

The influence of grazing on comparisons between pre-existing and restored saltmarshes

Article

Published Version

Dale, J. ORCID: <https://orcid.org/0000-0002-5242-8071>, Conway, L., Kennedy, M. P. and Sizmur, T. ORCID: <https://orcid.org/0000-0001-9835-7195> (2024) The influence of grazing on comparisons between pre-existing and restored saltmarshes. *North West Geography*, 24 (2). ISSN 1476-1580 Available at <https://centaur.reading.ac.uk/117460/>

It is advisable to refer to the publisher's version if you intend to cite from the work. See [Guidance on citing](#).

Published version at: <https://www.mangeogsoc.org.uk/publications/north-west-geography/volume-24-2024/>

Publisher: Manchester Geographical Society

All outputs in CentAUR are protected by Intellectual Property Rights law, including copyright law. Copyright and IPR is retained by the creators or other copyright holders. Terms and conditions for use of this material are defined in the [End User Agreement](#).

www.reading.ac.uk/centaur

CentAUR

Central Archive at the University of Reading
Reading's research outputs online

ISSN 1476-1580



North West Geography

Volume 24, Number 2, 2024

The influence of grazing on comparisons between pre-existing and restored saltmarshes

Jonathan Dale^{1*}, Laura Conway¹, Michael P Kennedy², Tom Sizmur¹

¹ Department of Geography and Environmental Science, University of Reading, RG6 6UR, UK

² Centre for Agroecology, Water and Resilience (CAWR), Coventry University, Ryton-on-Dunsmore, CV8 3LG, UK

* Corresponding Author: j.j.dale@reading.ac.uk

Abstract

Comparisons between saltmarshes restored through managed realignment (MR) and pre-existing reference sites might be influenced by livestock grazing. This study assessed the vegetation and sediment properties at four sites: two MR sites, a grazed reference site and an un-grazed reference site. Results indicate the grazed reference site had the lowest canopy height and biomass, whereas the MR sites had differences in sediment properties in comparison to the pre-existing sites. The role of grazing in MR is discussed, identifying that further research is required to evaluate the temporal influence to inform assessments and the post-breach management of MR sites.

Key Words

Livestock grazing; managed realignment; restoration; saltmarsh

Introduction

Saltmarshes provide a range of important ecosystem services, including carbon storage, habitat for wading and migratory birds, nursery grounds for commercial fish species, and coastal flood defence (e.g. Barbier *et al.*, 2011). However, these environments are threatened by erosion caused by sea level rise, reductions in sediment supply, and anthropogenic activities such as land claim (e.g. Burden *et al.*, 2020). These threats result in habitat loss and degradation. A number of approaches have been implemented to restore saltmarsh habitat, including managed realignment (MR), the processes of deliberately breaching, removing or lowering coastal flood defences to allow intertidal inundation of the coastal hinterland, typically in areas that have previously been drained and reclaimed for agricultural purposes (French, 2006).

Despite the global popularity of MR, with schemes implemented in countries such as the UK, Belgium, USA, Canada, and China, there is evidence to suggest that MR sites have a lower abundance of key plant species and more areas of bare ground in comparison to pre-existing reference sites (Mossman *et al.*, 2012). These differences have been attributed to alterations in the sediment structure following reclamation, including ploughing and dewatering,

resulting in poor drainage and anoxia due to higher levels of compaction and reduced hydrological connectivity (Spencer *et al.*, 2017; Tempest *et al.*, 2015). Differences in the vegetation found in MR sites have also been linked to the sites being topographically less variable than pre-existing sites (Lawrence *et al.*, 2018), meaning MR sites may not have the range of elevation niches saltmarsh vegetation requires (Kim *et al.*, 2013).

Whilst sediment structure and site topography are likely to affect vegetation colonisation in MR sites, there is also the possibility that variations in land use and habitat management have an influence. For example, livestock grazing of saltmarshes occurs globally (Bakker *et al.*, 2020) and has been demonstrated to reduce aboveground biomass and canopy heights (e.g. Nolte *et al.*, 2013). Grazing also causes changes to the sediment, including increasing the bulk density (Nolte *et al.*, 2015), although there is evidence to suggest that grazing may result in increased carbon sequestration (Elschot *et al.*, 2015; Mueller *et al.*, 2017). However, the influence of grazing has typically been overlooked when assessing vegetation and ecosystem service delivery in restored sites. For example, despite grazing being common practice in saltmarsh conservation management and encouraged through agri-environment

schemes (e.g. Mason *et al.*, 2019), only three of the 34 reference sites were actively grazed in the study by Mossman *et al.* (2012) into the vegetation colonisation in MR sites.

There is, therefore, a need to evaluate the extent to which differences in grazing regimes may influence ecological and sedimentological comparisons between MR and pre-existing reference sites. To address this need, the study presented herein provides an assessment of the difference in vegetation and sediment properties at grazed and un-grazed areas of a saltmarsh site, Crossens Marsh, on the Ribble Estuary, Lancashire, in comparison to two neighbouring MR sites of different ages, Hesketh Out Marsh West and Hesketh Out Marsh East (Figure 1), breached in 2008 and 2017 respectively.

