Reporting saltmarsh restoration in GHG inventories

Countries that are party to the United Nations Framework Convention on Climate Change, report their annual estimates of GHG emissions associated with anthropogenic activities to track progress towards

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https://doi.org/10.1016/j.ecolind.2025.113867
Received 17 December 2024; Received in revised form 23 June 2025; Accepted 7 July 2025
Available online 17 July 2025

international emission reduction commitments. To achieve these, the role of habitats such as saltmarshes that can function as a carbon sink becomes increasingly important under the Land Use, Land Use Change and Forestry (LULUCF) sector (IPCC, 2014), which is currently the only inventory sector in which countries can report a net sink and potentially offset anthropogenic emissions from elsewhere. However, the UK is lacking spatial datasets to monitor the outcomes of saltmarsh restoration (e.g. presence of saltmarsh plant communities) to include these habitats in the UK GHG inventory (BEIS 2021, Burden and Clilverd 2021).

The Intergovernmental Panel on Climate Change (IPCC) Wetlands Supplement (IPCC, 2014) provides guidelines for accounting for GHG emissions and removals from Wetlands, including management and restoration of saltmarsh, which has initiated reporting of saltmarsh habitats in national inventories in the USA and Australia (UNFCCC, 2023). For areas of saltmarsh created during managed/unmanaged coastal realignment to be included in a country's NDCs, the Tier 1 (IPCC default) methodology states that at least 10 % of the area needs to be vegetated before carbon dioxide emission changes associated with initiation of soil organic carbon accumulation can be counted (IPCC, 2014). However, it is good practice to use a country-specific approach (IPCC, 2014) that recognises national conditions. In the UK, the seaward extent of saltmarsh is often mapped to 5 % vegetation cover (NRW, 2017, EA, 2023) with the upper limit usually defined within the inland limit of halophytes, where they become $\leq$ 5 % of the terrestrial community. Definitions of saltmarsh extent for UK NDCs are being developed (Burden et al., 2024). National mapping datasets relate National Vegetation Classification (NVC) saltmarsh communities to functional zones: bare sediment/unvegetated, pioneer, low-mid marsh, high/upper marsh, which follow the Water Framework Directive metric requirements (WFD, 2014) (see Table 2). When a previously drained site undergoes managed realignment the site undergoes the following broad trajectory: sea walls are breached allowing the site to flood with salt water; terrestrial herbaceous vegetation dies off due to salt and inundation, bare ground develops and creek systems begin to form, annual pioneer saltmarsh species colonise the bare ground, and over time perennial saltmarsh species colonise the site (e.g. Garbutt et al., 2006, Friess et al. 2012). Pioneer species can colonise the site extremely rapidly, with some coverage occurring within the first year, meaning that these areas can be included in NDCs. At present there is insufficient data on greenhouse gas fluxes and carbon accumulation changes from saltmarsh to apply different emission factors (GHG emission/removal per unit area) to pioneer marsh and areas of more established saltmarsh (Burden and Clilverd, 2021, Mason et al., 2023).

1.2. Earth observation mapping of saltmarsh

Remote sensing strategies to map blue carbon stocks, including those in saltmarshes, have become increasingly used over the past 10 years (reviewed in Pham et al., 2023), though issues with passive satellite remote sensing, including hyper-spectral and multi-spectral approaches, such as cloud cover, atmospheric interference, and limitation to daylight hours have provided ongoing challenges in the use of this data for all habitats. Coastal saltmarshes are particularly challenging ecosystems to monitor using earth observation (EO) data due to their geomorphological and botanical variability over fine spatial scales, resulting from fluvial networks, salinity and inundation gradients (Hickey and Bruce, 2010), and due to the dynamic state of the tidal cycle (Gallant, 2015). Previous studies using single date images to assess saltmarsh vegetation have suggested that only images from the lower parts of the tidal cycle are used to minimise the impacts of inundation on classification (Légaré et al., 2022, Alam and Hossain, 2023) but this can significantly increase the data processing required at a national scale in order to account for the variation in tidal cycles and image acquisition timescales when selecting the relevant images.

The Normalised Difference Vegetation Index (NDVI) is widely accepted as a stable indicator of plant biomass, phenology and photosynthetic performance (overall "greenness") of vegetation including saltmarsh vegetation (Kerr and Ostrovsky, 2003). NDVI is a dimensionless index with values between 1 and −1 calculated from the difference between red and infra-red reflectance and is used to detect vegetation cover. Areas with very high vegetation cover will have values close to 1, while areas of bare ground and open water will have values at or below 0. The succession of saltmarsh colonisation from bare ground to perennial species means that the NDVI values and seasonal patterns can be used to delineate open water, bare ground, areas of annual vegetation and areas of perennial vegetation (Sun et al., 2018) and previous studies have found that NDVI can detect differences in saltmarsh vegetation (Sun et al., 2016, Sun et al., 2018, Yeo et al., 2020, Légaré et al., 2022, Warwick-Champion et al., 2022) but few studies have used time series of NDVI values to detect changes in saltmarsh vegetation over time (Sun et al., 2018). Results from the use of NDVI to determine saltmarsh vegetation communities have found that using a 12-month time series of images achieved increased accuracy over the use of single images (Sun et al. 2018). The advantages of using NDVI over land cover classification are due to its simplicity and reduced computational demand, while accurately discriminating vegetation from other surface types.

This study investigates if EO data and methods can effectively track changes in saltmarsh areas to improve our understanding of the outcomes of management actions that aim to create and restore saltmarsh (Hudson et al. 2021). The goal is to quantify the dynamic losses and gains in saltmarsh area due to erosion and settlement/colonisation. This information is key to including saltmarshes in the LULUCF sector of the UK Greenhouse Gas Inventory (GHGI), that ultimately will help monitor actions to protect and restore these habitats. The objectives are two-fold, to: 1) develop an application of Google Earth Engine (GEE) to evaluate land use and vegetation composition within managed realignment sites across the UK, with ground-truthing of satellite-determined vegetation cover at field sites; 2) produce a time series (2018–2022) of saltmarsh areas that could enable associated changes in carbon accumulation to be estimated for GHG reporting (e.g. using an area × emission factor approach).

2. Methodology

2.1. Study sites

The study was conducted across the UK, at five sites located between 50.7° and 57.7°N, and 4.1°W and 0.8°E (Fig. 1). Average temperature from 2001 to 2021 was 10.2 °C in England, 9.6 °C in Wales, and 7.8 °C in Scotland. Annual rainfall from 2001 to 2021 averaged 1,163 mm in the UK, 908 mm in England, 1516 mm in Wales, and 1,579 mm in Scotland (Kendon et al. 2022).

