Saltmarsh Restoration Potential in Scotland

Stefanie Carter, Zoe Clelland, Sanchi Gupta, Angus Garbutt, Iain Malzer, Sanne van der Meer, Annette Burden

Client Ref: Project Reference 502445
Advancing the UK Saltmarsh Code in Scotland
Issue number 1
31.03.2024

UK Centre for Ecology & Hydrology

Contents

Please cite as:
Carter, S., Clelland, Z., Gupta, S., Garbutt, A., Malzer, I., van der Meer, S., Burden, A. (2024) *Saltmarsh Restoration Potential in Scotland*. UK Centre for Ecology & Hydrology report to NatureScot. 79pp.

Acronyms

BCR	Benefit-cost Ratio
BD	Bulk Density
BODC	British Oceanographic Data Centre
DTM	Digital Terrain Model
FE	Finance EARTH
FIRNS	Facility for Investment Ready Nature in Scotland
HAT	Highest Astronomical Tide
LiDAR	Light Detection And Ranging
MHWS	Mean High Water Spring
MLWS	Mean Low Water Spring
MR	Managed Realignment
MTL	Mean Tide Level
NVC	National Vegetation Classification
OC	Organic Carbon
OCAR	Organic Carbon Accumulation Rates
RSPB	Royal Society for the Protection of Birds
RTE	Regulated Tidal Exchange
SAC	Special Area of Conservation
SCM	Site Condition Monitoring
SD	Standard Deviation
SET	Surface Elevation Tables
SNH	Scottish Natural Heritage
SPA	Special Protection Areas
SSSI	Site of Special Scientific Interest
UKCEH	UK Centre for Ecology & Hydrology
WFD	Water Framework Directive

1. Introduction

This review of saltmarsh restoration potential in Scotland was compiled as part of the "Advancing the UK Saltmarsh Code in Scotland" project funded by NatureScot through Facility for Investment Ready Nature in Scotland (FIRNS) funding and by the National Lottery Heritage Fund. The project was delivered through a partnership of Finance Earth (FE), Royal Society for the Protection of Birds (RSPB) and the UK Centre for Ecology & Hydrology (UKCEH). The Saltmarsh Code, which is currently in development for the UK by a consortium of organisations led by UKCEH, is a mechanism to accelerate saltmarsh restoration with private finance via the voluntary carbon market. The FIRNS funded project advanced the Saltmarsh Code within Scotland by developing Scotland-specific business cases for saltmarsh carbon sales for pilot project sites, engaging with local stakeholders on green finance and saltmarsh restoration in the Solway Firth and Firth of Forth and producing this review on saltmarsh restoration potential.

The review first provides an overview of the extent, condition, pressures and threats of existing saltmarsh within Scotland, which is followed by an overview of completed saltmarsh restoration projects in Scotland through managed realignment (MR) and other restoration techniques. The report then explores the restoration potential of saltmarsh based on existing publications and finally reviews blue carbon data for Scottish saltmarsh including potential restoration sites.

2. Overview of existing saltmarsh in Scotland

Scottish saltmarshes are different from English and Welsh saltmarshes as they have fewer saltmarsh communities and mostly lack particular plant species common elsewhere on UK marshes, such as *Atriplex portulacoides* and *Limonium vulgare* (Proctor, 1987; JNCC, 2004). The Solway marshes present a natural limit for many typical saltmarsh species, north of which they do not occur (Adam, 1993). Scotland generally has less pioneer marsh and is dominated by mid and upper marsh plant communities. (JNCC, 2004).

The most recent survey of Scottish saltmarshes took place from 2010 to 2012 and was published by Haynes (2016). According to the report an area of 7,704 ha was surveyed and contained 5,840 ha of saltmarsh habitat (identified based on the National Vegetation Classification (NVC)). The report initially states that known saltmarshes larger than 3 ha were surveyed and that the actual saltmarsh area will be higher because of additional < 3 ha sites. However, the methods section specifies that 25 sites under 3 ha were also included, and that the final GIS file contains 226 sites under 3 ha.

How many saltmarsh sites exist in Scotland and what sizes they comprise of, depends on the definition of a 'site'. When a 'site' is a geographical region, several saltmarsh sites are clumped together under one name; a well-known example and the largest of these is Caerlaverock which consists of three separate areas of saltmarsh. Caerlaverock is very closely located to Priestside, yet they are still considered separate sites (Figure 1). Nearby Greenmerse consists of four separate areas of saltmarsh and even though one is physically connected to Kirkconnell Merse, they are considered separate sites (Figure 2). Under this anthropogenic definition of a 'site', there are 244 saltmarsh sites in Scotland mapped in the Haynes (2016) GIS layer. A small number of sites make up almost half of the saltmarsh extent, whereas the smallest 60% of sites (all under 10 ha) only make up just over 10% of the saltmarsh area (Table 1). Figure A1-1 (Appendix 1) shows the distribution of saltmarsh by site size. There are several areas with larger sites (over 50 ha) on both the East and the West coast of Scotland, with the most numerous clusters of sites located around the Solway Firth and Firth of Forth.

Figure 1: Three separate saltmarsh sites make up Caerlaverock, Solway Firth (in shades of blue); despite being approximately 2 km away from the main Caerlaverock site, the small most western marsh is still considered part of the site. Caerlaverock sits adjacent to Priestside Bank (green), but despite the proximity, they are considered separate sites.

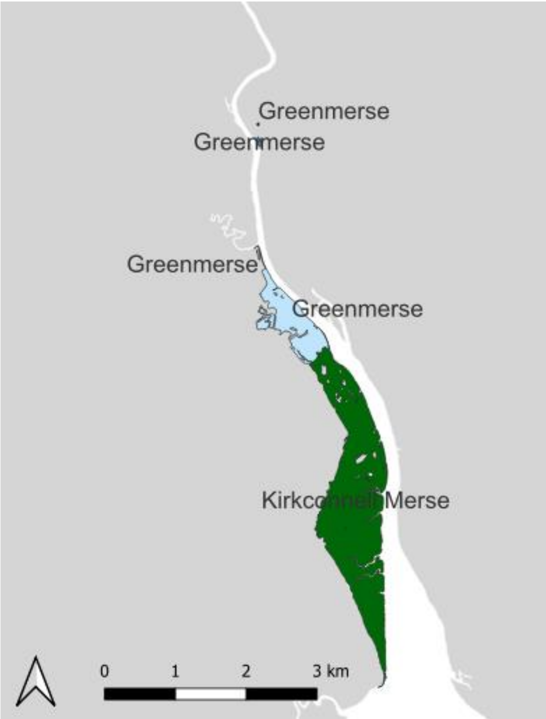

Figure 2: Greenmerse, Solway Firth, consists of four separate sites (in shades of blue, smaller sites appear as dots next to name). The largest site is physically connected to Kirkconnell Merse (green); yet they are considered separate sites.

Table 1: Saltmarsh size distribution with a site defined as a distinctly named geographical region as shown in Figures 1 and 2. Size calculations after Haynes (2016) GIS file.

Site area (ha)	% of total saltmarsh area	Number of sites	% of total number of sites
> 100	49.52	9	3.69
> 50 and < 100	12.36	11	4.51
> 25 and < 50	13.63	21	8.61
> 10 and < 25	13.6	48	19.67
> 5 and < 10	7.05	58	23.77
> 3 and < 5	2.50	37	15.16
< 3	1.34	60	24.59
Total	**100**	**244**	**100.00**

When defining a saltmarsh 'site' as an uninterrupted stretch of land (example in Figure 3) there are 1806 connected sites of saltmarsh with seven large sites (> 100ha) making up one third of the saltmarsh area. Noteworthy are the 1,533 individual small (< 3 ha) sites (Table 2). Figure A1-2 shows a similar distribution of saltmarsh sites as Figure A1-1 but with more smaller sites.

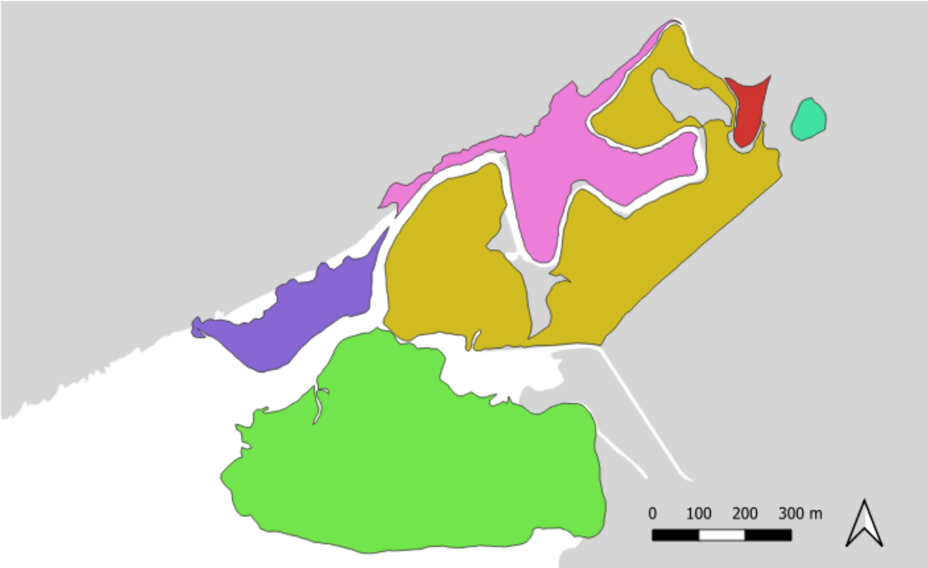

Figure 3: Under the connectivity site definition Southwick, Solway Firth, is made up of six separate marshes.

Table 2: Saltmarsh size distribution with a site defined as a connected and uninterrupted stretch of land as shown in Figure 3. Size calculations after Haynes (2016) GIS file.

Site area (ha)	% of total saltmarsh area	Number of sites	% of total number of sites
> 100	33.84	7	0.39
> 50 and < 100	5.76	6	0.33
> 25 and < 50	13.77	24	1.33
> 10 and < 25	17.28	66	3.65
> 5 and < 10	11.59	95	5.26
> 3 and < 5	4.84	75	4.15
< 3	12.92	1533	84.88
Total	**100.00**	**1806**	**100.00**

Two saltmarsh habitats listed under the EU Habitats Directive Annex 1 were considered as part of the Haynes (2016) survey with the vast majority of this (5,075 ha) being Atlantic Saltmarsh (H1330). The other was Pioneer Marsh (H1310) which made up only 5% (Table 3). When split into zones, upper saltmarsh makes up more than half of the Scottish saltmarsh extent, followed by lower and middle marsh with just over a quarter and pioneer marsh just under 9% (Table 4). These numbers reflect the trend that saltmarshes in Scotland generally have less pioneer marsh than marshes in England and Wales (Burd, 1989; JNCC, 2004). Appendix 1 contains maps showing the distribution of each saltmarsh zone by size (Figures A1-3 to A1-7).

The previous survey of Scottish marshes was carried out as part of the saltmarsh survey of Great Britain (Burd, 1989) during the 1970s and 1980s and reported 6,089 ha of saltmarsh for Scotland. The difference in extent reported in these two surveys is most likely due to different methodologies applied rather than real change in extent over time. Nonetheless, it is estimated that Scotland has lost at least 3,000 ha of saltmarsh in the past 400 years (Angus et al., 2011). The anticipated decline of saltmarsh extent due to climate change (i.e. sea level rise, coastal squeeze and an increase in storm intensity) predicts an area of 5,190 ha by 2060 (Beaumont et al., 2014[1]) – a loss of 650 ha from the Haynes (2016) baseline.

Table 3: Saltmarsh extent in Scotland split into Habitats Directive Annex 1 habitats after Haynes (2016) report. Additional vegetation is SM1 (*Zostera* communities; SM6 (*Spartina anglica* saltmarsh, excluded because it is considered invasive); SM23 (*Spergularia marina-Puccinellia distans* saltmarsh community); SM 27 and SM28 (both strandline and disturbance communities); and 'other vegetation'.