Methods

Study Site

Hesketh Out Marsh East and West consists of a total of 350 ha of restored intertidal habitat which had previously been reclaimed for agricultural use, through the construction of a sea wall, in the early 1980s (Gregory, 1986; MacDonald *et al.*, 2020). Intertidal inundation was returned to Hesketh Out Marsh West in 2008, whereas MR at Hesketh Out Marsh East was implemented in 2017. Four breaches were constructed in the sea wall at both sites with a series of channels excavated to reinstate the historic pre-reclamation creek network, and the agricultural linear drainage ditches were infilled (Tovey *et al.*, 2009). The sites are set back from the main estuary

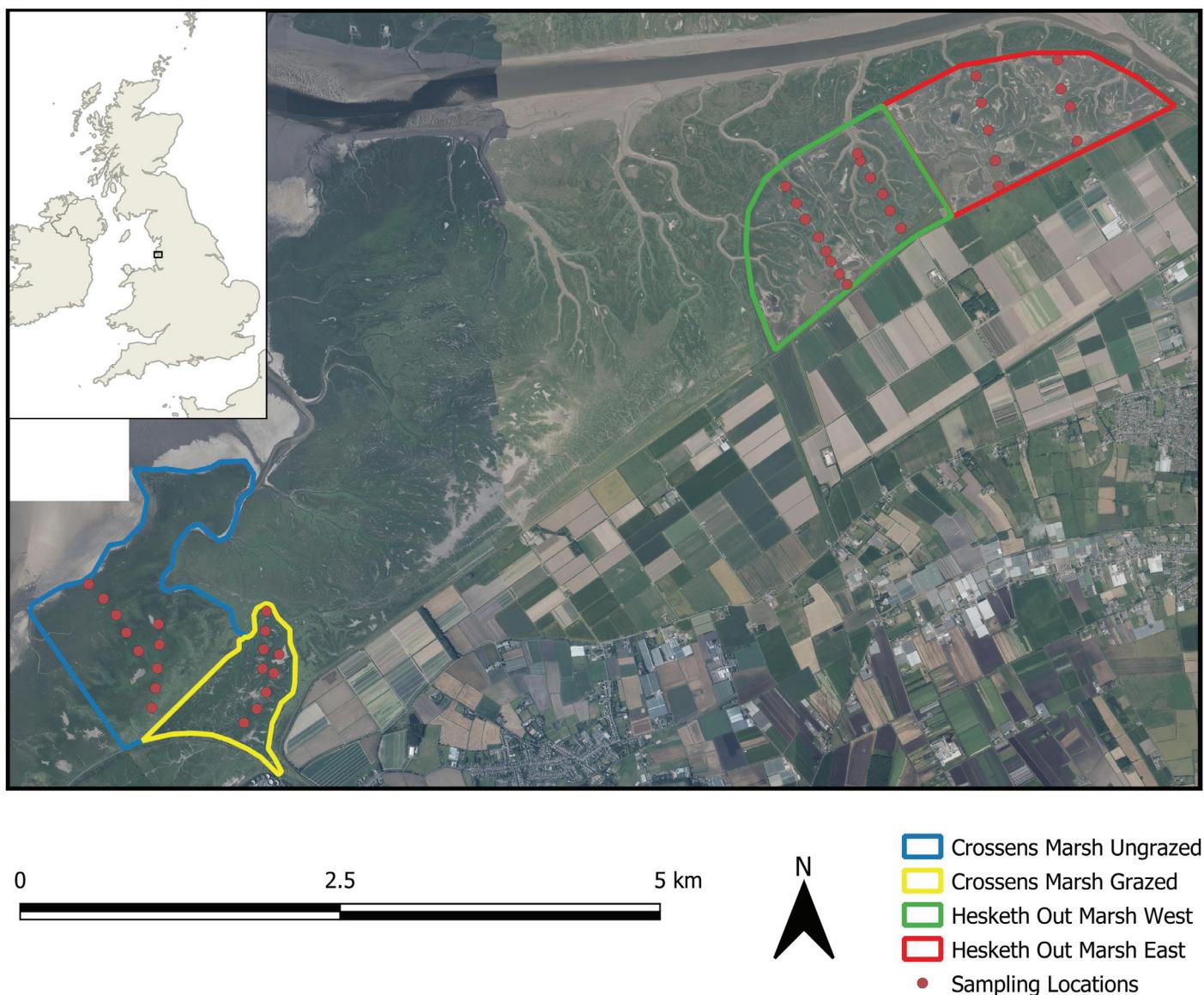


Figure 1: Location of the study sites, sampling locations and the Ribble Estuary (insert) © Getmapping Plc

channel and are fronted by a large, 500 m wide, area of saltmarsh (Figure 1). Both sites are also relatively high in the tidal frame, with most of the area for saltmarsh to colonise being at or around the elevation of mean high-water spring tides. Moderate seasonal summer grazing does occur at both sites, with cattle being allowed onto the sites in July. However, sampling took place on 26th (West) and 28th (East) June 2023, before grazing commenced at the sites. Sampling also took place at two pre-existing reference sites located at Crossens Marsh, to the west of Hesketh Out Marsh (Figure 1). The eastern site at Crossens Marsh is subject to season cattle grazing, commencing in mid-May, whereas no grazing occurs on the western site. Both sites were sampled on 27th June 2023.