Five contrasting managed realignment (MR) study sites (Table 1) were selected from the OMREG database of completed coastal habitat creation schemes (https://www.omreg.net). No MR sites were reported for Northern Ireland. Selected sites included established and newly created marsh (1–3 yrs) to capture rapid changes in colonisation and sediment supply following rewetting. The sites also cover natural gradients of environmental and physical characteristics that are thought to influence the evolution of saltmarsh habitat over time. Relative sea level rise increases from the northwest to the southeast (Shennan et al. 2009), sediment supply generally increases south to north (Ladd et al. 2019), and soil type differs between the west (sand dominance, greater mineral content) and east (silt/clay dominance, greater organic content) coasts. The restoration activities undertaken at the study sites were multi-purpose – to improve flood protection, create new intertidal habitat, improve biodiversity, naturalise the coastline, and for recreation. Ordered by location, north to south, the restoration study sites are:

- Meddat Marsh, Nigg Bay, Scotland's first coastal realignment – restored in February 2003, involving 20 m-wide breaches in the

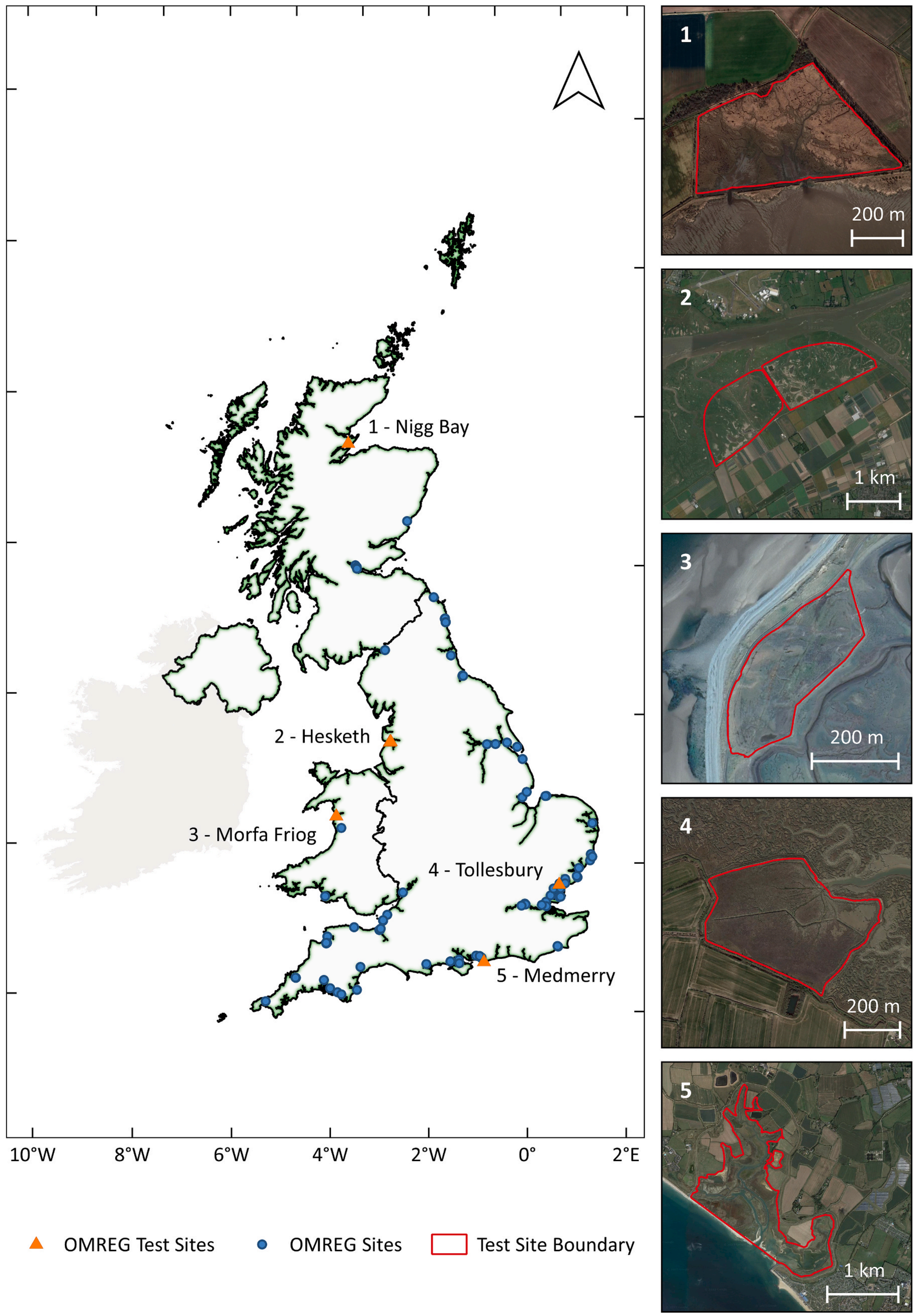

Fig. 1. Managed and unmanaged realignment sites across the UK (from https://www.omreg.net, accessed May 2023), and five selected EO test sites in England, Scotland, and Wales. Satellite imagery and site boundaries from each test site are shown inset.

Table 1
Restoration information for the five study locations (NB: Hesketh is separated into 2 sites by restoration date), ordered by location north to south, from https://www.omreg.net/.

Scheme Name	Country	Previous Land Use	Year Restored	Area Reported by OMREG (ha)
Nigg Bay (Meddat Marsh)	Scotland	Grassland – rough grazing cattle	2003	25
Hesketh Out Marsh West	England	Arable	2008	180
Hesketh Out Marsh East	England	Arable	2017	160
Morfa Friog	Wales	Mesotrophic grassland	2015	7.5
Tollesbury	England	Arable	1995	21
Medmerry	England	Pastoral grassland; arable	2013	302

Table 2
Saltmarsh zone for saltmarsh (SM) communities as defined by National Vegetation Classification (NVC) in existing mapping resources for Scotland (NatureScot 2016), England (EA 2023), and Wales (NRW 2019), including types not present in these datasets.

	Scotland	Wales	England
Pioneer	SM3-9, SM11-12	*(see "Low" description)*	SM7-SM9
Low	SM10, SM13a	SM4-SM15	
Mid	SM13b-13f, SM14-15	SM16-SM23	–
Mid-Low	–	–	SM10-SM13, SM16-17, SM21-23
Upper	SM16a-SM16f, SM17-23, SM26-27	SM24-SM28	SM18-SM20, SM24-SM28

existing sea wall to reconnect approximately 25 ha of land with the sea. Prior to restoration, the land was used as rough grazing for cattle. Vegetation surveys conducted nine years after the realignment found that 93 % of quadrats sampled contained saltmarsh plant communities, 6 % wet grassland and 1 % bare mud, which established rapidly following restoration, indicating overall success of the scheme (Elliott 2015). The study area was defined using the Saltmarsh Survey of Scotland (SMSS) spatial layer (NatureScot 2016).