Annex 1 Habitat	NVC communities	Area (ha)	% of total saltmarsh extent
Pioneer Marsh (H1310)	(SM7), SM8, SM9, SM27	298	5.1
Atlantic Saltmarsh (H1330)	SM10, SM11, SM12, SM13, SM14, SM15, SM16, SM17, SM18, SM19, SM20	5,075	86.9
Additional vegetation	SM1, SM6, SM23, SM27, SM28, plus 'other vegetation'	467	8.0
TOTAL		**5,840**	**100%**

[1] This is based on a predicted 4.5% decrease for a 20-year period (French, 1997).

Table 4: Saltmarsh extent in Scotland by saltmarsh zone after Haynes (2016) report.

Annex 1 Habitat	NVC communities	Area (ha)	% of total saltmarsh extent
Littoral	SM1, SM2	8	0.14
Pioneer	SM5, SM6, SM8, SM9, SM10, SM12	517	8.85
Lower and middle	SM13, SM14, SM15	1,628	27.88
Upper	SM16, SM17, SM18, SM19, SM20, SM23	3,305	56.59
Strandline and disturbance	SM27, SM28	358	6.13
Other vegetation and cover	n/a	24	0.41
Total		**5,840**	**100**

3. Designations, protection, condition, pressures and threats

3.1 Designations and protection

The Haynes (2016) report includes a Site of Special Scientific Interest (SSSI) and Special Area of Conservation (SAC) analysis but does not report much detail. To obtain a better assessment of saltmarsh site protection in Scotland, we overlaid the Haynes (2016) saltmarsh survey shapefile with the most recent GIS layers for Special Protection Areas (SPAs) (JNCC, 2022), SACs (SNH, 2023a) , SSSIs (SNH, 2023b) and Ramsar sites (JNCC, 2019).This assessment only compares the area extent of the conservation designations; it does not specifically target sites designated for the their saltmarsh features.

Across the entire saltmarsh extent, just over three quarters are SSSIs, about 58% are both SPAs and Ramsar sites and 41% are SACs. The designation of sites varies greatly between NVC plant communities, saltmarsh zones and site area size (Tables 5 to 8).

Whilst a few NVC plant communities are 100% protected by some designations, these are very small in overall area contribution to saltmarshes. The designation cover for the two NVC plant communities with the largest areas - SM16 and SM13 - is similar to the average cover for all the saltmarshes combined (Table 5). The upper saltmarsh zone, which makes up over half of the saltmarsh in Scotland, has the lowest percentage of area with a conservation designation (Table 6).

Noteworthy is that smaller sites have significantly less protection from designations compared to larger sites. This is evident for both geographically named sites (Table 7) and connected and uninterrupted sites (Table 8).

Table 5: Percentage of saltmarsh area covered by conservation designations Special Protection Area (SPA), Special Area of Conservation (SAC), Site of Special Scientific Interest (SSSI) and Ramsar by National Vegetation Classification (NVC) after Haynes (2016) GIS file.

Dominant NVC community	% of the total area	SPA (%)	SAC (%)	SSSI (%)	Ramsar (%)
SM1	0.13	100.00	0.00	100.00	100.00
SM2	0.001	0.00	0.00	0.00	0.00
SM5	0.01	100.00	0.00	100.00	100.00
SM6	1.66	1.07	0.90	74.25	1.07
SM8	4.20	96.48	52.01	97.86	96.34
SM9	0.20	84.29	0.73	96.60	83.97
SM10	0.86	75.41	21.65	75.96	74.77
SM12	1.26	98.20	45.86	99.96	98.20
SM13	28.60	60.90	42.92	81.55	60.68
SM14	0.30	100.00	100.00	100.00	100.00
SM15	0.00	0.00	100.00	100.00	0.00
SM16	55.55	52.55	40.27	73.18	51.75
SM17	0.06	50.06	0.00	81.54	69.91
SM18	0.77	61.00	42.16	58.82	51.62
SM19	0.14	9.25	10.30	37.60	9.25
SM20	0.25	44.74	45.93	55.57	37.81

SM23	0.01	3.83	0.00	5.99	0.00
SM25	0.00	0.00	100.00	100.00	0.00
SM27	0.05	0.00	0.00	0.00	0.00
SM28	5.86	79.30	49.00	85.74	78.92
Total	**100.00**	**58.48**	**41.25**	**77.65**	**57.86**

Table 6: Percentage of saltmarsh area covered by conservation designations Special Protection Area (SPA), Special Area of Conservation (SAC), Site of Special Scientific Interest (SSSI) and Ramsar after Haynes (2016) GIS file by saltmarsh zones as defined in the Haynes (2016) report, section 4.

Zone	% of the total area	SPA (%)	SAC (%)	SSSI (%)	Ramsar (%)
Littoral	0.14	98.92	0	98.92	98.92
Pioneer	8.23	74.89	36.10	91.08	74.74
Lower and middle	28.91	61.31	43.52	81.75	61.09
Upper	56.80	52.51	40.19	72.81	51.59
Strandline and disturbance	5.92	78.18	48.41	84.97	77.81
Total Saltmarsh	100.00	58.48	41.25	77.66	57.86

Table 7: Percentage of saltmarsh area covered by conservation designations Special Protection Area (SPA), Special Area of Conservation (SAC), Site of Special Scientific Interest (SSSI) and Ramsar by site size after Haynes (2016) GIS file, whereas a site is defined as a distinctly named geographical region (see section 2).

Site area (ha)	SPA (%)	SAC (%)	SSSI (%)	Ramsar (%)
> 100	74.70	56.94	96.78	74.66
> 50 and < 100	55.41	32.21	71.85	55.38
> 25 and < 50	60.24	40.95	79.98	59.24
> 10 and < 25	27.46	13.82	44.31	25.51
> 5 and < 10	30.54	17.77	43.73	27.98
> 3 and < 5	14.65	9.79	22.54	14.33
< 3	7.91	0.84	17.22	7.82

Table 8: Percentage of saltmarsh area covered by conservation designations Special Protection Area (SPA), Special Area of Conservation (SAC), Site of Special Scientific Interest (SSSI) and Ramsar by site size after Haynes (2016) GIS file, whereas a site is defined as a connected and uninterrupted stretch of land (see section 2).

Site area (ha)	SPA (%)	SAC (%)	SSSI (%)	Ramsar (%)
> 100	75.66	71.32	99.38	75.62
> 50 and < 100	81.06	46.00	99.08	81.13
> 25 and < 50	84.83	35.18	97.97	84.84
> 10 and < 25	45.49	20.52	63.37	45.19
> 5 and < 10	35.30	23.86	53.26	33.47
> 3 and < 5	31.17	23.53	54.27	30.00
< 3	23.74	16.79	39.31	21.46

3.2 Condition, pressures and threats

Haynes (2016) Scottish saltmarsh survey included condition monitoring of Habitats Directive Annex 1 H1310 pioneer saltmarsh and H1330 Atlantic saltmarsh based on methodologies developed by Scottish Natural Heritage (SNH). Site key attribute and features were noted and assessed against specified targets. About two thirds of 244 saltmarsh sites failed at least one or more targets of the site condition monitoring (SCM) (Haynes, 2016).

Condition failure was irrespective of site designation with designated and non-designated sites recording condition failures for approximately the same proportion of sites (Haynes, 2016). Condition failure was also mainly unrelated to site size, although proportionally larger sites (> 50 ha) failed more (Table 9). Noteworthy in terms of geographical distribution are condition failures across large areas in the Solway Firth and in northeast Scotland around Moray, Dornoch and Cromarty Firths (Figures A1-8 and A1-9).

Table 9: Number of saltmarsh sites failing and passing the site condition monitoring (SCM) in the Scottish saltmarsh survey, based on Haynes (2016) report Table 3-6.

Site area (ha)	Number of sites failing the SCM	Number of sites not failing the SCM
> 100	8	1
> 50 and < 100	10	1
> 25 and < 50	16	6
> 10 and < 25	32	15
> 5 and < 10	34	24
> 3 and < 5	24	13
< 3	39	21
Total	**163**	**81**

The main pressure and threat on saltmarshes is habitat modification in the form of sea defences, drainage channels (agricultural improvement) and creek modification, which cause changes to vegetation communities and impedes natural community transition. This is more evident on designated sites because these modifications historically occurred on the larger saltmarshes (Haynes, 2016).

Equally significant, overgrazing, poaching and vehicle damage occurs more frequently on smaller, undesignated marshes, where controls are not in place. These actions can negatively affect the sward and lead to erosion and eventually saltmarsh destruction (Haynes, 2016).

Other pressures and threats include pollution from outflow pipes and washing up of sanitary waste on the shore line as well as nutrient enrichment and non-native species (mainly *Spartina* sp. but other species are also present) v.

The main threat in the future is climate change. Changes in tidal currents, wave exposure and the possibility of sea defences are the major threats for H1310 Pioneer Marsh, whereas H1330 Atlantic Saltmarsh it is changes in tidal flow and hydromorphological change (Haynes, 2016).

A different source for the condition of Scottish saltmarsh is the “Protected Nature Sites Application” (NatureScot, 2023), which covers SACs, SPAs, SSSIs and Ramsar sites but no undesignated sites. However, for saltmarsh only SSSIs and Ramsar sites are listed. Of 62 saltmarsh features listed 53 are classed as favourable, 3 as recovering, 5 as unfavourable and 1 as not assessed[2]. Most of the sites were assessed as part of the 2012 to 2018 assessment cycle, but ten assessments are older than this, whereas one is more recent. Whether a condition is classed as favourable, recovering or unfavourable, depends on whether a set of targets have been met. Out of the 53 favourable features, three were last assessed as ‘unfavourable recovering’, three as ‘favourable declining’ and one as ‘partially destroyed’.

The database listed pressures for 33 sites[3], with overgrazing and invasive species being the most frequently listed pressures, as demonstrated in Figure 4.

Due to different site naming conventions and classifications, a comparison of the condition assessments between the two resources – Haynes (2016) and NatureScot (2023) – is limited to 16 sites only for which the names appear identical, but these few sites do illustrate how contrasting the assessments are (Table 10). Half of these sites are considered as ‘favourable’ by NatureScot (2023) but failed the SCM in the Haynes (2016) survey. Detailed methodologies do not seem to be readily available for both assessments, it is therefore impossible to tell whether the different monitoring outcomes are due to difference in assessment methodology or change over time.

[2] These numbers were derived by selecting ‘condition’ and filtering by feature category ‘coast’ and feature ‘saltmarsh’.

[3] These were obtained by selecting ‘pressure’ and filtering by feature category ‘coast’ and feature ‘saltmarsh’.

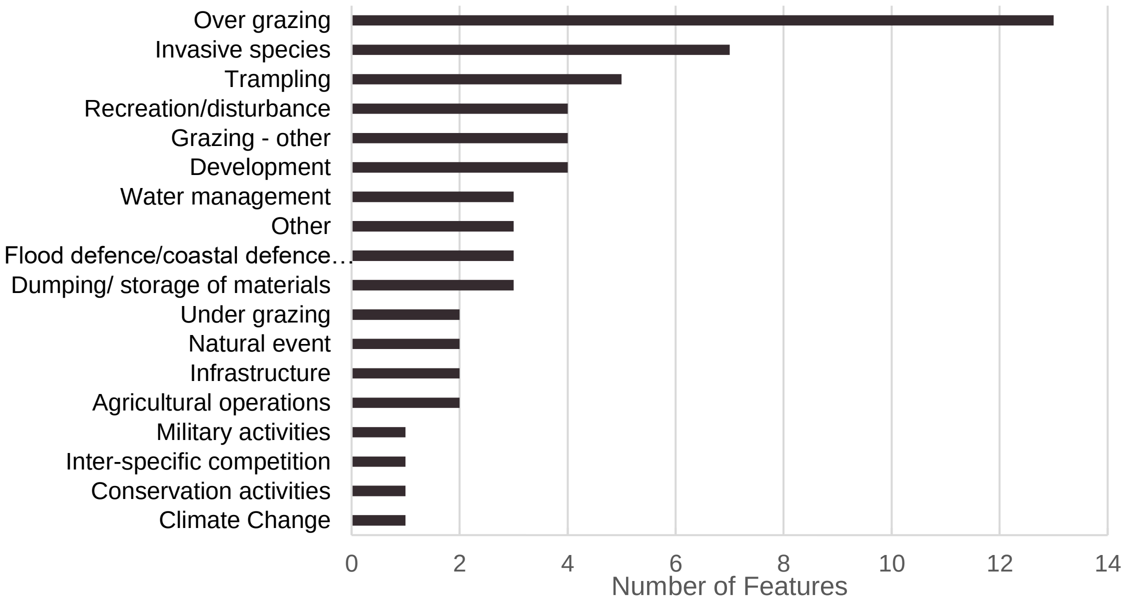

Figure 4: Pressures exerted on 33 Scottish saltmarsh features (i.e. sites) listed by number of occurrences based on NatureScot (2023).