Field and laboratory sampling

Sediment sampling and vegetation surveys were conducted along two transects per site with between four and eight sampling locations established on each transect, positioned to ensure coverage across the entirety of each site (Figure 1). At each sampling location, measurements were made of the vegetation cover and percentage of bare ground using a 0.5 x 0.5 m quadrat. The canopy height (five replicates) was measured and the vegetation from a 0.1 x 0.1 m sub-division of the quadrat was collected for above ground dry biomass analysis. Vegetation cover was recorded to the nearest 5%, with rare species assigned a value of 1%. The Simpson's Diversity Index (Simpson, 1949) was then calculated using percentage cover to represent abundance (after Tomascik and Sander (1987)). A sediment sample was also collected at each sampling location using a bulk density ring (5 cm deep, 5 cm diameter). The samples were stored in a sealed polyethene bag at 3.5°C in the University of Reading's cold store until analysis.

In the laboratory, above ground dry biomass was measured by weighing vegetation samples after drying at 40°C in an oven for 48 hours. Sediment moisture content was assessed by oven drying pre-weighed samples at 105°C for 48 hours, re-weighing, and calculating as a percentage of the dry mass. The dry bulk density (mass per unit volume) of each sediment sample was calculated using the dry sediment weight and the volume of the bulk density ring. Organic matter content was measured by quantifying mass lost following ignition in a muffle furnace at 450°C for six hours. Organic carbon concentration was measured using a Thermo Flash EA 1112 NC analyser and used to calculate organic carbon density by multiplying the organic carbon content by the dry bulk density (Howard *et al.*, 2014).

Statistical Analysis

To evaluate differences between the four sites, Kruskal-Wallis tests were conducted for each variable as data were not normally distributed (Anderson-Darling test, $p < 0.05$). The overall difference between the sites was assessed through Principal Component Analysis (PCA), which has been used previously to (partially) differentiate between saltmarsh sites (e.g. Reid and Spencer, 2009). Analysis was conducted in Minitab (version 21) and a 95% confidence interval was used throughout.

Results

Fifteen plant species were identified across the four sites, although some species were not found at every site (Table 1). Thirteen species were identified at the grazed Crossens Marsh site with mid-low marsh species such as *Festuca rubra*, *Lysimachia maritima*, *Plantago maritima* and *Suaeda maritima* found across the site. Ten species were found at both Hesketh Out Marsh West and the un-grazed Crossens Marsh site, with the sites containing more upper marsh species including *Atriplex prostrata* and *Festuca Rubra*. At Hesketh Out Marsh East seven species were identified with mid-low marsh species *Puccinellia maritima* and *Suaeda maritima* identified at most sampling locations, and a higher coverage of bare ground found in comparison to the other three sites.

The marsh was more diverse at the grazed section of Crossens Marsh and less diverse at Hesketh Out Marsh West (Figure 2a), although this site also had the greatest variability. Simpson's Diversity Index did not differ significantly between the four sites ($p = 0.29$). Vegetation height ($p = < 0.001$) and above ground biomass ($p = 0.013$) differed significantly between sites (Figure 2b-c). Post-hoc testing indicated the Crossens Marsh grazed site had significant differences in the vegetation height compared to all other sites (Hesketh Out Marsh East: $p = 0.035$, Crossens Marsh ungrazed and Hesketh Out Marsh West: $p = 0.001$). The grazed Crossens Marsh site had significant differences in biomass in comparison to the Crossens ungrazed ($p = 0.037$) and Hesketh Out Marsh West ($p = 0.044$) sites.

Moisture content ($p = 0.003$), organic content ($p = 0.001$), and organic carbon density ($p = 0.002$) (Figure 2d-f) differed significantly between sites. Values for all three variables were typically lower in the MR sites compared to the pre-existing reference marshes, with the lowest values found at Hesketh Out Marsh East; the more recently breached of the two sites. Post-hoc testing indicated that moisture content was only significantly different between the Crossens ungrazed site and Hesketh Out Marsh East ($p = 0.002$), whereas organic content differed between