- Hesketh Marsh (West and East), Ribble Estuary, north-west England – adjacent sites that, respectively, were restored in 2008 and 2017, and total project areas of 180 ha and 160 ha. The seawall was breached in four locations at each site, including preparatory work to excavate the historic creek network, which has resulted in multiple branched creeks across the restored marshes, as well as the excavation of ponds for seabirds. Prior to restoration, the sites were agricultural land. The managed realignment at Hesketh West was rapidly colonised by pioneer and lower saltmarsh habitat across the site, predominantly by an SM13a *Puccinellia maritima* vegetation community type (Skelcher, 2015, Fellows and Shirres, 2017). At Hesketh East, substantial mud deposition occurred in the early stages after the realignment followed by the development of algal mats. Subsequently, significant colonisation of halophytic plants occurred from 2019, supporting established pioneer communities of *Atriplex* sp., *Salicornia* and *Puccinellia* (Gledhill 2020). The study areas for both sites were defined using the Environment Agency (EA) zonation layer (EA 2023).
- Morfa Friog, Mawddach Estuary, Wales – restored in 2015 via a small breach that was excavated in the bordering flood embankment, to create approximately 7.5 ha of coastal wetland. The site was previously a mesotrophic grassland, presumably used for grazing, which was replaced by pioneer saltmarsh vegetation by 2019, predominantly *Salicornia spp*. The study area was defined using the Natural Resources Wales (NRW) habitat survey layer (Lush and Lewis, In press).
- Tollesbury, Blackwater Estuary, Eastern England – restored in 1995 – is one of the earliest realignment sites in the UK. The managed realignment involved one (60 m wide) breach in the sea wall and covered a project area of 21 ha of previously arable land. After the sea defences were breached, saltmarsh species were planted using plugs and turfs, however there was low survival (3 %) of the introduced species due to waterlogging, tidal action and grazing pressure from geese. Six years after the breach, the realignment site was dominated by pioneer vegetation (*Salicornia europaea agg.* and *Suaeda maritima*) (Garbutt et al., 2006), which still persisted 25 years after the breach (dominated by *Spartina anglica*) (McMahon et al. 2023) reflecting the low elevation of the site. The study area was defined using the EA zonation layer (EA 2023).
- Medmerry Marsh, southern England – established when an open-coast managed realignment was undertaken in September 2013 that created a 110 m wide breach through a mobile shingle beach barrier. Previous land uses at the site included pastoral grazing, and arable farming. In the early stages after the restoration, the site was characterised by large areas of bare mud and remnant stubble and plant litter from the previous land use. By 2016 the bare mud was colonised by *Salicornia* and *Suaeda maritima*, which formed the dominant vegetation above and around the high tide line, with accompanying *Spergularia media* and *Atriplex* spp. (RSPB, 2016). Cattle grazing has continued at the restored site, which has a reported project area of 302 ha. The study area was defined using the EA zonation layer (EA, 2023).

2.2. Earth observation mapping

The Sentinel 2 mission, which consists of two satellites recording 12 spectral channels, provides global coverage of visible and infra-red imagery with an approximately 5-day return period from the two satellites and an image resolution of 10 m (ESA, 2017). As the highest spatial resolution freely available spectral data, this work focusses on the use of Sentinel 2 data, along with SRTM (Shuttle Radar Topography Mission) topographic data (USGS, 2018). The outline schematic showing the classification process is shown in Fig. 2 and described in more detail in the sections below.

2.2.1. Developing a training dataset

Using the Google Earth Engine application Your Maps, Your Way (YMYW) (Morton and Schmucki, 2023), which enables the user to create detailed land cover maps of their area of interest, a training dataset for the main saltmarsh area – Hesketh Out Marsh – was developed, from which saltmarsh specific input data to the NDVI based model could be obtained. Ground data for 2020 for the site was obtained from the Environment Agency (Gledhill, 2020, EA, 2023) and used to delineate training polygons of the main saltmarsh classes of interest (Table 3), as well as other land uses in the area.

Within YMYW atmospherically corrected Sentinel 2 scenes with less than 20 % cloud cover collected between 01/01/2020 and 31/12/2020 were cloud masked in Google Earth Engine using the function "maskS2clouds". From these, quarterly composite images, composed of the median cloud-free pixel value at each point, were created for each spectral channel and stacked into a multi-band raster for further analysis. Height, aspect, and slope were derived from the 30 m Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) (USGS, 2018). Random forest supervised classification with 100 trees and 1,500 training pixels per class (split 70:30 into training and validation points) were used to create a land cover map (Fig. 3) covering the managed realignment areas created in 2012 and 2018, the natural saltmarsh remaining along the Ribble estuary, the surrounding farmland, and urban areas.

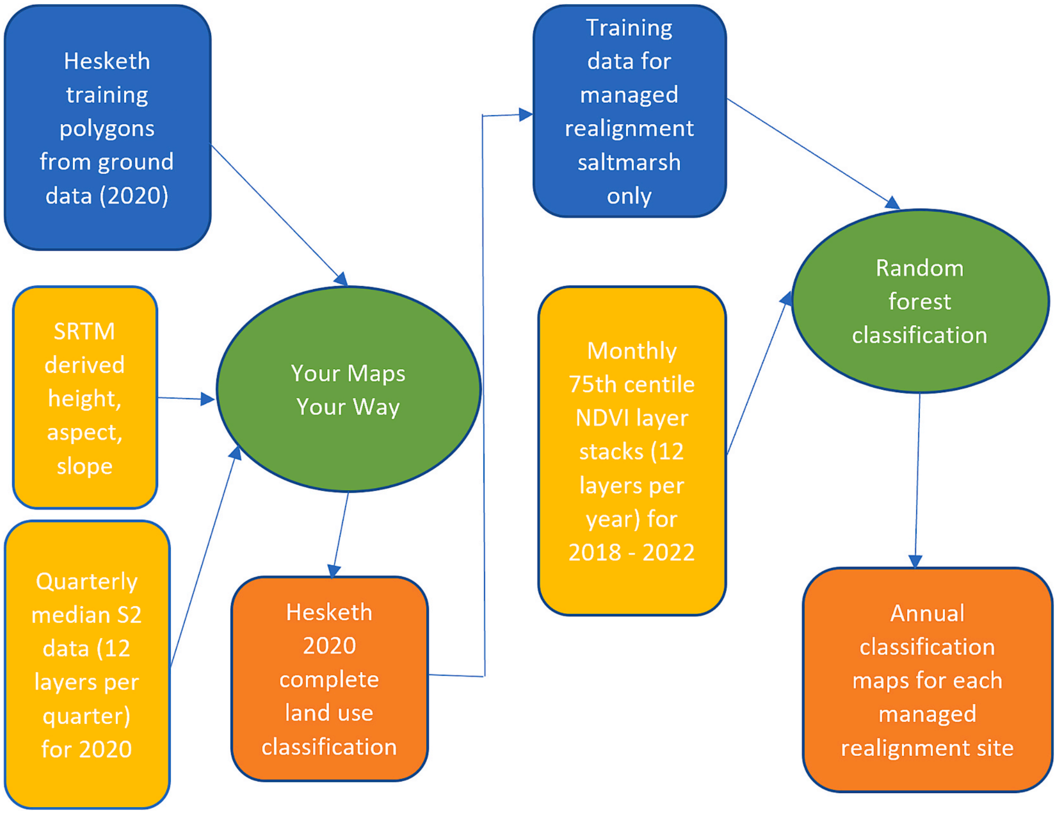

Fig. 2. EO methodology. NB: blue is input training data, yellow is input EO data from Google Earth Engine, green is the classification method, and orange is the outputs. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 3
Number of input training polygons into the Your Maps Your Way application (Morton and Schmucki 2023).