Table 10: Comparison for condition assessments from Haynes (2016) and NatureScot (2023) for identically named sites, SCM = site condition monitoring.

Site / feature name	Summary Condition (NatureScot, 2023)	SCM failed (Haynes, 2016)
Bridgend Flats	Favourable	N
Gress Saltings	Favourable	N
Loch Moidart	Favourable	N
Luskentyre Banks and Saltings	Favourable	N
Montrose Basin	Favourable	N
Inner Clyde	Favourable	Y
Beauly Firth	Favourable	Y
Dornoch Firth	Favourable	Y
Eden Estuary	Favourable	Y
Gruinart Flats	Favourable	Y
Munlochy Bay	Favourable	Y

Waulkmill	Favourable	Y
Whiteness Head	Favourable	Y
Morrich More	Recovering	Y
Kentra Bay and Moss	Unfavourable	Y
Northton Bay	Unfavourable	Y

A further broad assessment of saltmarsh condition is available as a Marine Online Assessment Tool (Phillips et al., 2018), which applies the Water Framework Directive methods. According to the tool, the Northern North Sea is above target for its regional seas saltmarsh status, whereas the sea to the north and west of Scotland have not been assessed. More detail on the condition of coastal waters is available from the Scottish Government (2011), which includes a more detailed map.

4. Overview of completed saltmarsh restoration projects in Scotland

4.1 Managed realignment

The OMReg online habitat creation scheme data base (ABPmer, 2024) lists 4 MR projects through which saltmarsh habitat was created (Table 11). Montrose Basin is the oldest – completed in 1997 – and created 0.3 ha of saltmarsh involving a 30 m wide breach (ABPmer, 2024). Further information does not appear to be available, and the actual area is not obvious on satellite imagery.

The next MR project was undertaken by the RSPB at Nigg Bay, Cromarty Firth (Figure 5). The project was completed in 2003, included two 20 m wide breaches and created 25 ha of habitat of which 17 ha are intertidal mudflats and saltmarsh with the remaining 8 ha being transitional grassland (ABPmer, 2024; Tinch & Ledoux, 2006). The reported estimated total costs for the project vary from £38,000 (Tinch & Ledoux, 2006), over £47,480 (Elliott, no date), to £53,840 (Scottish Government, 2011), excluding land requisition and project management staff time (Elliott, no date). Of six MR schemes reviewed by Tinch & Ledoux (2006) Nigg Bay was the best value at the time for investment, based on costs per area of habitat created. Overall, the project was considered a success for both habitat creation and trialling MR in Scotland with the main weakness being the nature of long-term post-restoration monitoring, which was mainly carried out by students but not beyond their individual projects (ABPmer, 2024; Chambers et al., 2022). Detailed reports on the project itself and post-realignment monitoring are available from the RSPB (Chisholm et al., 2004; Elliot (2015)).

In 2007, the Kennet Pans, Firth of Forth (Figure 6), MR project was completed, which created 8.2 ha of mudflats, saltmarsh and transitional grassland of which only 1 ha is predicted to be saltmarsh (ABPmer, 2024; MacDonald et al., 2017). The MR project was carried out to create compensatory habitat to minimise detrimental impacts to the Firth of Forth SPA by the construction of the Clackmannanshire Bridge (Transport Scotland, 2017). Not much information appears to be publicly available on the success of the project, but the Transport Scotland (2017) evaluation refers to "poor saltmarsh establishment at the toe of the embankment" and MacDonald et al. (2017) mention post-MR sediment loss which led to higher carbon content in the neighbouring agricultural soils.

Skinflats, Firth of Forth (Figure 7), was first established through Regulated Tidal Exchange (RTE) in 2009 and then converted into an MR scheme in 2018. The existing embankments (installed by RSPB for the RTE on the site) were reinforced and a 25m breach was excavated in the old seawall. Initial concerns about potential flood risk proved negligible and the breached wall appears stable. The MR work created 10 ha of intertidal habitat and 1 ha of terrestrial habitat. The project was of very short duration with very tight deadlines due to funding availability, which proved to be a challenge at times but was completed as planned (ABPmer, 2024; Inner Forth Landscape Initiative, no date).

Table 11: Details of Managed Realignment (MR) schemes completed in Scotland based on the OMReg data base (ABPmer, 2024). Area (ha) refers to intertidal habitat created.

Scheme Name	Lead Organisation	Location	Habitats Created	Completion Year	Area (ha)
Montrose Basin	n/a	Montrose Basin (Angus)	Saltmarsh	1997	0.3
Meddat Marsh (Nigg Bay)	RSPB	Cromarty Firth (Highland Region)	Mudflat, Saltmarsh, Transitional Grassland	2003	25
Kennet Pans	Transport Scotland	Firth of Forth (Fife)	Mudflat, Saltmarsh, Transitional Grassland	2007	8.2
Skinflats	RSPB	Firth of Forth (Falkirk)	Lagoon, Saltmarsh, Transitional Grassland, Terrestrial Habitat	2018	10

Figure 5: Google Earth Pro satellite image of Meddat Marsh (Nigg Bay) from March 2022. A pre-restoration image is not freely available in similarly high resolution.

Figure 6: Google Earth Pro satellite images of Kennet Pans (Firth of Forth) from January 2005 (left) and September 2021 (right).

Figure 7: Google Earth Pro satellite images of Skinflats (Firth of Forth) from January 2005 (left) and September 2021 (right).

4.2 Other forms of restoration

Saltmarsh restoration in the form of planting locally raised plants sourced from donor habitats started in the Eden Estuary in 2000 – a first for the UK. In her original trials in October 1999 and March 2000 Clare Maynard planted sprigs and seeds from *Bolboschoenus maritimus*, *Phragmites australis* and *Puccinellia maritima* at one location each on the northern and southern shore of the Eden Estuary. The seeds did not germinate for *B. maritimus* and *P. australis*, therefore only the sprig planting could be compared for the three species. *B. maritimus* outperformed the other species in terms of seedling survival, shoot formation and sediment accretion (Maynard et al., 2011; Maynard, 2014). The second phase of planting started in 2010 and carried on up until 2017 when at least 0.2397 ha had been planted altogether (Maynard, 2020). Both phases of the restoration planting were investigated and evaluated by Wade (2018) and Taylor (2019) as part of their PhD thesis.

Whilst seedling establishment seemed successful initially, the overall wash-out rate was over 70 % and considered too high; planting trials therefore required a different approach. Clare Maynard subsequently led the Green Shores project from 2017 to 2020 (Maynard, 2020). Planting trials were extended to two further sites (Tayport Common, Tay Estuary and Dornoch Sands, Dornoch Firth) and included several additional saltmarsh species (*Festuca rubra*, *Plantago maritima*, *Aster tripolium*, *Salicornia europaea* agg. and *Triglochin maritima*). At each of the four sites about 0.3 ha (200 x 15 m) were planted. The planting involved the use of bio-rolls (biodegradable wave breaks), which increased the rate of success for plant establishment. Nonetheless, wash-out rates were still higher than hoped for and combined with the labour-intensive effort required for planting (a total of 9,000 hours delivered by 300 volunteers) highlights that more effective methods need to be developed for saltmarsh restoration through transplanting (Maynard, 2020; Chambers et al., 2022).

As mentioned in section 3.2, overgrazing is a key pressure on saltmarsh habitats. Likewise, undergrazing or no grazing can lead to unfavourable shifts in vegetation species composition (e.g. Bakker, 1985; Tessier et al., 2003). Managing grazing regimes for saltmarsh restoration is an approach currently practised by the RSPB at Mersehead and Kirkconnell Merse as part of their EU LIFE funded project “LIFE 100% for Nature”. Fencing and placing of water troughs and livestock bridges allows cattle to be moved across the saltmarsh – as opposed to stationary grazing – and reach areas previously left ungrazed. Initial observations show that cattle have removed dense vegetation and improved sward structure (Dempster, 2023). Mason et al. (2019) summarise recommendations for optimal saltmarsh grazing.

A map highlighting all restoration projects is available in Appendix 2 (Figure A2-1).

5. Saltmarsh restoration potential in Scotland

5.1 Historic intertidal loss

A first step for restoration potential would be to consider areas which historically supported saltmarsh but lost the habitat due to land claim or sea-level rise. However, there is a significant gap in data availability regarding the mapping of historic saltmarsh or historic intertidal habitat extents in Scotland.

The Water Framework Directive (WFD) (2000/60/EC) requires the classification of the quality status of transitional and coastal waters. This includes an assessment of “marine angiosperms”, which covers saltmarsh. To address the implementation of the WFD, the Environment Agency estimated the historic intertidal habitat with Light Detection And Ranging (LiDAR) in England and Wales (WFD UKTAG, 2014). Occurrence of historic intertidal habitat was assumed for all areas below the highest astronomical tide and located behind artificial flood defence. This data set was analysed by Stamp et al. (2022). They estimate that 2,483 km^2 of intertidal habitat was lost from estuaries in England and Wales between 1843 and WFD UKTAG (2014) assessment. A similar LiDAR analysis does not appear to exist for Scotland.

Ladd et al. (2019) looked at changes in saltmarsh extent between 1846 and 2016 for 26 estuaries across Great Britain, but the only Scottish site included is the Solway Firth. They manually mapped saltmarsh extent with OS maps and aerial photographs periodically throughout the considered time span. Within the Solway there are five specific areas covered by Ladd et al. (2019) that are on the Scottish side of the estuary (Table 12).

Table 12: Corresponding naming conventions of saltmarsh sites on the Scottish side of the Solway in Ladd et al. (2019) and Haynes (2016).

Site name Ladd et al. (2019)	Site name(s) Haynes et al. (2016)
Kirkconnell	Kirkconnell Merse, Carse Bay and Greenmerse
Caerlaverock	Caerlaverock and Glencaple
Priestside	Priestside
Redkirk	Gretna to Redkirk
Bowness Wath	Annan, Browhouses, Milnfield Merse, Torduff Point

For these five areas we extracted the historic layers from Ladd et al. (2019) and the contemporary saltmarsh extent from Haynes (2016) and overlaid these on a Digital Terrain Model (DTM) (Scottish Government, 2019) and Google Earth Pro satellite imagery to understand where historic saltmarsh loss occurred, what habitats cover the areas now and what elevation range currently occurs across historic saltmarsh areas.

Losses occurred on the seaward side, where mudflats now occur on areas previously occupied by saltmarsh (example Figure 8), although it is unclear from the data whether an actual loss occurred or whether this is potentially due to different mapping methodologies or errors from manually mapping historic saltmarsh occurrence. Losses on the landward side may have also occurred due to habitat transition to non-saltmarsh NVC communities (Figure 9), but again, this may also be due to mapping error.

Figure 8: Potential saltmarsh loss or mapping error on the seaward side at Carse Bay showing mudflats where saltmarsh may have existed in the past. Yellow = existing saltmarsh (Haynes, 2016); blue outline = historic saltmarsh (Ladd et al., 2019).