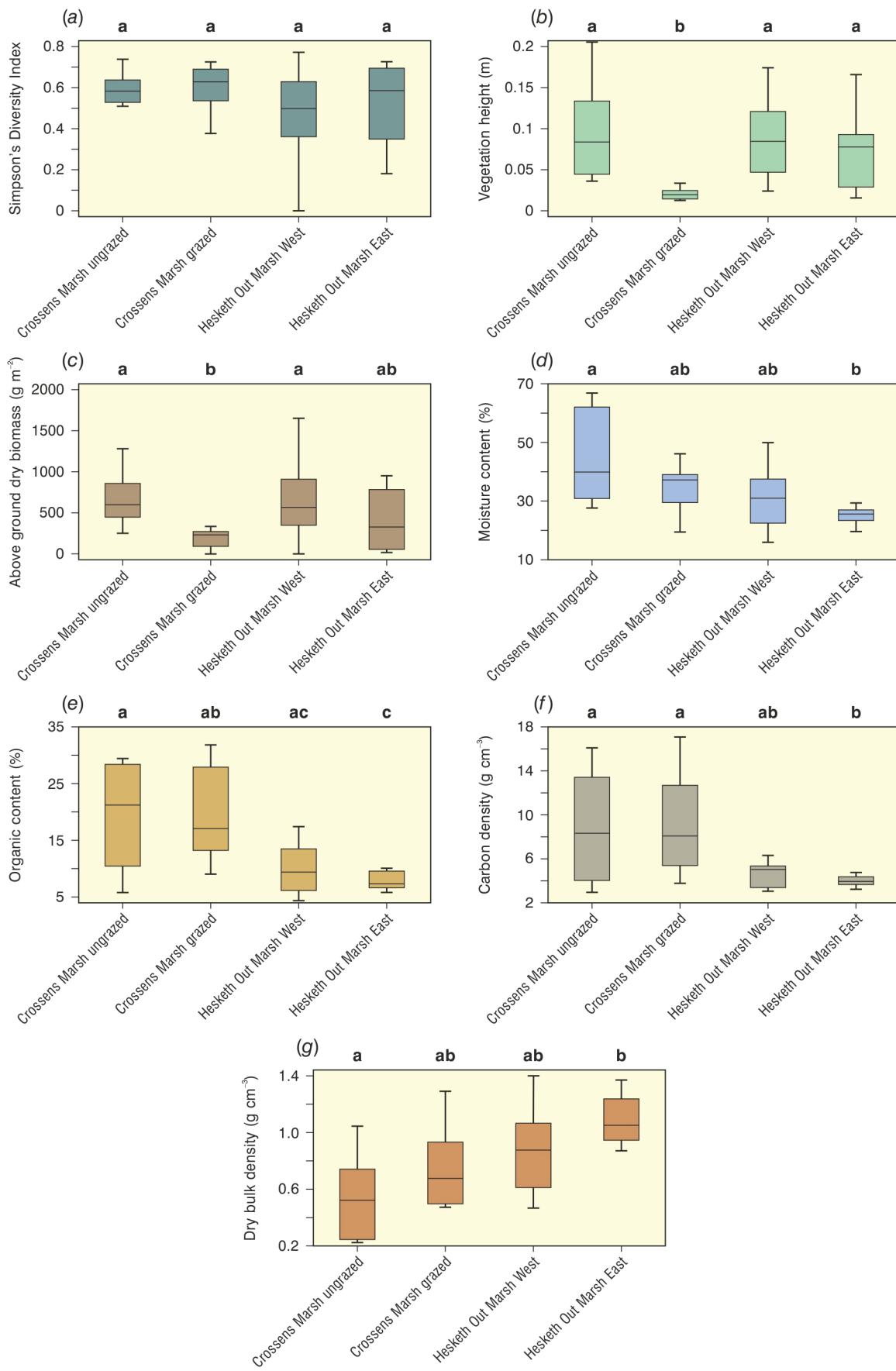


Figure 2: Distribution (median, interquartile range, and range) of (a) Simpson's Diversity Index, (b) vegetation height, (c) above ground dry biomass, (d) moisture content, (e) organic content, (f) carbon density, (g) dry bulk density for each site. Significant differences were found between sites for each variable apart from Simpson's Diversity Index. Groupings of statistical significance are indicated by lower case letters.

Crossens ungrazed and Hesketh Out Marsh East ($p = 0.028$), and between the Crossens grazed site and both Hesketh Out Marsh West ($p = 0.023$) and East ($p = 0.009$). Organic carbon content differed significantly between Hesketh Out Marsh East and both the Crossens reference sites (ungrazed: $p = 0.041$, grazed: $p = 0.004$). In contrast, although bulk density (Figure 2e) differed significantly between sites ($p = 0.001$) and was greater at the MR sites in comparison to the reference sites, it was only significantly different between Hesketh Out Marsh East and the ungrazed Crossens site ($p = 0.001$). Between the two reference sites at Crossens Marsh, moisture content, organic content and organic carbon density were typically lower, and bulk density was greater, at the grazed site.

Principal Component Analysis (Figure 3) indicated that the first two components accounted for 76% of the variability, with the first component (eigenvalue = 3.47, variability = 50%) showing clear discrimination between the pre-existing and MR sites (Figure 3). Eigenvectors demonstrated that organic content (0.50), organic carbon density (0.49), moisture content (0.49) and bulk density (-0.49) had the greatest contribution to the first component. Some differentiation was demonstrated between the grazed and un-grazed areas of the pre-existing Crossens Marsh in the second component (eigenvalue = 1.86, variability =

26 %), which was associated with above ground biomass (eigenvector = -0.69) and canopy height (eigenvector = -0.67).