Land Cover Class	Number of polygons
Sediment	36
Pioneer Marsh	14
Low Marsh	15
Upper Marsh	5
Water	25
Urban	53
Arable	58
Grassland	35
Woodland	21

2.2.2. *NDVI data*

To develop a comparatively simple classification scheme that can be rapidly reproduced on an annual time scale and requires less site-specific training data we calculated 75th centile monthly NDVI values calculated from cloud free Sentinel 2 optical imagery for each pixel (Eq. (1)).

$$NDVI = \frac{(Band\ 8 - Band\ 4)}{(Band\ 8 + Band\ 4)} \tag{1}$$

Equation (1): calculation of the NDVI from Bands 8 and 4 (infra-red and red respectively) in the Sentinel 2 dataset.

The 75th centile monthly NDVI values offered a good balance between accurate representation of the NDVI data and being less susceptible to influence from outliers, including removing high tide images from the dataset. Previous studies (Sun et al. 2018, Alam and Hossain 2023) have noted the need to consider tidal phase when selecting optical imagery for analysis of saltmarsh vegetation to minimise the effects of inundation on the subsequent classification. In this study the tidal phase was implicitly considered as manual checks of the available cloud free Sentinel 2 imagery showed that the sites were only fully inundated at very high tides, and the use of the 75th centile pixel value when creating the monthly images meant that these principally did not affect the final values. The 75th centile was chosen in preference over the median pixel value to ensure that periods within the month where the location was not inundated were preferentially retained within the model. This was especially necessary for Tollesbury because the low-lying position of the site in the tidal zone means that it is inundated during proportionally more of the tidal cycle.

Atmospherically corrected Harmonized Sentinel 2 imagery was cloud masked using the function “mask2clouds” in GEE as previously; NDVI values were calculated for each cloud free pixel and 75th centile NDVI values for each month were retained for use in the classification. Only years where there was a full set of monthly values (i.e., 12 months of data per year) were retained in the analysis, meaning that data was available between 2018 and 2022. For each site annual 12-layer raster stacks of the monthly 75th centile NDVI values were developed to input into a Random Forest Classification (see below) to classify annual land cover across the saltmarsh areas. From January 25th 2022 the European Space Agency (ESA) updated its processing baseline for the Sentinel 2 level 2A data products meaning that the data is not directly comparable with previous years. To allow for this a harmonized Sentinel 2 Level 2A product has been developed (https://developers.google.com/earth-engine/datasets/catalog/COPERNICUS_S2_SR_HARMONIZED#description) that uses the same processing as previous years. Therefore, the harmonized datasets were used for all analyses in this work to ensure continuity.

2.2.3. *Time series development*

Random Forest Regression is an ensemble machine learning technique that establishes multi-variate regression relationships (Kuhn and Johnson 2013). Random Forests have been widely used with both classification and regression analyses, particularly with large datasets,

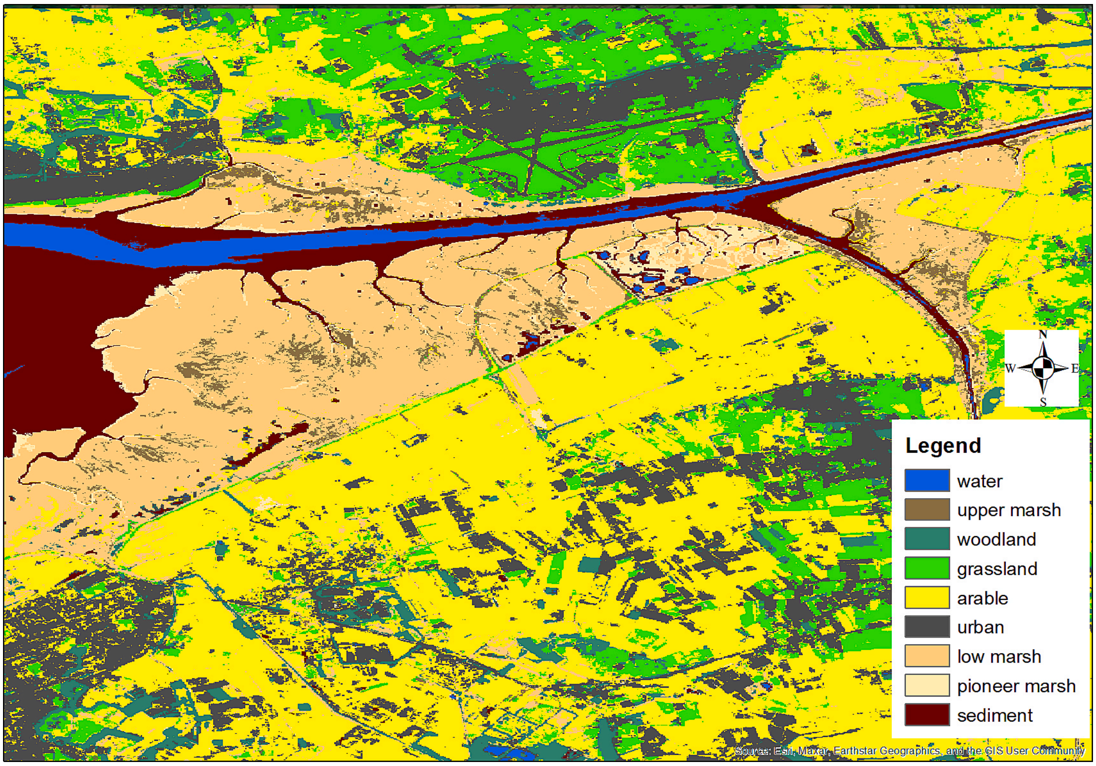

Fig. 3. Initial land cover classification of Hesketh Out Marsh and surrounding area for 2020.

with applications including habitat and soil classification mapping (Kilcoyne et al. 2017, Veronesi and Schillaci 2019). Random Forest models have produced the most consistent results out of several for modelling bare peat coverage using remotely sensed data (Trippier et al. 2020). Following this evidence a Random Forest approach was determined to provide the best statistical approach to classify the NDVI layer stacks into the categories of interest (open water, bare sediment, pioneer marsh, low marsh and upper marsh).