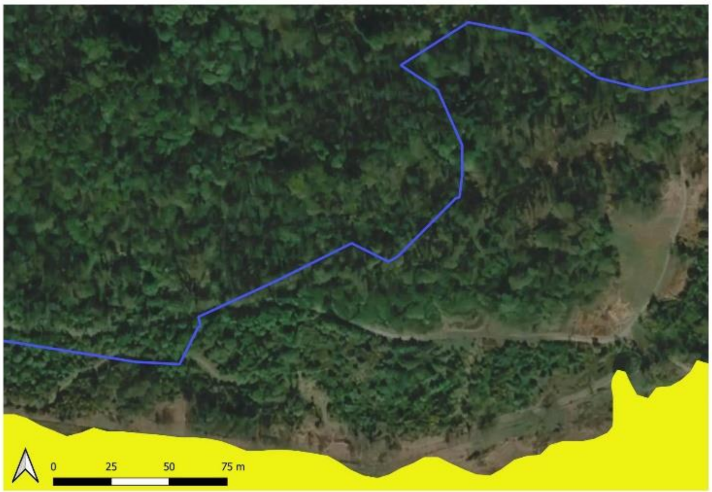

Figure 9: Figure 9: Potential saltmarsh loss due to habitat transition or mapping error on the landward side at Caerlaverock showing trees where saltmarsh may have existed in the past. Yellow = existing saltmarsh (Haynes, 2016); blue outline = historic saltmarsh (Ladd et al., 2019).

To identify areas where saltmarsh loss has occurred historically due to land claim, we applied the following criteria:

- had saltmarsh historically as identified by Ladd et al. (2019),
- of similar low-lying elevation as the adjacent saltmarsh, and
- currently separated from existing saltmarsh by a sea defence

This approach identified two sites, one 7.4 ha area at Kirkconnell (Figures 10 and 11) and one 2.5 ha area at Bowness Wath (Figures 12 and 13). However, the Kirkconnell example highlights the limitations of the application of historic saltmarsh mapping to identify potential sites for restoration. At least two further areas (Figure 14) in the immediate vicinity have the potential to become saltmarsh based on their elevation, and the fact they are situated behind a sea defence, but these would not have been captured by the historic mapping approach alone.

The main constraint of using historic saltmarsh occurrence to identify potential restoration sites is that reliable maps only exist from the 1840s onwards (as applied by Ladd et al., 2019 and Stamp et al., 2022), but historic land claims would have happened before then. A different or additional approach is therefore needed to identify all potential sites.

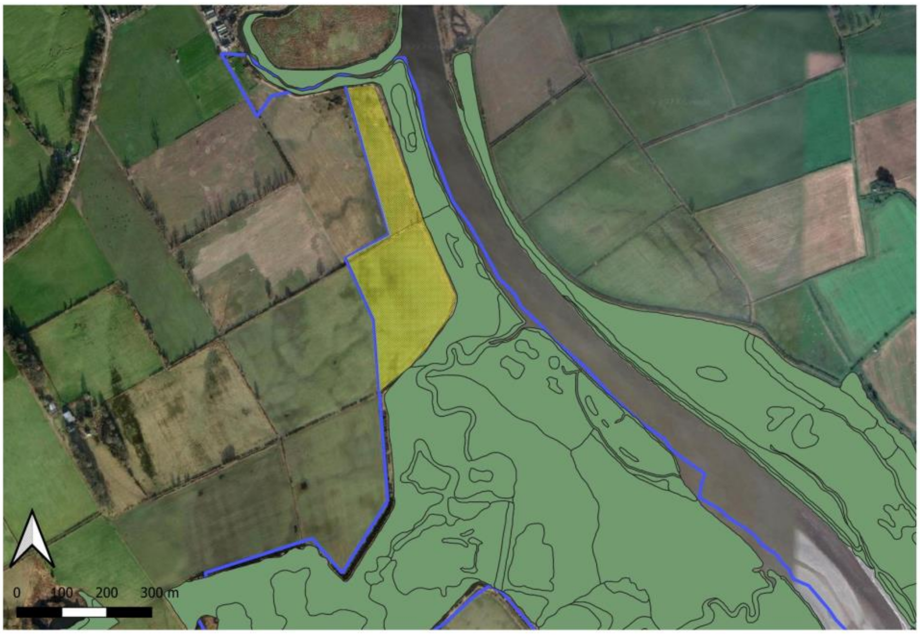

Figure 10: Potential site for restoration (shaded in yellow) at Kirkconnell based on historic marsh extent (blue outline, Ladd et al., 2019); green areas are areas surveyed by (Haynes (2016) including non-saltmarsh NVC communities.

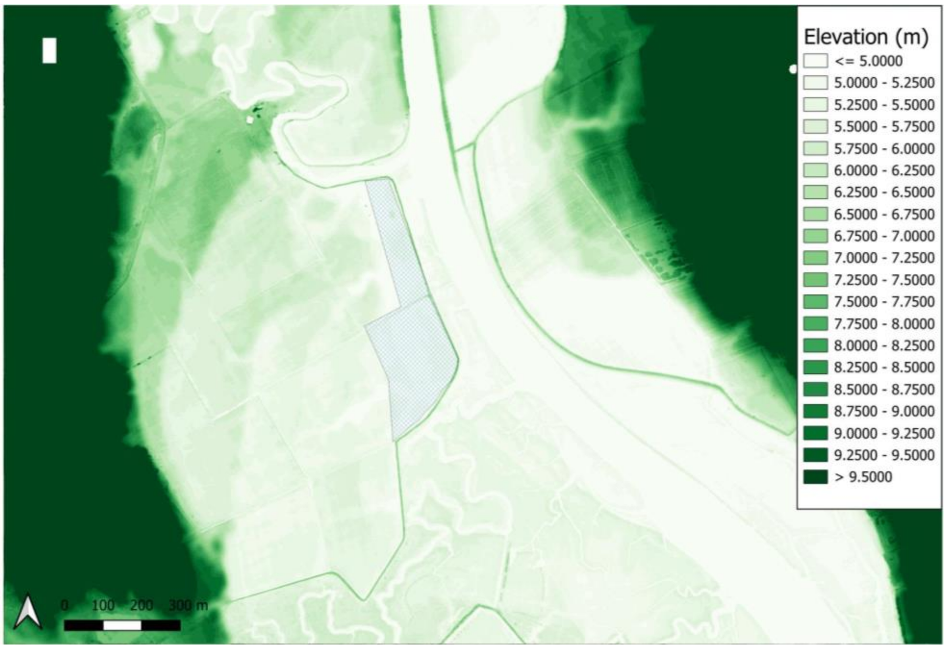

Figure 11: Figure 11: Potential site for restoration (shaded in pale blue) at Kirkconnell with LiDAR data (Scottish Government, 2019) showing the enclosed historic marsh has a similar height to the neighbouring existing marsh.

Figure 12: Figure 12: Potential site for restoration (shaded in yellow) at Bowness Wath based on historic marsh extent (blue outline, Ladd et al., 2019); green areas are areas surveyed by (Haynes (2016) including non-saltmarsh NVC communities.

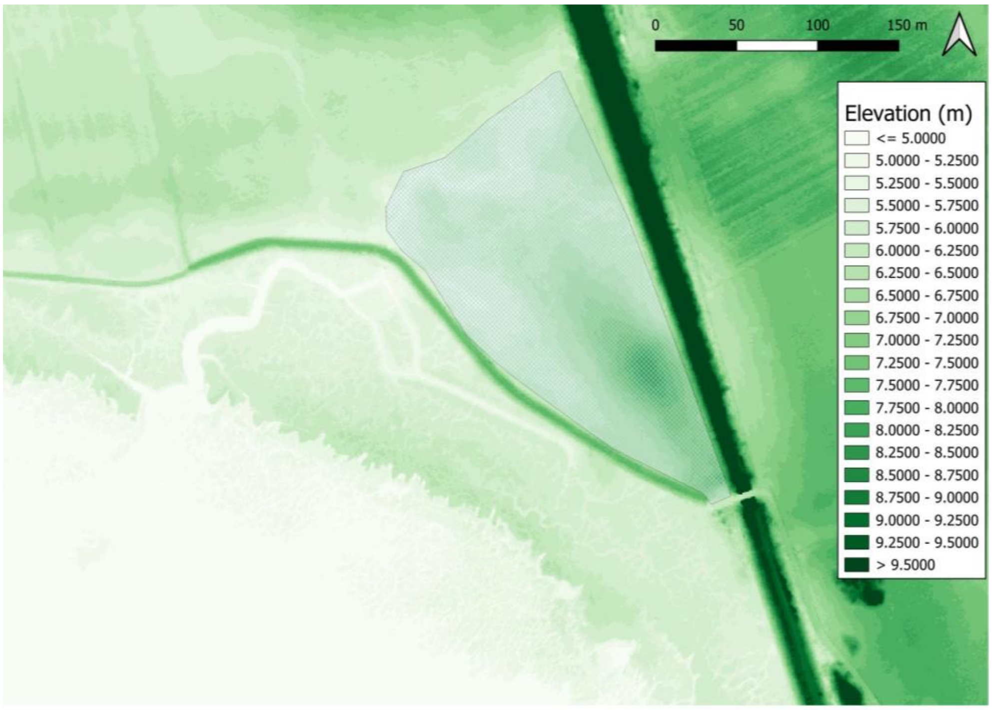

Figure 13: Potential site for restoration (shaded in pale blue) at Bowness Wath with LiDAR data (Scottish Government, 2019) showing the enclosed historic marsh has a similar height to the neighbouring existing marsh.

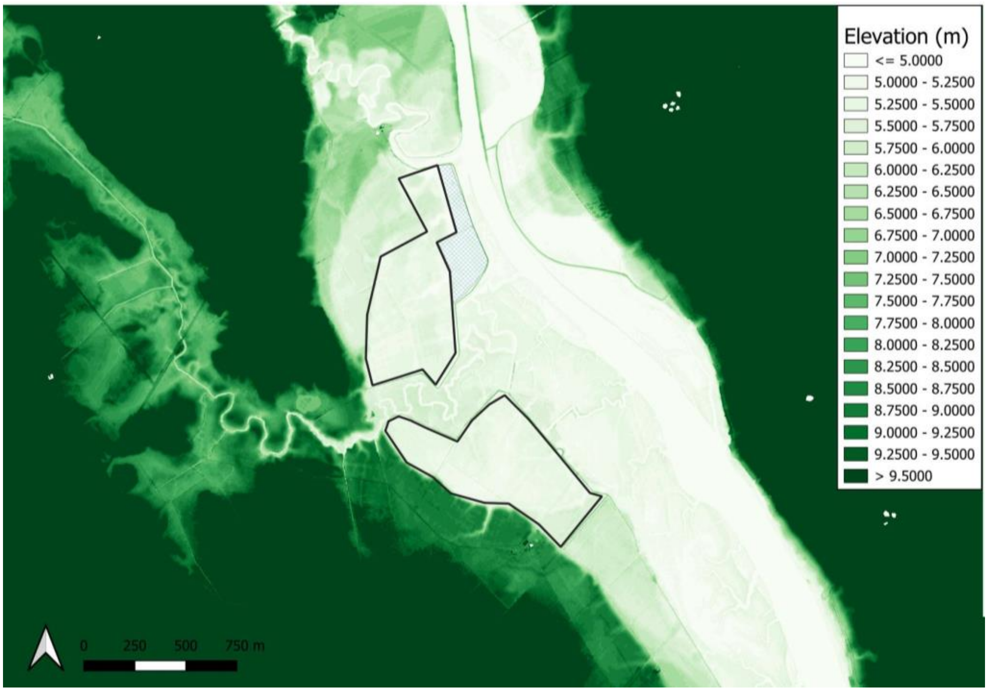

Figure 14: : Potential sites for restoration with LiDAR data (Scottish Government, 2019), one site identified by historic mapping (shaded in pale blue), and two additional sites identified by comparing the height of nearby land with that of the saltmarsh height.