Discussion

Despite the extent of saltmarsh grazing for conservation management (e.g. Mason *et al.*, 2019), the influence of grazing on the comparison between restored and pre-existing natural marshes has been widely overlooked. In this study, lower canopy heights and biomass values were found at a grazed reference site in comparison to an un-grazed reference site and two MR sites, although a greater species richness was found at the grazed reference site. Differences in plant community composition between each site was also identified (Table 1). The ungrazed Crossens Marsh site and the older Hesketh Out Marsh West contained species typically found in the upper marsh, whereas mid-lower species dominated the grazed Crossens Marsh site and Hesketh Out Marsh East, the more recently breached of the two MR sites investigated. These findings are consistent with observations made at other sites (e.g. Bos *et al.*, 2002; Esselink *et al.*, 2000; Nolte *et al.*, 2015; Nolte *et al.*, 2013), and highlight the importance of considering site age and the influence of grazing when comparing between MR and pre-existing reference sites. This influence is particularly

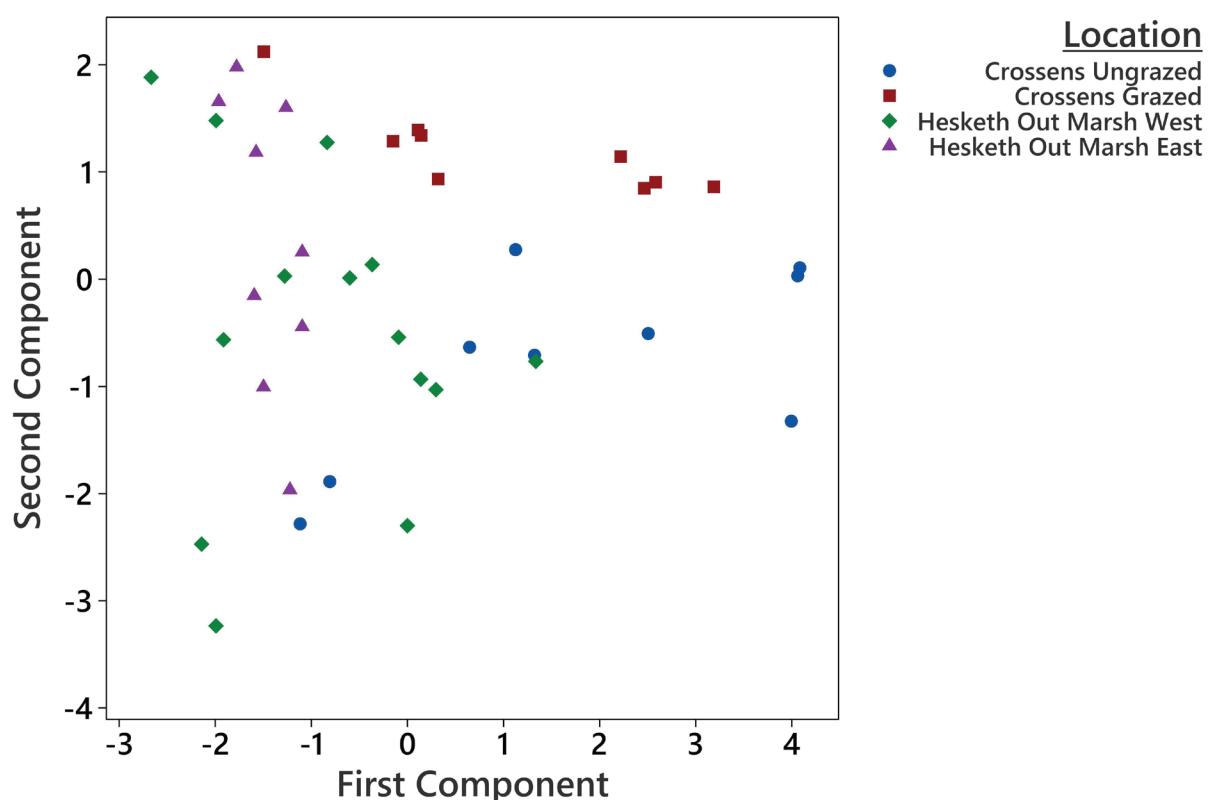


Figure 3: Principal component scores for the vegetation and sediment properties at the four sites. Collectively components 1 and 2 accounted for 76% of the variability.

Table 1: Percentage of sampling locations surveyed at each site where bare ground and each species were found, and the average percentage cover (\pm standard error) when present.