Classified saltmarsh areas at Hesketh out marsh from Section 2.2.1 provided training input to a random forest classification of the 2020 monthly NDVI dataset, which classified the monthly 2020 NDVI raster data. The model was used to predict areas of saltmarsh at the five trial sites at an annual time step from 2018 – 2022. The yearly predictions generated by the model are aligned with inventory reporting requirements and the timing of field data collection. Due to processing limitations the model was run separately for each area of interest. Random Forest modelling was carried out in R (version 4.1.2) using the package RandomForest (Liaw and Wiener, 2002).

2.2.4. *Verification of classification at other sites*

Upscaling of the method to other MR sites in the UK was verified with vegetation survey data. Surveys were undertaken for this project at MR sites at Medmerry on 04/08/2022 and Tollesbury on 29/11/2022, which used handheld GPS units to mark vegetated saltmarsh areas, and assessed percentage of vegetation cover particularly in transitional zones at the mudflat-saltmarsh interface to differentiate between bare mud and pioneer saltmarsh communities. Saltmarsh map layers from a national survey were available for Medmerry in 2020 (EA 2023) and a site survey for Morfa Friog in 2018 (Lush and Lewis, In press). National mapping data sets that included data for Tollesbury in 2016 (EA 2023) and Nigg Bay in 2011 (NatureScot 2016) were outside of the Sentinel 2 image period. However, these survey data were useful for sense-checking the presence/absence of vegetated saltmarsh in the modelled results.

3. Results

3.1. *Initial classification*

The initial classification of the managed realignment site at Hesketh (Fig. 3), and the surrounding area gave an overall accuracy of 90 %. The confusion matrix for the validation data is shown in Table 4. Water and bare/unvegetated sediment were modelled with 95 % and 98 % accuracy, respectively. Pioneer communities exhibited 75 % accuracy between modelled and measured data, low marsh showed 100 % agreement, whereas upper marsh was identified with 29 % accuracy. Nearly three quarters of the validation points for upper saltmarsh were misclassified as grassland, which could be due to niche overlap with terrestrial vegetation communities in this zone.

3.2. *NDVI classification*

The initial Random Forest classification of the monthly NDVI data for 2020 at Hesketh Marsh found that water was consistently correctly classified (73 % accuracy), though with some confusion with bare sediment (Table 5). Sediment and pioneer saltmarsh communities were classified with moderate accuracy (54 % and 56 % accuracy, respectively), with a similar amount of bare sediment incorrectly identified as pioneer saltmarsh and vice versa. Most misclassified units for pioneer saltmarsh were attributed to low marsh. Lower saltmarsh was consistently classified with high accuracy (74 %), though upper saltmarsh was often misclassified as low marsh (Table 5). This is consistent with the initial classification of the training dataset using Your Maps Your Way (Morton and Schmucki, 2023), where these areas were more poorly differentiated in part because of the small area of upper saltmarsh at the Hesketh site. The classification showed that Hesketh Out Marsh West was more vegetated and had more vegetation consistent with low and upper saltmarsh compared to the more recently restored Hesketh Out Marsh East. Despite difficulties with the model determining between the low and upper saltmarsh communities, overall the model was able to

Table 4
Confusion matrix for the initial classification validation data at Hesketh managed realignment site showing the performance of the model (max 643 validation points per category; overall accuracy = 90 %).

Modelled actual	Water	Upper marsh	Forest	Grass	Arable	Urban	Low marsh	Pioneer marsh	Bare soil
Water	**612**	0	0	0	0	0	0	0	31
Upper marsh	0	**110**	0	275	0	0	0	0	0
Forest	0	0	**639**	0	0	4	0	0	0
Grass	0	0	0	**605**	37	1	0	0	0
Arable	0	0	2	7	**599**	9	25	0	2
Urban	0	0	0	2	26	**598**	0	4	13
Low marsh	0	0	0	0	0	0	**643**	0	0
Pioneer marsh	0	2	0	0	49	0	65	**480**	47
Bare soil	0	0	0	0	2	3	0	8	**630**

Table 5
Confusion matrix for the NDVI classification validation data at Hesketh managed realignment site showing the performance of the model (max 3651 validation points per category; overall accuracy = 62 %).

Modelled Actual	Water	Upper marsh	Low marsh	Pioneer marsh	Bare soil
Water	**108**	1	0	2	36
Upper marsh	1	**276**	540	56	20
Low marsh	0	407	**2686**	497	61
Pioneer marsh	2	66	550	**1086**	222
Bare soil	32	27	67	278	**478**

differentiate with high accuracy (91 %) between vegetated and unvegetated saltmarsh, which is needed to begin tracking carbon emission changes associated with plant colonisation after restoration.

Comparisons of the upscaled NDVI classification at other sites are shown in Appendices A–C. Comparisons of modelled and surveyed saltmarsh areas for Morfa Friog, Medmerry and Tollesbury revealed close agreement between vegetated and unvegetated saltmarsh areas, with 95 %, 86 %, and 80 % correctly identified, respectively. Indicative zonation classes are given for Morfa Friog (Lush and Lewis, In press), which show overlap between the NDVI-assigned pioneer communities and the NRW-surveyed Low-Mid saltmarsh communities. Medmerry exhibited moderate accuracy at differentiating between pioneer communities and more established saltmarsh communities. Large areas of *Spartina* (cordgrass) at Medmerry MR, which occur low in the tidal zone, were largely assigned to pioneer saltmarsh in the model. There were few survey points for Tollesbury, but those available indicate that the model assigned low marsh communities to pioneer marsh.

3.3. Time series

The NDVI-derived times series of saltmarsh extent for all study sites are shown in Figs. 4–8 (See also Appendices D–I). Hesketh Out Marsh covers the two Hesketh sites – Hesketh Out Marsh West and Hesketh Out Marsh East. The results show that these are at differing stages of restoration, as to be expected from their differing restoration dates (Table 1). Saltmarsh extent at Hesketh West is relatively stable over time, dominated by established (low to upper) marsh vegetation communities (Fig. 4 & 9a-b), while Hesketh East shows a rapid change from a bare sediment dominated area in 2018 (one-year post restoration), through pioneer marsh and then primarily low marsh by 2022 (Fig. 4). The area of the site that would be considered vegetated marsh is increasing year on year, with an increase from approximately 30 % in 2018 to 85 % in 2022 (Fig. 9c).