5.2 Modelling

Scotland wide

Austin et al. (2022) produced a report, which highlights potential sites for MR along the Scottish coast. To identify the sites they developed a spatial model based on a coastal elevation model and tidal inundation data. The coastal elevation model was created from a 5 m resolution DTM, which is available for the entire Scottish coastline, combined with higher resolution (1 m or 2 m) DTMs, where the relevant LiDAR data was available. Tidal inundation data were a mix of hourly tide gauge records – available from the British Oceanographic Data Centre (BODC) – and unpublished in-situ inundation data from across central Scotland from previous research projects. The authors state the model assumed that low to mid marsh would form anywhere between the occurrence of the highest astronomical tide (HAT) and mean high water spring (MHWS) and high marsh would occur between MHWS and mean tide level (MTL) – although it can probably be assumed that the opposite was applied, and the mix-up of high and low-mid marsh occurrence is an accidental error in the write-up.

The model was fine-tuned to predict the formation of low-mid and high marsh saltmarsh only – as opposed to other coastal habitats such as beach and shingle –

and produced 15 potential sites (Appendix 3, Figure A3-1). The total area of predicted saltmarsh across the 15 sites is estimated at 9.93 km^2 or 993 ha; however some newly created marsh appears to be located on existing marsh with a shift in vegetation zones in place (from high marsh to low-mid marsh) rather than actual saltmarsh creation predicted. The total newly created saltmarsh area is therefore more likely to be 8.5 km^2 or 850 ha (after the deduction of 1.43 km^2 of existing marsh).

The authors further assessed these sites on aerial imagery and grouped them into four categories: highly suitable, suitable, less suitable and not suitable, depending on whether saltmarsh and significant infrastructure are currently present at these sites. Table A4-1 in Appendix 4 provides an overview of all 15 sites including the reasoning behind the grouping into the suitability categories. Of these, 11 sites were considered suitable covering 8.48 km^2 or 848 ha and creating a total of 7.05 km^2 or 705 ha of new marsh. The next recommended step for these sites is monitoring of marsh zones in relation to tidal datums.

Austin et al. (2022) also calculated the potential carbon stock for the top 10 cm of soil these sites can hold (see section 6.2). The calculations are based on previous work by Austin et al. (2021) from which bulk density and organic carbon (OC) content were taken. These sites were also further assessed to understand what impact potential sea-level rise would have on the hypothetically created saltmarsh under different climate change scenarios.

The identification of only 15 sites for potential MR schemes across the whole of Scotland seems rather low; especially considering that several local efforts to identify saltmarsh sites with restoration potential as outlined below highlighted much higher numbers of potential sites and in areas where Austin et al. (2022) identified none. This discrepancy is most likely due to the model parameters applied by Austin et al. (2022).

Solway Firth

The Solway Firth Partnership commissioned a report to map the potential for saltmarsh and 'pseudo-saltmarsh' (i.e. transitional communities which cannot be fully recognised as saltmarsh as defined by Griffin (2023)) within the Solway Firth, which was completed by Griffin (2023). Griffin (2023) combined LiDAR data with the Haynes (2016) GIS layer to determine the elevation for the different NVC communities for the Solway Firth. The elevation values for existing saltmarsh were used to interrogate the LiDAR data for adjacent sites (within 1 km of existing saltmarsh sites mapped by Haynes (2016)) larger than 0.2 ha of similar elevation. Griffin (2023) predicts 92 sites (Appendix 3, Figure A3-2) within the Solway Firth totalling around 1,537 ha within the 1 to 6 m height bracket and a further potential 1,891 ha between 6 to 8 m in height under more extreme climate scenarios. The report includes comments on proximity to neighbouring saltmarsh and presence of infrastructure but does not classify the sites into suitable or unsuitable for restoration such as Austin et al. (2022) did. Further work is currently being carried out and involves monitoring of selected identified sites with mini-buoys (Balke et al., 2021) for tidal inundation (pers. comm. C. McFarlan, Solway Firth Partnership Manager).

5.3 Desktop studies combined with site visits

Inner Forth

In 2012 the RSPB published the “Inner Forth Futurescape” feasibility study (RSPB, 2012), which explored the potential of intertidal habitat restoration within the Inner Forth. A total of 21 sites (Appendix 3, Figure A3-3) were assessed by desktop research of maps combined with site visits for their suitability for habitat restoration. Nine of these sites were not considered further in the report because the opportunities presented at the sites were limited. The remaining 12 sites (covering 683 ha) were all deemed suitable and assessed for their habitat creation potential, contribution to flood management and visitor development potential. The potential project duration and potential restoration costs were also estimated.

Out of the 12 potential sites for intertidal habitat restoration two have had further development since the report was published in 2012. The Skinflats MR work was completed in 2018 as described in section 4.1. For the Inch of Ferryton the RSPB commissioned several follow-on studies to investigate potential habitat restoration work.

Inner Forth – Inch of Ferryton

Several reports have progressed the Inch of Ferryton site and are summarised here to highlight the details and complex approaches required for such large-scale habitat restoration work. The potential MR site at the Inch of Ferryton consists of two farms surrounded by an old embankment, which has previously occasionally allowed saline sea water in during flood and storm events, affecting the condition of the farming land, which also has to be pump-drained to take freshwater run-off over the embankment. In addition to the farm buildings and farm access, the site also contains infrastructure in the form of electricity pylons and gas pipelines, which make MR proposals more challenging and costly.

The first report commissioned by the RSPB (ABPmer, 2014a) was an options appraisal study to evaluate different approaches for the future of the site. Five options were considered: the ‘do nothing’ approach would likely lead to breaching of the embankment within the next 20 years (leading to loss of farming land but creation of intertidal habitat); the ‘maintain status quo’ option would reinforce the existing embankments to prevent breaching and to maintain the farmland; two MR approaches (maximum and constrained) would create 132 ha or 74 ha of intertidal habitat, respectively; and RTE would create 33 ha of intertidal habitat. The constrained MR and RTE approaches would also maintain some arable and grazing land.

The initial estimated costs for the five options ranged from £371,700 for the RTE to £9,247,000 for the maximum MR scheme. Costs also depended on the source of the material, the slope on the embankment, footpath provision on the embankment crest and use of geotextiles.

The cost-benefit analysis showed that whether a positive net present value and benefit-cost ratio (BCR) can be achieved highly depended on whether the scheme implementer must bear the gas pipeline upgrade costs, which is possible but may not necessarily be the case. It also depended on the number of annual visitors the completed site would attract (>30,000 per year results in a positive BCR for MR and RTE). For all scenarios, the 'maintain status quo' option always had the lowest BCR.

Stage 1 considered all five options and selected option 4 'constrained MR' as the preferred option because it avoids the major infrastructure issues and also only affects one landowner. This option was then further explored in Stage 2 (ABPmer, 2014b).

Within the Stage 2 appraisal study the estimated costs were adjusted to allow additional work for ecological enhancements and freshwater drainage. If all natural materials could be sourced from within the site, then the total costs were now estimated to be £4.3 million, excluding land purchase costs; converting to £54,000 per ha, which was under the 2013 average for MR and RTE projects as stated in the report. The anticipated 74 ha of intertidal areas would consist of 26 ha lagoons, 15 ha mudflats and 32 ha saltmarsh. Over time with accretion more areas were predicted to become saltmarsh.

In 2019 the RSPB commissioned a further report from ABPmer to clarify questions and uncertainties around the implementation of a potential MR scheme with regards to the potential unmanaged breach of the site, the electricity pylons, further hydrodynamic modelling and the size and cost of an Environmental Impact Assessment (ABPmer, 2019).

In 2023 the RSPB commissioned a further assessment of the MR designs (GDG, 2023) alongside a flood risk assessment for Inch of Ferryton (Kaya Consulting, 2023). The additional MR design work considered the engineering required to deliver the previous recommendations and concluded that the constrained approach, which would necessitate significant secondary defences, is not able to be implemented for cost and practical reasons. Estimated costs would be £14.8m (GDG, 2023).
The only other option to deliver MR would be to implement the full MR scheme. Before this could happen, those who own the wider land area and infrastructure

would need to decide they wanted to do this, which is not currently the case. The revised figures for this wider scheme within a 155 ha site, are estimated to create 80 ha saltmarsh with estimated costs of £5m (pers. comm. T. Wilson, Senior Conservation Officer, RSPB).

The flood risk assessment focussed on the possibility of overtopping of existing defences and related consequences. Up to the current 25-year event (revised from the aforementioned 20 years), the existing defences will protect the area from flooding, but beyond that it is likely that flood waters will overtop the embankments. Within a 200-year climate change event the land will be inundated up to 1.5 km inland. If overtopping was followed by a breach, the flooding could be even greater.

The report concluded that the proposed MR scheme would be an acceptable land use under current planning laws for areas at flood risk; however, only if the development does not increase the flood risk of neighbouring areas. This flood risk assessment therefore also assessed the impact on neighbouring land. The general conclusion of the report was risk of flooding can be reduced but not totally eliminated. Measures to protect neighbouring property may involve property level protection or waterproofing of buildings.

Firth of Clyde

Hansom et al. (2017) produced a report on the impacts of sea-level rise on the coastal areas of the Firth of Clyde. This included feasibility studies for four sites within the Firth for MR: three sites along the Inner Clyde Estuary and one site at the head of the Holy Loch sea loch. The site on the northern shore of the Inner Clyde is considered unsuitable because of the poor condition of the existing saltmarsh and existing infrastructure, which is likely to inhibit any MR scheme. The other three sites (Appendix 3, Figures A3-4, A3-5 and A3-6) are all considered suitable. It is unclear from the report how these sites were selected. The report only states “Following close discussions with FoCF team and further funding from project partners, two key areas were examined in detail”, with FoCF presumed to be Firth of Clyde Forum.

The sites were assessed by walkover surveys, which included an assessment of current saltmarsh condition, identification of landward migration of saltmarsh species and presence of pioneer species. MHWS and mean low water spring (MLWS) were mapped for all of the sites.

It is unclear from the report which criteria were used to identify the individual potential restoration sites; nor does the report indicate the area sizes. We created polygons for the suggested sites – visual tracing off the report maps combined with details from the descriptive text – and used these to estimate the area sizes (Table 13) and overlaid these on LiDAR imagery to highlight land elevation compared to neighbouring saltmarsh.

Table 13: Overview of potential sites for MR at the Firth of Clyde. Extent of existing saltmarsh from Haynes (2016) GIS data; extent of potential saltmarsh area calculated from manually created polygons based on report maps (Hansom et al., 2017); suitability after Hansom et al. (2017).

Site Name	Extent of existing saltmarsh (ha)	Extent of potential saltmarsh (ha)	Suitability
Inner Clyde North	5.75	n/a	Not suitable
Inner Clyde South	13.62	83.21	Potential
Newshot Island	0.77	41.94	Potential
Holy Loch	14.50	94.75	Potential

5.4 Summary of restoration potential

Sections 5.1 to 5.3 highlighted different approaches for the identification of saltmarsh restoration potential. Mapping of historical saltmarsh extent in the Solway Firth combined with LiDAR data found two sites which historically were saltmarsh and are now agricultural fields surrounded by sea walls. At the same time this approach illustrated that other potential sites could be missed if only historical mapping was used due to the lack of reliable maps pre-1840s.

The use of modelling with LiDAR DTMs and the potential inclusion of tidal extent completed so far identified a much wider range of potential sites – up to 107 across Scotland – but the correct setting of thresholds for elevation and tidal range are key to accurately identify potential sites. These parameters vary depending on location and if an all-Scotland approach for modelling would be pursued, it would need to include local variability in saltmarsh elevation and tidal range.

Local knowledge combined with desk studies and site visits have identified a further three sites in the Firth of Clyde and 12 sites in the Inner Forth. Within the latter one site – Inch of Ferryton – has been further assessed. The Inch of Ferryton example highlights the different stages and considerations that sites identified for restoration potential may need to undergo. It also highlights the importance of realistic expectations for saltmarsh creation and how these may change under different MR design schemes.