	Crossens Marsh ungrazed (n=10)		Crossens Marsh grazed (n=9)		Hesketh Out Marsh West (n=14)		Hesketh Out Marsh East (n=9)	
	Occurrence (%)	Average cover when present (%)	Occurrence (%)	Average cover when present (%)	Occurrence (%)	Average cover when present (%)	Occurrence (%)	Average cover when present (%)
Bare Ground	10	5 \pm 0	67	31 \pm 15	86	23 \pm 0	89	55 \pm 12
<i>Aster tripolium</i>	70	33 \pm 11	33	9 \pm 6	79	33 \pm 5	56	40 \pm 8
<i>Atriplex prostrata</i>	90	36 \pm 8	11		79	13 \pm 7	56	22 \pm 9
<i>Atriplex portulacoides</i>	30	57 \pm 29	0		7	80 \pm 0	0	
<i>Festuca rubra</i>	90	66 \pm 7	89	38 \pm 15	86	72 \pm 10	0	
<i>Lysimachia maritima</i>	0		78		0		0	
<i>Juncus geradi</i>	0		33	40 \pm 28	0		0	
<i>Lolium prenne</i>	10	25 \pm 0	11	5 \pm 0	0		0	
<i>Plantago maritima</i>	0		67	38 \pm 0	7	35 \pm 0	0	
<i>Puccinellia maritima</i>	10	15 \pm 0	0		7	1 \pm 0	78	73 \pm 12
<i>Salicornia perennis</i>	10	1 \pm 0	44	19 \pm 11	29	7 \pm 2	44	10 \pm 25
<i>Spartina anglica</i>	10	5 \pm 0	11	5 \pm 0	0		11	1 \pm 0
<i>Spergularia marinaria</i>	0		11	1 \pm 0	21	5 \pm 3	22	1 \pm 0
<i>Suaeda maritima</i>	30	25 \pm 5	67	19 \pm 6	29	12 \pm 5	89	24 \pm 7
<i>Trifolium repens</i>	0		11	50 \pm 0	0		0	
<i>Triglochin maritima</i>	20	3 \pm 2	22	10 \pm 0	7	40 \pm 0	0	

important when evaluating the success of MR (Billah *et al.*, 2022) in terms of habitat loss compensation, restoration, and biodiversity net gain.

Although lower canopy heights and biomass values were found at the grazed site (Figure 2), principal component analysis (Figure 3) indicated that variations in sediment properties between the MR sites and reference sites provided greater differentiation than the influence of grazing. Furthermore, the principal component analysis was only able to discriminate differences in canopy height

and biomass at the reference sites in the second component, despite differences being found between the two MR sites. All vegetation and sediment property measurements at the older Hesketh Out Marsh West, except for Simpson's Diversity Index, were similar to those at the pre-existing reference sites regardless of grazing activity (Figure 2). These trends are indicative of site evolution, and the transgression of the site towards physical and ecological functioning that is equivalent to the reference sites (e.g. Spencer *et al.*, 2017), although further investigation is required to evaluate the

temporal influence of grazing as sites evolve following breaching.

Measurements in this study were taken before seasonal grazing was introduced at the MR sites. Further investigation is therefore required to evaluate the impact of grazing on restored sites over time, and the extent to which land use management after site breaching inhibits vegetation colonisation. Land management is particularly important for assessments of sediment compaction as grazing may contribute further to compaction and changes to sediment structure caused by the reclamation process and terrestrial land use, as observed at other MR sites such as Medmerry (Dale *et al.*, 2019) and Orplands Farm (Spencer *et al.*, 2017). Nevertheless, the sediment property measurements presented in this study, specifically higher bulk density values, provide some evidence of compaction at the Hesketh Out Marsh sites. This finding is despite Hesketh Out Marsh only being reclaimed in the 1980s (Gregory, 1986), and therefore being subject to terrestrial land use for considerably less time than both the Medmerry and Orplands Farm MR sites, which were reclaimed in the early nineteenth century (Bone, 1996; Tempest *et al.*, 2015). Whilst these physical disturbances have been recognised to be irreversible (Spencer and Harvey, 2012; Viles *et al.*, 2008), the influence of how long a site is reclaimed for and the potential for further compaction by grazers following site breaching requires further study, in order to evaluate the influence of land management in MR sites on ecosystem functioning and recovery.

Concerns have been raised during the design of other MR schemes that the area to be breached is considerably lower in elevation than the surrounding intertidal habitat, due to dewatering and sedimentation on the seaward side (e.g. Cox *et al.*, 2006; Temmerman *et al.*, 2003), and may not be suitable for supporting saltmarsh habitat. In contrast, this was not the case at Hesketh Out Marsh due to the comparably short period between reclamation and implementation of MR (Gregory, 1986), with the site remaining relatively high in the tidal frame. Consequently, most of both Hesketh sites were at an appropriate level to support saltmarsh habitat prior to breaching, which is unusual for a MR site and unlike