Medmerry is a varied site, with saltmarsh occurring on either side of well-developed creeks. The site was characterised by large areas of littoral/unvegetated sediment (see Fig. 5). Over the monitoring period the land cover was relatively stable over time, consistently at approximately 50 % saltmarsh vegetation cover (Fig. 9d).

At the Tollesbury site, which was first restored in 1995, the vegetation is primarily low marsh, with very little vegetation indicative of upper saltmarsh despite over 30 years in restoration management. This is indicative of its low-lying position in the tidal profile resulting in frequent flooding/flushing of the site that has limited the successional development of saltmarsh communities (McMahon et al., 2023). Tollesbury shows a different temporal pattern to the other sites used in the work, with results from 2020 showing a large reduction in vegetation cover and corresponding increase in bare sediment that is almost reversed in 2021 (Fig. 6). Despite this reversal there is a small decrease in vegetated cover over time (Fig. 9e, f). The decline in saltmarsh extent in 2020 is either of short duration due to rapid recovery of the vegetation in 2021, or is an artifact of difficulties with the image collection due to limited cloud free imagery and extensive flooding in early 2020, resulting in the final imagery being affected by inundation to an extent.

Nigg Bay has remained relatively stable over the monitoring period, with over 95 % vegetation cover, although the model predicts a reduction in upper marsh vegetation cover between 2018 and 2019 that does not recover in succeeding study years (Figs. 7 and 9g).

The site at Morfa Friog shows a transition from pioneer marsh to low marsh between 2018 and 2022 with the overall vegetation cover remaining relatively stable over time, again with high vegetation cover of between 96–100 % of the site through the time series (Figs. 8 and 9h).

In general those sites that have been restored for longer have more stable vegetated areas, with the exception of Tollesbury (as discussed in 3.3 above). The results from our pilot sites suggest that managed realignment sites in the UK can reach a stable area of low marsh vegetation after about 3–8 years, with subsequent smaller, slower changes to areas of upper marsh vegetation.

The project areas reported on the OMREG database (Table 1) were very similar to the model domain areas that were derived from national datasets (Table 6), except for Medmerry. When comparing these total project areas with the modelled vegetated saltmarsh area (the areas that

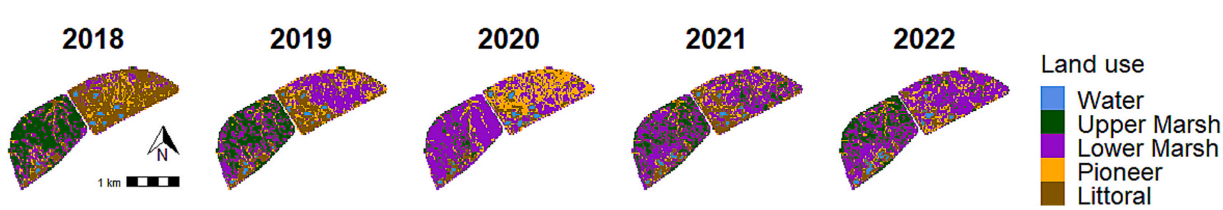

Fig. 4. EO-derived time series of mapped vegetation change (bare to colonised) on rewetted saltmarsh (2018–2022) at Hesketh West and East, England managed realignment sites.

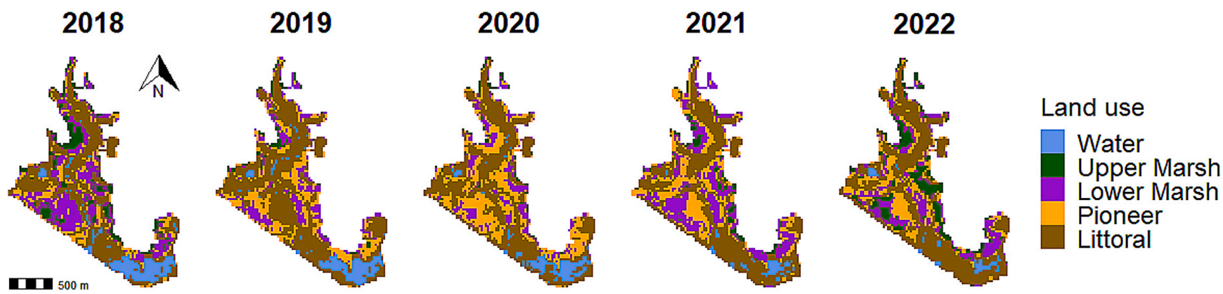

Fig. 5. EO-derived time series of mapped vegetation change (bare to colonised) on rewetted saltmarsh (2018–2022) at Medmerry, England managed realignment site.

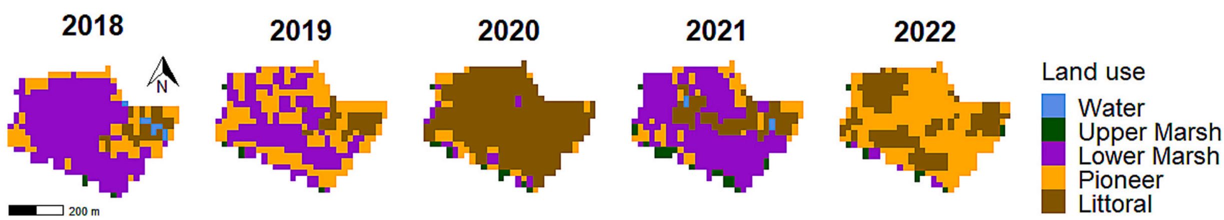

Fig. 6. EO-derived time series of mapped vegetation change (bare to colonised) on rewetted saltmarsh (2018–2022) at Tollesbury, England managed realignment site.

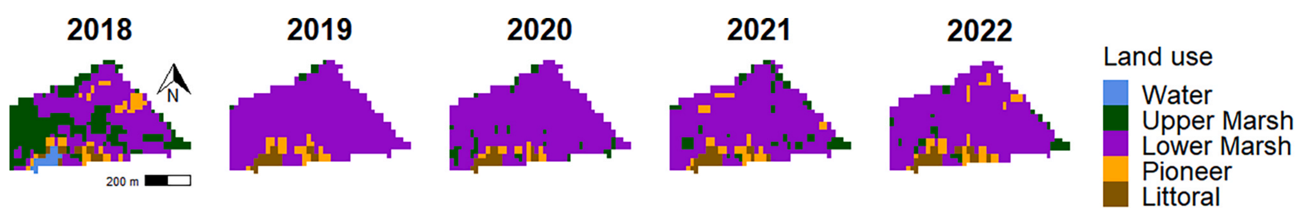

Fig. 7. EO-derived time series of mapped vegetation change (bare to colonised) on rewetted saltmarsh (2018–2022) at Nigg Bay, Scotland managed realignment site.