All four studies combined have identified 118 potential sites, but these overlap on four locations between the RSPB (2012) and Austin et al. (2022) data sets; thereby giving a new total of 114 sites (Appendix 3, Figure A3-7) across 2,615.9 ha (Table 14). Whilst this may appear to be a large area – just under 50% of the current saltmarsh extent in Scotland – it is worth noting that all of these sites need to undergo further considerations in terms of suitability for tidal range and elevation, presence of infrastructure and landowner support. It is therefore unlikely that all identified sites could be taken forward. Furthermore, the Inch of Ferryton example highlighted that not all of the created intertidal habitat would become saltmarsh. For Inch of Ferryton this varied between 43% of the intertidal area under the constrained MR scheme and 50% of the intertidal area under the full MR scheme.

Considering the location of these sites in relation to existing saltmarsh, there is a distinct lack of studies on Scotland's west coast and within the estuaries in the northeast (Dornoch Firth, Cromarty Firth, Beauly Firth and Moray Firth) (Appendix 3, Figure A3-7). Further work is therefore required to map the full potential for saltmarsh restoration within Scotland.

Table 14: Overview of studies that have identified sites with saltmarsh restoration potential. Four of the original 118 identified sites were removed due to an overlap between RSPB (2012) and Austin et al. (2022). The lower areas estimates for each of the overlapping sites were retained to provide a more conservative estimate. This resulted in a reduction of sites by one for Austin et al. (2022) and by three for RSPB (2012).

Geographical Area	Source	Number of sites	Area (ha)
Firth of Forth	RSPB (2012)	9	313
Firth of Clyde	Hansom et al. (2017)	3	219.9
Scotland (all)	Austin et al. (2022)	10	546
Solway Firth	Griffin (2023)	92	1,537
Total		**114**	**2,615.9**

6. Blue carbon potential for saltmarsh restoration sites

6.1 Scottish blue carbon data

Several reports and peer-reviewed papers on Scottish saltmarsh carbon have been published in recent years, such as Smeaton et al. (2023), Miller et al. (2023), Smeaton et al. (2022a) and Austin et al. (2021). Cunningham & Hunt (2023) provide a review of the evidence for all Scottish blue carbon habitats, including saltmarshes and consider all existing literature including the above-mentioned publications apart from Smeaton et al. (2023), which presumably was published after Cunningham & Hunt (2023).

Saltmarsh carbon can be looked at from different angles with figures for carbon stocks, carbon density and carbon accumulation usually reported. The available data for these for Scotland are summarised in Tables 15 to 17. Saltmarsh assessments typically either consider the surficial (usually 10 cm) soil carbon or the total marsh including the entire soil core depth and aboveground and belowground biomass. Miller et al. (2023) report that 99.9% of their estimated carbon stock for Scotland is held in the soil with the remainder being contributed by biomass. This raises the question whether the inclusion of potentially time-consuming estimates of aboveground and belowground biomass are required in future studies. The contrast of surficial soil depth and the entire marsh depth, however, is significant (Tables 15 and 16).

Table 15: Overview of Scottish saltmarsh organic carbon (OC) stocks (Mt C) from published literature. Total marsh refers to soil C stocks from the entire soil profile and aboveground and belowground biomass C stocks. SD = standard deviation.

Study	Study focus	OC stock (Mt C)	SD	% of relevant GB stock
Beaumont et al. (2014)	Total marsh	0.57	n/a	9.5
Austin et al. (2021)	Surficial (10 cm) soil	0.368	0.102	-
Smeaton et al. (2022a)	Surficial (10 cm) soil	0.368	0.091	15.9
Miller et al. (2023)	Total marsh	1.15	0.21	-
Smeaton et al. (2023)	Total marsh	0.935	0.262	17.96

Table 16: Overview of Scottish saltmarsh organic carbon density (t C ha^{-1}) from published literature. Total marsh refers to the inclusion of the entire soil profile. Original values were reported as kg C m^{-2} and converted to t C ha^{-1}. SD = standard deviation.

Study	Study focus	Soil carbon density (t C ha^{-1})	SD
Beaumont et al. (2014)	Total Marsh	-	-
Austin et al. (2021)	Surficial (10 cm) Soil	36.4 – 65.7	-
Smeaton et al. (2022a)	Surficial (10 cm) Soil	63.1	15.6
Miller et al. (2023)	Total Marsh	186	39
Smeaton et al. (2023)	Total Marsh	163.2	39.2

Table 17: Overview of Scottish saltmarsh organic carbon accumulation rates from published literature. SD = standard deviation.

Study	Accumulation rate low-mid marsh (g C m^{-2} yr^{-1})	SD	Accumulation rate high marsh (g C m^{-2} yr^{-1})	SD	Annual C addition (t C yr^{-1})	SD
Miller et al. (2023)	103.4	18.4	71.5	9.3	4,385*	481

* First-order estimate for the whole of Scotland as described further below.

Surficial soil carbon is quicker and easier to capture therefore resulting in larger data sets. For Scotland this information is available from 46 sites (Ruranska et al., 2020; Austin et al., 2021); whereas full marsh assessments have been made for 14 sites (Smeaton et al., 2023 and Miller et al., 2023) and sedimentation and accumulation rates are only available for four sites (Miller et al., 2023). This has implications for robustly upscaling the existing data from individual marshes to all of Scotland. Further consideration should also be given to the number of cores taken at each marsh which ranges from two to four wide cores per marsh for the Miller et al. (2023) accumulation rates to 4 to 55 surficial (10 cm) samples per marsh (Ruranska et al., 2020); Smeaton et al., 2022a). Regarding the OC accumulation rates extrapolated to all of Scotland, Miller et al. (2023) do recommend caution on their wider interpretation. They consider the data first-order estimates, which are based on few data points. Please see section 6.3 for further details on data availability and replication.

6.2 Saltmarsh restoration blue carbon potential

Out of the four studies exploring restoration potential in Scotland across different areas (see section 5) two contain estimates on the potential blue carbon gain: Austin et al. (2022) and Griffin (2023). Austin et al. (2022) estimated the blue carbon potential of the identified sites with restoration potential by calculating the potential surficial (10 cm) OC soil stock with dry bulk density and OC data available from Austin et al. (2021), assuming that MR saltmarshes will reach a point, where they function as natural marshes in terms of OC capture and storage. The retention of the surficial OC stock was considered under different seal-level rise scenarios.

The 11 suitable and identified sites could potentially hold an additional 53,976 t OC or 0.05 Mt surficial OC stock (Table 18), which is a conservative estimate and would be higher if the entire saltmarsh depth were considered. However, the reported standard deviation (SD) of the surficial OC stock is at least 50% of the total predicted surficial soil OC stock for each of the sites, which highlights how variable and uncertain the estimates are. The authors conclude that nearly 50% of the additional carbon would be retained by 2100 under the most extreme future sea-level rise scenario.

Griffin (2023) estimates an additional total of 50 to 60 t C ha^{-1} across the 92 Solway Firth sites provided these develop from intensive pastures to mid-level saltmarsh. This would result in a total of approximately 90,000 t OC or 0.09 Mt OC. This is also an estimate for surficial (10 cm) C stocks only based on Austin et al. (2022) calculations.

Hansom et al. (2017) and RSPB (2012) do not provide OC stock estimates for their sites; however the first feasibility study for Inch of Ferryton does include carbon sequestration[4] into the cost-benefit analysis based on the ABPmer ‘Blue Carbon Calculator’. These are reported as annual carbon sequestration rates (t C yr^{-1}) with initially high rates in the first 5 years, which then drop in the subsequent post-MR year brackets (ABPmer, 2014a). The actual numbers vary greatly not only between year brackets but also between the different restoration schemes considered. Table 19 shows the anticipated carbon gains for potentially created intertidal habitats under the full MR scheme. Within the first 40 years post MR the site could potentially accumulate 8,855 t C.

[4] Defined by ABPmer (2014a) as “… sequestration on mud by accretion and sequestration on marsh by both accretion and vegetative growth once marsh is full established.”

Table 18: Estimated soil OC (t) gain by sites with restoration potential as identified by Austin et al. (2022). SD = standard deviation.

Site name	Surficial soil OC (t)	SD
Baldrium, Dornoch Firth	1,958	1177
Ardmore, Dornoch Firth	646	330
Montrose, Montrose Basin	9,415	4981
Skinflats, Firth of Forth	2,776	1421
Inch of Ferryton, Firth of Forth	1,311	754
Tyninghame	7,002	3618
Dunmore, Firth of Forth	4,498	2355
Eden Estuary	2,733	1420
Kirkhill, Moray Firth	10,800	6783
Tayport, Tay Estuary	1,544	789
Carron Pools, Firth of Forth	11,293	5806
Total	**53,976**	-

Table 19: Average annual carbon sequestration (t C yr^{-1}) for Inch of Ferryton as estimated by ABPmer (2014a) for the full MR scheme, which is expected to create132 ha of intertidal habitat and 80 ha of saltmarsh (ABPmer, 2014a; pers. comm. T. Wilson, Senior Conservation Officer, RSPB).

Year bracket	Average annual carbon sequestration (t C yr^{-1})
Year 1 – 5	495
Year 6 to 15	298
Year 16 to 40	136
Years 41 to 100	75

6.3 Data availability for blue carbon calculations

In order to accurately estimate the full blue carbon potential of sites identified for saltmarsh restoration potential through MR, a key set of parameters is required:

- Marsh elevation
- Tidal range / tidal inundation
- Bulk density (BD) and soil OC content from a nearby reference marsh
- Sediment accretion rates

Marsh Elevation

Data for marsh elevation can be obtained from the Scottish Remote Sensing Portal (Scottish Government, 2024) and Digimap (EDINA, 2024); however, the coast areas have not been entirely captured by LiDAR and data gaps exists, especially in the north and on the west coast.

Tidal range / tidal inundation

Tidal range data is available from EasyTide (ADMIRALTY, 2024) for 217 locations in Scotland (Appendix 5, Figure A5-1).

Bulk density and soil organic carbon content – surficial (10 cm) soil

BD and OC content data are available for 46 marshes across Scotland collected as part of the Carbon Storage in Intertidal Environments (C-SIDE) project. There are a total of 471 samples, 266 of which were collected with modified syringe samples and 205 with narrow (3 cm) gouge augers (Ruranska et al., 2020). Austin et al. (2021) upscaled these samples through modelling to all saltmarshes in Scotland for their first assessment of saltmarsh blue carbon stock in Scotland. This has created a modelled data set of surficial (10 cm) soil OC stock for 237 marshes (Smeaton et al., 2021).

Smeaton et al. (2022a) also utilised the C-SIDE data set for surficial soil and upscaled the data alongside additional samples from England and Wales to all of Great Britain. This has created a separate modelled data set of surficial (10 cm) soil OC stock for 236 marshes (Smeaton et al., 2022a, supplementary material), which differs in marsh OC stock compared to Ruranska et al. (2020) due to different levels of vegetation characteristics available (NVC plant community vs zone) for Scotland and England. Therefore, the upscaling approach had to be adjusted (C. Smeaton, pers. comm.).

A further data set for surficial (10cm) soil samples was compiled by Miller et al. (2022). This consists of 79 syringe samples from five marshes and included two marshes which had not been covered by Ruranska et al. (2020).

BD and OC content are available from a total of 550 samples across 48 marshes in Scotland (Table 20; Appendix 5, Figure A5-2).

Table 20: Overview of studies, which have collected and generated data for bulk density and soil organic content of surficial (10 cm) soil samples.

Study	Method	Sample numbers	Marsh numbers
Ruranska et al., 2020)	Coring / field sampling (2018-2019)	471	46
Austin et al. (2021); Smeaton et al. (2021)	Modelling	-	237
Smeaton et al. (2022a, supplementary data)	Modelling	-	236
Miller et al. (2022)	Coring / field sampling (2021)	79	5
Total Scotland*		**550**	**48**

* field-based numbers

Bulk density and soil organic carbon content – full depth soil

Full soil depth core data are available from Miller et al. (2022) for 148[5] narrow (3 cm diameter) cores from seven marshes[6] and 18 wide (6 cm diameter) cores from the same marshes. The data from the wide cores for four of these marshes were used in Miller et al. (2023).