other potential MR sites in the Ribble Estuary (Tovey *et al.*, 2009). However, the sites are unlikely to have experienced the high levels of accretion observed at other MR sites following site breaching (e.g. Dale *et al.*, 2021; Dale *et al.*, 2017; Mazik *et al.*, 2007) as a result of the relatively high elevation and lack of available accommodation space. It is, therefore, also likely that the rapid accumulation of carbon observed at other MR sites (Mossman *et al.*, 2022; Wollenberg *et al.*, 2018) would have not occurred. This assertion is supported by the lower density of organic carbon found at both Hesketh Out Marsh sites, in comparison to both the grazed and un-grazed reference sites. Whilst this might limit the possibility of the site providing a net gain in ecosystem services, the short duration between reclamation and implementation of MR did allow the pre-reclamation drainage network to be reinstated (Tovey *et al.*, 2009). This approach contrasts with the use of agricultural drainage ditches or constructed channels, as has been the case at other MR sites, and the influence of re-instating the intertidal channel network remains unknown and requires further research to assess how site design influences site evolution and ecological functioning.

Conclusion

This study provides an assessment of the difference in vegetation and sediment properties at two MR salt marsh sites and both a grazed and an un-grazed pre-existing reference site. Results are consistent with findings from elsewhere, with the grazed reference site having a lower canopy height and biomass, although no significant difference in diversity was found between sites. Further research is required to evaluate the influence of these factors on site functioning to inform assessments of site evolution and, along with temporal measurements of plant growth and colonisation, to ensure comparisons with pre-existing references sites are appropriate. Improved comparisons between sites will inform the post-breach management of restored sites to maximise the opportunity for plant colonisation and establishment of occur, and to support the development of a functioning intertidal ecosystem and ecosystem service provision.

References

Bakker, J.P., Schrama, M., Esselink, P., Daniels, P., Bhola, N., Nolte, S., de Vries, Y., Veeneklaas, R.M., Stock, M., 2020. Long-Term Effects of Sheep Grazing in Various Densities on Marsh Properties and Vegetation Dynamics in Two Different Salt-Marsh Zones. *Estuaries and Coasts* 43, 298-315.

Barbier, E.B., Hacker, S.D., Kennedy, C., Koch, E.W., Stier, A.C., Silliman, B.R., 2011. The value of estuarine and coastal ecosystem services. *Ecological Monographs* 81, 169-193.

Billah, M.M., Bhuiyan, M.K.A., Islam, M.A., Das, J., Hoque, A.T.M.R., 2022. Salt marsh restoration: an overview of techniques and success indicators. *Environmental Science and Pollution Research* 29, 15347-15363.

Bone, A.E., 1996. The shaping of the Selsey coastline: a review of the geomorphology, archaeology and history. *Tertiary Research* 16, 5-14.

Bos, D., Bakker, J.P., de Vries, Y., van Lieshout, S., 2002. Long-term vegetation changes in experimentally grazed and ungrazed back-barrier marshes in the Wadden Sea. *Applied Vegetation Science* 5, 45-54.

Burden, A., Smeaton, C., Angus, S., Garbutt, A., Jones, L., Lewis, H., Rees, S., 2020. Impacts of climate change on coastal habitats, relevant to the coastal and marine environment around the UK. *MCCIP Science Review 2020*.

Cox, T.J.S., Maris, T., De Vleeschauwer, P., De Mulder, T., Soetaert, K., Meire, P., 2006. Flood control areas as an opportunity to restore estuarine habitat. *Ecological Engineering* 28, 55-63.

Dale, J., Burgess, H.M., Berg, M.J., Strong, C.J., Burnside, N.G., 2021. Morphological evolution of a non-engineered managed realignment site following tidal inundation. *Estuarine, Coastal and Shelf Science* 260, 107510.

Dale, J., Burgess, H.M., Cundy, A.B., 2017. Sedimentation rhythms and hydrodynamics in two engineered environments in an open coast managed realignment site. *Marine Geology* 383, 120-131.

Dale, J., Cundy, A.B., Spencer, K.L., Carr, S.J., Croudace, I.W., Burgess, H.M., Nash, D.J., 2019. Sediment structure and physicochemical changes following tidal inundation at a large open coast managed realignment site. *Science of the Total Environment* 660, 1419-1432.

Elschot, K., Bakker, J.P., Temmerman, S., van de Koppel, J., Bouma, T.J., 2015. Ecosystem engineering by large grazers enhances carbon stocks in a tidal salt marsh. *Marine Ecology Progress Series* 537, 9-21.

Esselink, P., Zijlstra, W., Dijkema, K.S., Diggelen, R.v., 2000. The effects of decreased management on plant-species distribution patterns in a salt marsh nature reserve in the Wadden Sea. *Biological Conservation* 93, 61-76.

French, P.W., 2006. Managed realignment - The developing story of a comparatively new approach to soft engineering. *Estuarine, Coastal and Shelf Science* 67, 409-423.

Gregory, J., 1986. Soils and drainage of Hesketh Out Marsh. *Proceedings of the North of England Soils Discussion Group* 21, 7-9.