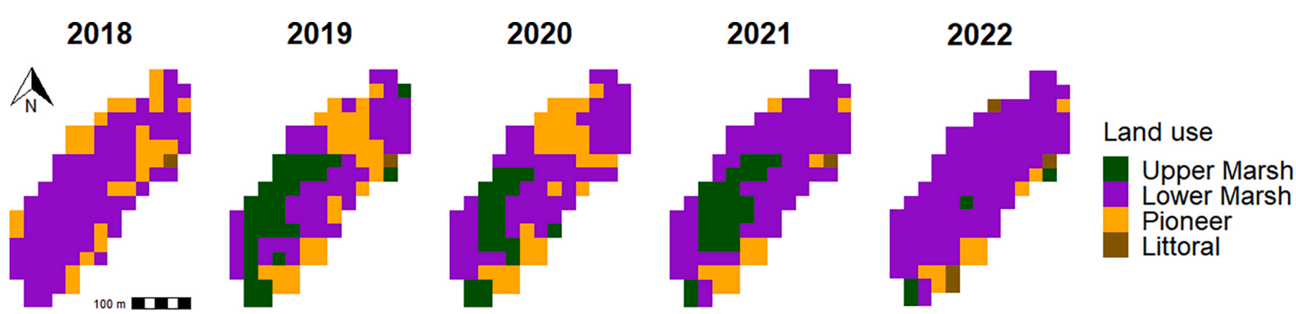

Fig. 8. EO-derived time series of mapped vegetation change (bare to colonised) on rewetted saltmarsh (2018–2022) at Morfa Friog, Wales managed realignment site.

would be reported under IPCC guidance in the UK GHGI), we found that Medmerry and Hesketh East show particularly high differences that would significantly over-estimate the vegetated area (by 2 to 4-fold, respectively) if the total project areas were used. However for Hesketh East, this discrepancy is almost eliminated by the end of the time series (Table 6). This shows that the area of vegetated saltmarsh can be quite different to the designated MR project area, particularly in large sites and those that have only recently been restored and have not yet been colonised by saltmarsh vegetation, which were found to have large areas of bare sediment and water.

4. Discussion

4.1. EO approach for long-term monitoring of saltmarsh habitat

Previous studies using EO data to map saltmarsh vegetation and carbon stocks have focused on developing a single time point classification map (Sun et al. 2016, Sun et al. 2018, Yeo et al. 2020, Légaré et al. 2022, Warwick-Champion et al. 2022) rather than develop a methodology that can be used to map saltmarsh changes over time – particularly the rapid changes that occur following managed realignment. The results of this study have shown that vegetation changes following managed realignment can be tracked from initial bare sediment, through colonisation by pioneer vegetation species, through to established saltmarsh vegetation, using monthly NDVI values derived from Sentinel 2 imagery. The differences in values and intra-annual

Fig. 9. Time series of NDVI-derived saltmarsh areas, in hectares (top two panels), and the percentage of saltmarsh to other land (sediment and water) for each managed realignment site.

Table 6
Model domain area taken from national spatial datasets (NatureScot 2016, EA 2023, Lush and Lewis, In press), and EO-derived time series of estimated rewetted saltmarsh area, in hectares, at managed realignment study locations in the UK.

	Model domain	2018	2019	2020	2021	2022
Nigg Bay	24.6	23.1	23.5	23.6	23.4	23.3
Hesketh West	162.7	144.4	145.5	149.7	146.2	145.9
Hesketh East	159.2	45.4	103.4	129.6	115.5	137.2
Morfa Friog	6.4	6.3	6.3	6. 5	6.3	6.2
Tollesbury	18.7	16.4	16.2	2.9	14.6	11.7
Medmerry	182.8	91.1	71.5	83.2	100.1	93.8

variability in NDVI values correspond to water, bare sediment, annual vegetation and perennial vegetation, as described by Sun et al. (2018), meaning that between year changes can be mapped across disparate saltmarsh habitats. Previous time series assessments of blue carbon habitat have focused on differentiating saltmarsh, mangroves and tidal flat from newly industrialised areas in Java (Sejati et al. 2020), rather than differentiating within saltmarsh habitat.

This method does not seek to map saltmarsh carbon accumulation directly from satellite imagery, as has been attempted previously (e.g. Byrd et al. 2018, Ladd et al. 2022, Warwick-Champion et al. 2022) but instead sought to provide the area of vegetated saltmarsh in order that an emission factor approach (area * GHG emission per unit area) can be used to estimate GHG fluxes for incorporation into the UK GHG Inventory. Previous carbon stock assessments in saltmarshes have shown that an area * soil organic carbon stock value approach gives a similar overall value to a more detailed model based on remotely sensed data (Ladd et al. 2022).

Sentinel 2 data is increasingly being used to map habitat dynamics within blue carbon systems due to its comparatively high temporal and spatial resolution (Pham et al. 2023). Alongside this the increasing availability of cloud-based spatial systems designed to deal with large quantities of satellite derived data, such as Google Earth Engine, means that the data availability is greater than ever previously. As our results have shown this means assessments of change over time can use these vast data sources to produce detailed outputs without the need for access to high performance computing systems. There are, however, limitations to the use of passive remote sensing data (which includes Sentinel 2 data) for time series assessment. The first of these is that this approach still requires sufficient ground data (from the same time as the satellite imagery) to train and validate the initial model, as well as further model outputs. Additionally, there are further challenges posed by passive remote sensing including the availability of cloud free, atmospherically corrected imagery (including the effects of sunglint on wet sediment, and interference from aerosols and water vapour) and the implications of working in tidal habitat types (Pham et al. 2023). The use of 10 m resolution data limited some of the small-scale habitat variability that could be detected but at a site scale provided sufficient information to detect change over time from bare ground to vegetated following managed realignment at the test sites.

4.2. Tidal effects

Cloud masked, atmospherically corrected imagery is now available within Google Earth Engine, but for this work removing tidally impacted data proved more difficult. The approach of creating a composite image for each month of the year meant that we could look in more detail at within year patterns of NDVI but also meant that we could not easily remove high tide images, particularly due to the changing times of high tide around the GB coast. In order to mitigate this we followed the approach of taking the 75th centile NDVI value for each month. This aimed to reduce the errors caused by taking the maximum value and for all sites except Tollesbury meant we removed the effects of tidal inundation on the dataset. The use of the median value meant that inundated images were included, but for all sites except Tollesbury use of the 75th centile NDVI value per month resulted in non-inundated images. The comparatively low elevation of Tollesbury relative to the tidal cycle meant the site was inundated on comparatively more of each tidal cycle and for more of the period around spring high tides, increasing the possibility that a given month would only have inundated imagery available.