The Smeaton et al. (2023) publication is based on narrow (3 cm diameter) cores from 13 marshes, nine of these are from Smeaton et al. (2022b) and the remainder are filed under Miller et al. (2022).
Smeaton et al. (2022b) contains a total from 226 narrow (3 cm diameter) cores from ten Scottish marshes; one of which - Dale Voe, Shetlands – was not used for Smeaton et al. (2023). Accounting for the overlap between both studies and data

[5] The supporting information states 148, but the actual data set contains data for 149.

[6] The supporting information states seven marshes, however, Skinflats and Forth (Alloa) coring locations are within 50 to 200 m of one another on the southern bank of the Firth on either side of the Clackmannanshire Bridge; they therefore appear as one marsh on Scotland wide maps.

sets, the total number of narrow cores taken to date is 313 from 14[7] marshes (Table 21; Appendix 5, Figure A5-3).

Table 21: Overview of studies, which have collected data for bulk density and soil organic content of full soil depth soil samples.

Study	Core diameter	Method	Sample numbers	Marsh numbers
Miller et al. (2022)	Narrow (3 cm)	Coring / field sampling (2018-2020)	148 (149)	7
Miller et al. (2022)	Wide (6 cm)	Coring / field sampling (2020)	18	7
Smeaton et al. (2022b)	Narrow (3 cm)	Coring / field sampling (2018-2019)	226	10
Total Scotland			**313**	**14**

Sediment accretion rates

Data from which sediment accretion rates and organic carbon accumulation rates (OCAR) can be calculated are available for five marshes from Miller et al. (2022), who took seven wide cores and analysed these for radionuclides for approximately the last 150 years. Data for four marshes were used in Miller et al. (2023) to actually calculate accretion rate and OCARs. Teasdale et al. (2011) also used the radiometric dating method for a similar age range for four cores from four marshes to calculate accretion rates.

LiDAR data was used by Masselink & Jones (2024) to obtain sediment accretion rates for one marsh (Skinflats / Bothkennar Fields). They compared elevation of an agricultural field, which was claimed in 1784, to that of a neighbouring natural saltmarsh. The difference of elevation was divided by the number of years of accretion to obtain annual sediment accretion rates. LiDAR data can have an error value of up to 15 cm, which creates large error margins for comparisons of small elevation differences; but becomes more negligible when larger elevation differences are compared such as in Masselink & Jones (2024).

Taylor (2019) monitored sediment deposition at permanent stations on a natural marsh and a marsh restored by planting of *B. maritimus*. They did not calculate

[7] Or 13 marshes if the adjoining Skinflats and Forth (Alloa) are considered as one site.

accretion rates but reported elevation change for their study period which lasted for 289 days, which could be upscaled to an entire year.

The Masselink & Jones (2024) marsh is also included by Miller et al. (2023). Sediment accretion rates are therefore available for a total of nine marshes, with OCAR data calculated for four of these (Table 22; Appendix 5, Figure A5-4).

Table 22: Overview of studies providing data for sediment accretion rates.

Study	Method	Sample numbers	Marsh numbers
Miller et al. (2023)	Coring / field sampling (2020)	7	4
Teasdale et al. (2011)	Coring / field sampling	4	4
Masselink & Jones (2024)	LiDAR calculations	-	1
Taylor et al. (2019)	Elevation change measured with sediment erosion bars	24	2
Total Scotland		**25**	**9**

6.4 Limitations of existing data

The data for surficial samples was used by Austin et al. (2021) to model surficial OC stocks for Scottish marshes and by Smeaton et al. (2022a) – with additional data from England and Wales – to model surficial OC stocks for Great Britain. It appears that neither models were validated either by additional ground data or a subset of the original data; nor was model accuracy reported. Comparing both data sets shows large differences between marsh stock values (examples in Appendix 6, Table A6-1), which the authors attribute to different modelling approaches (C. Smeaton, pers. comm.; see section 6.3).

The data for full marsh soil OC stock as reported by Smeaton et al. (2023) for 13 marshes is associated with very high standard deviations ranging from 22% to 80% of the reported C stock (Appendix 6, Table A6-2), which highlights how variable the data within each marsh are.

Available accretion rates also demonstrate a wide range from 0.6 mm yr^{-1} to 7.4 mm yr^{-1} (Appendix 6, Table 6-3).

Whilst a lot of work on Scottish carbon stocks has been completed in recent years large spatial data gaps still exist. Extrapolation of data from one marsh to another or a larger area is difficult due to high variability within and between marshes and any upscaled data need to be treated with caution and the potential error margins need to be considered. This is reiterated by Miller et al. (2023).

Furthermore, none of these estimates consider the fraction of labile carbon (subject to microbial decomposition) and recalcitrant carbon (mineralised). A higher proportion of labile carbon is present towards the surface, which then becomes recalcitrant carbon lower down in the soil profile. Assessing carbon stocks through carbon content of cores without considering the fraction of labile and recalcitrant carbon only estimates the carbon deposited but not necessarily the carbon stored for long time periods, because the labile carbon fraction may still undergo decomposition and removal (Gore et al., 2024). The existing estimates of carbon stocks may therefore be an overestimate.

Calculations for the potential carbon gains of future restoration sites and carbon credits to be sold at different stages post-MR are currently limited due to a general lack of data, but mainly lack of annual accretion rates from most marshes. Burden et al. (2019) have demonstrated that initial saltmarsh sediment accretion is much higher initially after MR and then gradually levels off until the restored marsh has caught up with the MTL. Sediment accretion rates for Scottish saltmarshes are only available for nine sites. They vary quite significantly between sites and marsh zone (see section 6.3) and none of these are from MR restoration sites.

To gather further sediment accretion rates for Scotland the following methods would be applicable:

- Radiocarbon dating as applied by Teasdale et al. (2011) and Miller et al. (2023)
- Using elevational differences between natural, mature marsh and neighbouring low-lying claimed fields as applied by Masselink & Jones (2024). This is only possible if historic records provide exact dates of when the land claim took place. This will be more accurate for more historic land claims – as opposed to more recent claims – due to LiDAR errors which can be up to 15 cm.
- Frequently measuring accretion at fixed points with sediment erosion bars or surface elevation tables (SETs). This approach has to date created the best UK-derived data set for post-MR accretion at Tollesbury, Essex (Garbutt, 2018), which ranges from 1995 to 2007. Initial measurements were monthly up until 1998, then bimonthly up until 2000 and biannual until 2007. This was completed for 20 stations within the one MR site to also capture spatial variation in accretion. As part of an on-going UKCEH project, nine SETs were set up in Scotland in 2023; six of which are on the Solway Firth and three at Dornoch Point (Harley & Garbutt, 2023). However, these show accretion on

natural marshes and will not provide accretion rates for saltmarshes restored through MR. Inclusion of SETs at existing and future MR sites would gather this required data.

7. Summary and recommendations

The full extent of Scottish saltmarsh was mapped by Haynes (2016) with the exception of some smaller marsh under 3 ha in size and is currently believed to be 5,840 ha. Scottish saltmarshes have less pioneer marsh and lack certain plant species compared to English and Welsh mashes. Almost 50% of the saltmarsh area is within nine marshes over 100 ha in size; whilst the majority of marshes are generally small (< 25 ha). Larger marshes have a higher rate of protection from conservation designations than smaller marshes.

Haynes (2016) also include detailed information on the condition, pressures and threats of saltmarshes in Scotland. Condition failure is unrelated to site designation and largely also unrelated to marsh size.

To date four saltmarsh restoration projects have been completed through MR in Scotland. The first to be completed was Montrose Bay in 1997, followed by Nigg Bay in 2003, Kennet Pans in 2007 and Skinflats in 2018. Altogether they have created around 43.5 ha of intertidal habitat. Other forms of restoration applied in Scotland include planting, use of wave breaks to protect planted seedlings, and grazing management.

Further saltmarsh restoration potential through MR has been assessed by four published studies involving modelling, desk-based studies and walkover surveys for 114 sites across approx. 2,615.9 ha of intertidal habitat. However, it is unrealistic to assume all of these sites will undergo restoration in the long-term and the actual extent of created saltmarsh may be a smaller fraction of the predicted intertidal habitat.

Carbon stocks for Scottish saltmarsh have been modelled for both surficial (10 cm) soils and full profile depths. The available data for surficial soils is comprised of 550 samples from 48 marshes, whereas the data for full profile depths is limited to 313 cores from 14 marshes. Calculations for potential MR projects in relation to carbon gained after certain time intervals post breach is particularly challenging due to the lack of sediment accretion rates, which is only available from nine marshes and shows high variability within marshes.

Surficial carbon stocks are estimated to be around 0.368 Mt C +/- 0.102 (Austin et al., 2021) and full carbon stock estimates range from 0.935 Mt C +/- 0.262 (Smeaton et al., 2023) to 1.15 Mt C +/- 0.21 (Miller et al., 2023). A full carbon estimate for the identified sites with restoration potential cannot be calculated due to lack of data. The available data suggest a minimum of 0.145 Mt C, which is mainly based on surficial stocks and therefore likely to be an underestimate.

In order to gain a full understanding of the saltmarsh restoration potential across Scotland and the associated carbon gain potential, further work is required in at least two areas:

- Restoration potential has only been identified in selected areas with gaps evident for the west and northeast of Scotland. Modelling exercises such as completed by Griffin (2023) for the Solway Firth need to be repeated for areas currently not considered.
- In order to robustly calculate potential carbon credits for MR restoration sites, sediment accretion rates are required from a network of marshes across Scotland including MR sites as outlined in section 6.4.

8. References

ABPmer (2014a). *Inch of Ferryton Habitat Creation Options Appraisal Study: Stage 1 Final Report*. Report to SNH Scotland, pp 402.

ABPmer (2014b). *Inch of Ferryton Habitat Creation Options Appraisal Study: Stage 2 Report*. Report to RSPB Scotland, pp 44.

ABPmer (2019). *Inch of Ferryton managed realignment review (Advice / recommendations on a selection of queries)*. Report to RSPB Scotland, 26 pp.

ABPmer (2024). *OMReg Data Base*. Available from: https://www.omreg.net/

Adam, P. (1993). *Saltmarsh ecology*. Cambridge University Press.

ADMIRALTY (2024). *EasyTide*. Available from: https://easytide.admiralty.co.uk/

Angus, S., Hansom, J., Rennie, A. (2011). Habitat change on Scotland's coasts – *The Changing Nature of Scotland*. Eds. S.J. Marrs, S. Foster, C. Hendrie, E.C. Mackey, D.B.A. Thompson.TSO Scotland, Edinburgh, pp 183-198. Available from: https://www.researchgate.net/publication/235635843_Habitat_change_on_Scotland's_coasts

Austin , W , Smeaton , C , Riegel , S , Ruranska , P & Miller , L (2021). Blue carbon stock in Scottish saltmarsh soils . *Scottish Marine and Freshwater Science* , no. 13 , vol. 12 , Marine Scotland . https://doi.org/10.7489/12372-1

Austin, W., Smeaton, C., Houston, A., & Balke, T. (2022). *Scottish saltmarsh, sea-level rise, and the potential for managed realignment to deliver blue carbon gains*. University of St Andrews, ClimateXChange Report, pp 77. Available from: https://era.ed.ac.uk/handle/1842/39119

Bakker, J. P. (1985). The impact of grazing on plant communities, plant populations and soil conditions on salt marshes. *Vegetatio*, 62, 391-398. Available from: https://link.springer.com/article/10.1007/BF00044766

Balke, T., Vovides, A., Schwarz, C., Chmura, G. L., Ladd, C., & Basyuni, M. (2021). Monitoring tidal hydrology in coastal wetlands with the "Mini Buoy": applications for mangrove restoration. *Hydrology and Earth System Sciences*, 25(3), 1229-1244. https://doi.org/10.5194/hess-25-1229-2021

Beaumont, N. J., Jones, L., Garbutt, A., Hansom, J. D., & Toberman, M. (2014). The value of carbon sequestration and storage in coastal habitats. *Estuarine, Coastal and Shelf Science*, 137, 32-40. https://doi.org/10.1016/j.ecss.2013.11.022

Burd, F. (1989). *Saltmarsh survey of Great Britain: an inventory of British Saltmarshes.* Report No. 17, pp 180. Available from: https://www.vliz.be/imisdocs/publications/ocrd/259215.pdf

Burden, A., Garbutt, A., & Evans, C. D. (2019). Effect of restoration on saltmarsh carbon accumulation in Eastern England. *Biology letters*, 15(1), 20180773. https://doi.org/10.1098/rsbl.2018.0773

Chambers, C., Jones, K.L., Malcolm, F., Boyle, G., Sanderson, W.G., Garbutt, A., Jones, L., Unsworth, R.K.F. and Lilley, R.J., (2022). *Development of a marine and coastal enhancement project assessment framework for Scottish inshore waters*. NatureScot Research Report 1293. Available from: https://www.nature.scot/doc/research-report-no-1293-development-marine-and-coastal-enhancement-project-assessment-framework

Chisholm, K., Kindleysides, D., Cowie, N., (2004). *Identifying, developing and implementing coastal realignment projects in Scotland; Lessons learned from Nigg Bay, Cromarty Firth. RSPB, Inverness*, pp 29.