Howard, J., Hoyt, S., Isensee, K., Pidgeon, E., Telszewski, M., 2014. Methods for assessing carbon stocks and emissions factors in mangroves, tidal salt marshes, and seagrass meadows. *Conservation International, Intergovernmental Oceanographic Commission of UNESCO. International Union for Conservation of Nature*.

Kim, D., Cairns, D.M., Bartholdy, J., 2013. Tidal Creek Morphology and Sediment Type Influence Spatial Trends in Salt Marsh Vegetation. *The Professional Geographer* 65, 544-560.

Lawrence, P.J., Smith, G.R., Sullivan, M.J.P., Mossman, H.L., 2018. Restored saltmarshes lack the topographic diversity found in natural habitat. *Ecological Engineering* 115, 58-66.

MacDonald, M.A., de Ruyck, C., Field, R.H., Bedford, A., Bradbury, R.B., 2020. Benefits of coastal managed realignment for society: Evidence from ecosystem service assessments in two UK regions. *Estuarine, Coastal and Shelf Science* 244, 105609.

Mason, L.R., Feather, A., Godden, N., Vreugdenhil, C.C., Smart, J., 2019. Are agri-environment schemes successful in delivering conservation grazing management on saltmarsh? *Journal of Applied Ecology* 56, 1597-1609.

Mazik, K., Smith, J.E., Leighton, A., Elliott, M., 2007. Physical and biological development of a newly breached managed realignment site, Humber estuary, UK. *Marine Pollution Bulletin* 55, 564-578.

Mossman, H.L., Davy, A.J., Grant, A., 2012. Does managed coastal realignment create saltmarshes with 'equivalent biological characteristics' to natural reference sites? *Journal of Applied Ecology* 49, 1446-1456.

Mossman, H.L., Pontee, N., Born, K., Hill, C., Lawrence, P.J., Rae, S., Scott, J., Serato, B., Sparkes, R.B., Sullivan, M.J.P., Dunk, R.M., 2022. Rapid carbon accumulation at a saltmarsh restored by managed realignment exceeded carbon emitted in direct site construction. *PLOS ONE* 17, e0259033.

Mueller, P., Granse, D., Nolte, S., Do, H.T., Weingartner, M., Hoth, S., Jensen, K., 2017. Top-down control of carbon sequestration: grazing affects microbial structure and function in salt marsh soils. *Ecological Applications* 27, 1435-1450.

Nolte, S., Esselink, P., Bakker, J.P., Smit, C., 2015. Effects of livestock species and stocking density on accretion rates in grazed salt marshes. *Estuarine, Coastal and Shelf Science* 152, 109-115.

Nolte, S., Müller, F., Schuerch, M., Wanner, A., Esselink, P., Bakker, J.P., Jensen, K., 2013. Does livestock grazing affect sediment deposition and accretion rates in salt marshes? *Estuarine, Coastal and Shelf Science* 135, 296-305.

Reid, M.K., Spencer, K.L., 2009. Use of principal components analysis (PCA) on estuarine sediment datasets: The effect of data pre-treatment. *Environmental Pollution* 157, 2275-2281.

Simpson, E.H., 1949. Measurement of diversity. *Nature* 163, 688-688.

Spencer, K.L., Carr, S.J., Diggens, L.M., Tempest, J.A., Morris, M.A., Harvey, G.L., 2017. The impact of pre-restoration land-use and disturbance on sediment structure, hydrology and the sediment geochemical environment in restored saltmarshes. *Science of the Total Environment* 587–588, 47-58.

Spencer, K.L., Harvey, G.L., 2012. Understanding system disturbance and ecosystem services in restored saltmarshes: Integrating physical and biogeochemical processes. *Estuarine, Coastal and Shelf Science* 106, 23-32.

Temmerman, S., Govers, G., Meire, P., Wartel, S., 2003. Modelling long-term tidal marsh growth under changing tidal conditions and suspended sediment concentrations, Scheldt estuary, Belgium. *Marine Geology* 193, 151-169.

Tempest, J.A., Harvey, G.L., Spencer, K.L., 2015. Modified sediments and subsurface hydrology in natural and recreated salt marshes and implications for delivery of ecosystem services. *Hydrological Processes* 29, 2346-2357.

Tomascik, T., Sander, F., 1987. Effects of eutrophication on reef-building corals: II. Structure of scleractinian coral communities on fringing reefs, Barbados, West Indies. *Marine Biology* 94, 53-75.

Tovey, E.L., Pontee, N.I., Harvey, R., 2009. Managed Realignment at Hesketh Out Marsh West. *Proceedings of the Institution of Civil Engineers - Engineering Sustainability* 162, 223-228.

Viles, H.A., Naylor, L.A., Carter, N.E.A., Chaput, D., 2008. Biogeomorphological disturbance regimes: progress in linking ecological and geomorphological systems. *Earth Surface Processes and Landforms* 33, 1419-1435.

Wollenberg, J.T., Ollerhead, J., Chmura, G.L., 2018. Rapid carbon accumulation following managed realignment on the Bay of Fundy. *PLOS ONE* 13, e0193930.