4.3. Applicability for national accounting of saltmarshes

Saltmarshes are recognised for their benefits to climate mitigation due to their disproportionately high sequestration value per unit area compared to terrestrial habitats (Temmink et al. 2022), and relatively low methane emissions under saline conditions (IPCC 2014, Al-Haj and Fulweiler, 2020). Furthermore saltmarshes are valued for their importance for biodiversity and other ecosystem services (Foster et al. 2013, zu Ermgassen et al. 2021). Managed realignment is used to create or reinstate coastal wetlands often with multiple intended outcomes e.g., to reverse historic habitat loss, re-establish carbon sink functions, enhance conservation value of lands, and improve coastal defence from storms (Burden et al. 2013b, Curado et al. 2013, Boorman and Hazelden 2017). However few countries fully include saltmarshes and other blue carbon ecosystems, such as seagrass meadows and mangroves, in national and international policies to reduce GHG emissions, the exceptions being Australia and the USA (UNFCCC 2024). This is potentially because of the challenges of assessing changes in vegetation colonisation and carbon accumulation in these dynamic ecosystems and the ease in which standardised reporting frameworks can be applied.

This study aimed to provide a system for assessing changes in saltmarsh habitat over time, which is a key element for estimating greenhouse gas emissions and removals per unit area of saltmarsh creation following IPCC guidance (IPCC 2014), needed for the development of an emissions inventory of UK Saltmarshes. Across the 5 study sites that span Scotland, Wales and England, increases in saltmarsh area were found in the years immediately after restoration (1–3 yr), with rapid transition from bare sediment to colonised saltmarsh, whereas stable saltmarsh communities more resistant to erosion were found 4–27 years after restoration, which was consistent with previous vegetation surveys (Garbutt et al., 2006, Elliott 2015, Skelcher 2015, RSPB 2016, Gledhill 2020, Lush and Lewis, In press). We found that model results have the potential to be used at a national scale in the prediction of ecological responses to tidal inundation resulting from restoration, including past restorations, when ground observational data are not available.

There will be variation in the success of restoration projects, and the approach used in this study can consider this. Although newly created saltmarshes function quite differently to mature saltmarshes, often with differing vegetation assemblages and topographies (Mossman et al. 2012), we demonstrate that saltmarsh colonisation of a site can be captured using earth observation and linked with emission factors, which at Tier 1, the default method for estimating carbon dioxide removals at establishment of vegetation, is -3.3 ± 0.7 tCO_2 ha^{-1} yr^{-1} (IPCC 2014). Soil carbon removals for all unvegetated bare ground are assumed to be zero (IPCC 2014).

This study provides evidence for whether the communities are sustained over time to avoid over-estimating the area of restoration. We found large differences in the estimated project area and the area which successfully colonised with saltmarsh vegetation, indicating the applicability of this method for a monitoring / modelling protocol for restored sites, which we show is particularly important in the first few years following restoration to track stabilisation and colonisation periods. However, we recognise that this is only a proxy of success of the restoration, and full functionality of the sites should be measured.

For established marsh communities there was some confusion between low and high saltmarsh, likely due to the limited areas of upper marsh at Hesketh marshes, which were used to build the model. However this would not affect use in GHG accounting at the moment as there is not currently robust enough data to demonstrate a different emission factor for restored saltmarsh compared to near-natural / historic saltmarsh (Burden and Clilverd 2021). Areas of pioneer marsh that were misidentified as bare sediment, is largely because there is a continuum of marsh colonisation, and there is a grey area when sediment has enough vegetation to be considered a pioneer community. Additional training data in these margins could improve the differentiation between vegetated and unvegetated zones, however in theory the pioneer communities will be identified in successive years as they become more established in the marsh.

This project focused on change in saltmarsh habitat due to managed realignment activities, however future studies could monitor changes in the extent of natural/historic saltmarsh communities due to erosion and accretion processes, and the timeline for when the transitional communities in a restored saltmarsh become the same habitat as a natural/historic saltmarsh. This will require a clear definition of how natural/historic saltmarshes differ from restored sites, and how this is important for ecosystem function. The challenge may lie in the need for better differentiation between the plant communities in spatial datasets. Furthermore, the interesting effect of tidal inundation in the EO images could be utilised in future research to determine vegetation cover changes with degree of tidal inundation, which would be useful for linking field measurements of methane emissions and soil salinity with a particular saltmarsh area.

Ongoing continuous GHG flux measurements (CO_2 and CH_4) on natural and restored saltmarshes in the UK as part of the Saltmarsh Flux Tower Network, which is run by the UK Centre for Ecology and Hydrology (UKCEH), will allow the future development of country-specific emission factors as well as comparisons to be made among management practices and vegetation communities. In addition, a project to develop a database of saltmarsh GHG flux and carbon stock data applicable to the UK will provide a repository for data needed to develop country specific emission factors for the inclusion of these habitats in the GHGI (Clilverd et al., in press).

5. Conclusions

This study has provided an assessment of the changes in saltmarsh extent at managed realignment sites, coastal lands that have been breached to create new, or reestablish, saltmarsh. The results show that EO techniques can provide a way of tracking colonised areas of saltmarsh, with over 90 % accuracy of distinguishing between vegetated versus bare soils. Importantly, the research also indicates that restored areas tend to stabilise with low marsh vegetation within 3–8 years. This suggests the importance of regular monitoring in the initial years after restoration to accurately record saltmarsh restoration outcomes, which can be achieved using EO methods and can help inform the design and management of sites. This research, coupled with IPCC default carbon values, is a first step in developing an operational methodology for UNFCCC GHG inventory reporting, which has applicability to other countries, particularly those in the temperate/northern European climatic zone with similar saltmarsh ecology.

With increased understanding of the importance of saltmarsh habitat as a nature-based solution for climate change mitigation and adaptation, it is crucial that temporally explicit monitoring of these dynamic systems is integrated into national reporting frameworks, in order to capture important temporal shifts in vegetation and to characterise ecological outcomes of saltmarsh restoration.

This study has shown the potential of GEE time series analysis to quantify changes in saltmarsh areas due to restoration activities to derive emissions estimates. Upscaling of this methodology to all saltmarsh habitats across the whole of the UK would fill-in a key data gap that would enable reporting of saltmarshes in the UK Greenhouse Gas Inventory.

CRediT authorship contribution statement

Hannah Clilverd: Writing – original draft, Visualization, Supervision, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Jennifer Williamson:** Writing – original draft, Supervision, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Rachel Nickerson:** Writing – original draft, Visualization, Software, Methodology, Data curation. **Angus Garbutt:** Funding acquisition. **Annette Burden:** Writing – review & editing, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was supported by UKCEH Earth Observation Group. We thank the RSPB and Natural England for providing access to Medmerry and Tollesbury managed realignment sites. Special thanks are extended to Stefanie Carter, Joanna Harley and Lonieke Horninge who assisted with fieldwork, and Neil Forbes and Adam Taylor (RSPB) for providing site knowledge to ground truth the model.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2025.113867.

Data availability

Data will be made available on request.

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