Cunningham, C. and Hunt, C. (2023). *Scottish Blue Carbon - a literature review of the current evidence for Scotland's blue carbon habitats*. NatureScot Research Report 1326. Available from: NatureScot Research Report 1326 - Scottish Blue Carbon - a literature review of the current evidence for Scotland's blue carbon habitats | NatureScot

Dempster, N. (2023). *LIFE 100% for Nature annual summary monitoring report - Mersehead and Kirkconnell Merse (Atlantic salt meadow)*. RSPB report.

EDINA (2024) *Lidar*. Available from: https://digimap.edina.ac.uk/lidar

Elliot, S. (no date). *Case study 48 . Nigg Bay Coastal Realignment Project*. Report, pp 6. Available from: https://www.therrc.co.uk/sites/default/files/projects/48_niggbay.pdf

Elliot, S. (2015). *Coastal Realignment at RSPB Nigg Bay Nature Reserve. RSPB*, September 2015, pp 29. Available from: Nigg Bay Coastal Realignment | PANORAMA

Garbutt. A. (2018). *Bed level change within the Tollesbury managed realignment site, Blackwater estuary, Essex, UK between 1995 and 2007*. NERC Environmental Information Data Centre. https://doi.org/10.5285/f9513ece-a913-4774-8808-273dcf7ed0be

GDG (2023). *Inch of Ferryton Managed Realignment*. Report to RSPB Scotland, pp 54.

Gore, C., Gehrels, W. R., Smeaton, C., Andrews, L., McMahon, L., Hibbert, F., Austin, W. E. N., Nolte, S., Garrett, E. (2024). Saltmarsh blue carbon accumulation rates and their relationship with sea-level rise on a multi-decadal timescale in northern England. *Estuarine, Coastal and Shelf Science*, 108665. https://doi.org/10.1016/j.ecss.2024.108665

Griffin, L. R. (2023). *The potential for saltmarsh (merse) and pseudo-saltmarsh reinstatement or creation through managed realignment on the Solway Firth, Dumfries & Galloway*. ECO-LG Ltd report for the Solway Firth Partnership.

Hansom, J., Maxwell, F., Naylor, L. & Piedra, M. (2017). *Impacts of sea-level rise and storm surges due to climate change in the Firth of Clyde*. Scottish Natural Heritage Commissioned Report No. 891. Available from: https://www.nature.scot/doc/naturescot-commissioned-report-891-impacts-sea-level-rise-and-storm-surges-due-climate-change-firth

Harley, J., Garbutt, A. (2023). *Saltmarsh Accretion Monitoring Network Installation Report*. UKCEH report to WWF.

Haynes, T.A. (2016). *Scottish saltmarsh survey national report*. Scottish Natural Heritage. Commissioned Report No 786, pp 196. Available from: https://www.nature.scot/doc/naturescot-commissioned-report-786-scottish-saltmarsh-survey-national-report

Innerforth Landscape Initiative (no date). *End of Project Report - A3.8 Skinflats Managed Realignment*. pp4. Available from: https://inner-forth-futures.s3.eu-west-2.amazonaws.com/files/A3_8_End_of_project_report_for_website.pdf

JNCC (2004). *Common Standards Monitoring Guidance for Saltmarsh Habitats*. Joint Nature Conservation Committee. Available from: https://data.jncc.gov.uk/data/7607ac0b-f3d9-4660-9dda-0e538334ed86/CSM-SaltmarshHabitats-2004.pdf

JNCC (2019). *Site boundaries of wetlands of international importance under the Ramsar convention 2019*. Joint Nature Conservation Committee. Available from: https://hub.jncc.gov.uk/assets/f0e372e3-1580-4bf4-b31a-2b18ab9ca51d

JNCC (2022). *Boundaries of Special Protection Areas (SPAs) of Great Britain (including offshore areas)*. Joint Nature Conservation Committee. Available from: https://hub.jncc.gov.uk/assets/20dbc9b4-ceac-4bf2-8763-4ae387fa88c4

Kaya Consulting (2023). *Inch of Ferryton Managed Realignment Project, Clackmannanshire – Flood Risk Assessment*. Report to RSPB Scotland, pp 104.

Ladd, C.J.T.; Duggan-Edwards, M.F.; Bouma, T.J.; Pagès, J.F.; Skov, M.W. (2019). *Change in saltmarsh extent for six regions across Great Britain (1846-2016)*. NERC Environmental Information Data Centre. https://doi.org/10.5285/03b62fd0-41e2-4355-9a06-1697117f0717

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. https://doi.org/10.1016/j.ecss.2017.09.007

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(7), 1597-1609. https://doi.org/10.1111/1365-2664.13405

Masselink, G., & Jones, R. B. (2024). Long-term accretion rates in UK salt marshes derived from elevation difference between natural and reclaimed marshes. *Marine Geology*, 467, 107202. https://doi.org/10.1016/j.margeo.2023.107202

Maynard, C., McManus, J., Crawford, R. M., & Paterson, D. (2011). A comparison of short-term sediment deposition between natural and transplanted saltmarsh after saltmarsh restoration in the Eden Estuary (Scotland). *Plant Ecology & Diversity*, 4(1), 103-113. https://doi.org/10.1080/17550874.2011.560198

Maynard, C. (2017). Saltmarshes on the fringe: restoring the degraded shoreline of the Eden Estuary, Scotland. PhD Thesis, pp 169. Available from: https://research-repository.st-andrews.ac.uk/handle/10023/6559?show=full

Maynard, C. (2020). Saltmarsh Creation for Natural Flood Defence in the Tay & Eden Estuaries & the Dornoch Firth. Final Report, pp 28. Available from: https://royaldornoch.com/wp-content/uploads/2022/01/Green-Shores-final-report-280720.pdf

Miller, L.C., Smeaton C., Yang, H., Austin, W. E. N. (2022). Physical and geochemical properties of Scottish saltmarsh soils. Marine Scotland Data. https://doi.org/10.7489/12422-1

Miller, L. C., Smeaton, C., Yang, H., & Austin, W. E. (2023). Carbon accumulation and storage across contrasting saltmarshes of Scotland. *Estuarine, Coastal and Shelf Science*, 282, 108223. https://doi.org/10.1016/j.ecss.2023.108223

NatureScot (2023). *Protected Nature Sites*. NatureScot. Available from: https://informatics.sepa.org.uk/ProtectedNatureSites/

Phillips, G., McGruer, K., Crook, D., Doria, L., Herbon, C., Khan, J., Mackie, T., Singleton, G., Young, C. (2018). *Condition of intertidal saltmarsh communities in coastal waters determined using Water Framework Directive methods*. Marine Online Assessment Tool. Available from: https://moat.cefas.co.uk/biodiversity-food-webs-and-marine-protected-areas/benthic-habitats/intertidal-saltmarsh/

Proctor, J. (1987). Saltmarsh vegetation in the Forth estuary, Scotland. *Proceedings of the Royal Society of Edinburgh Section B Biological Sciences*, 93(3-4):355-361. https://doi.org/10.1017/S0269727000006801

RSPB (2012). *Inner Forth Futurescape - Feasibility Study*. Final Report, pp57.

Ruranska, P.; Miller, L.C.; Hindle, C.; Ladd, C.J.T.; Smeaton, C.; Skov, M.W.; Austin, W.E.N. (2020). *Dry bulk density, loss on ignition and organic carbon content of surficial soils from Scottish salt marshes, 2018-2019*. NERC Environmental Information Data Centre. https://doi.org/10.5285/81a1301f-e5e2-44f9-afe0-0ea5bb08010f

Scottish Government (2011). *Scotland's Marine Atlas: Information for The National Marine Plan*. Available from: https://www.gov.scot/publications/scotlands-marine-atlas-information-national-marine-plan/pages/12/

Scottish Government (2019). *LiDAR for Scotland Phase 3 – DTM*. Available from: https://www.spatialdata.gov.scot/geonetwork/srv/eng/catalog.search#/metadata/f1a18c6d-3f1b-46bb-a5eb-58e5f504c7cb

Scottish Government (2024). *Scottish Remote Sensing Portal*. Available from: https://remotesensingdata.gov.scot/

Smeaton, C., Miller, L.C., Ruranska, P., Austin, W.E.N. (2021). *Organic carbon density of surficial soils across Scottish saltmarshes*. Marine Scotland Data. https://doi.org/10.7489/12389-1

Smeaton, C., Burden, A., Ruranska, P., Ladd, C. J., Garbutt, A., Jones, L., McMahon, L., Miller, L. C., Skov, M. W., Austin, W. E. (2022a). Using citizen science to estimate surficial soil Blue Carbon stocks in Great British saltmarshes. *Frontiers in Marine Science*, 9, 959459. https://doi.org/10.3389/fmars.2022.959459

Smeaton, C.; Ladd, C.J.T.; Havelock, G.M.; Miller, L.C.; Garrett, E.; Hiles, W.; McMahon, L.; Mills, R.T.E.; Radbourne, A.; Rees-Hughes, L.; Riegel, S.; Barlow, N.L.M.; Skov, M.W. ; Gehrels, R.; Austin, W.E.N. (2022b). *Physical and geochemical properties of saltmarsh soils from narrow diameter gouge cores in UK saltmarshes collected between 2018 and 2021*. NERC EDS Environmental Information Data Centre. https://doi.org/10.5285/d301c5f5-77f5-41ba-934e-a80e1293d4cd

Smeaton, C., Ladd, C. J., Miller, L. C., McMahon, L., Garrett, E., Barlow, N. L., Gehrels, W. R., Skov, M. W., Austin, W. E. (2023). Organic carbon stocks of Great British saltmarshes. *Frontiers in Marine Science*, 10, 1229486. https://doi.org/10.3389/fmars.2023.1229486

SNH (2023a). *Special Areas of Conservation (Scotland)*. Scottish National Heritage. Available from:
https://www.data.gov.uk/dataset/2559b8bc-ddd6-4cb1-8a98-9422e1b1865a/special-areas-of-conservation-scotland

SNH (2023b). *Sites of Special Scientific Interest*. Scottish National Heritage. Available from:
https://spatialdata.gov.scot/geonetwork/srv/api/records/ECA527A8-DC9A-49F3-8911-F4CF9C3019A5

Stamp, T., West, E., Robbins, T., Plenty, S., & Sheehan, E. (2022). Large-scale historic habitat loss in estuaries and its implications for commercial and recreational fin fisheries*. ICES Journal of Marine Science*, 79(7), 1981-1991.
https://doi.org/10.1093/icesjms/fsac141

Taylor, B. (2019). *Saltmarsh restoration and blue carbon dynamics in a Scottish estuary*. PhD thesis, pp 214. Available from:
https://research-repository.st-andrews.ac.uk/handle/10023/20891

Teasdale, P. A., Collins, P. E., Firth, C. R., & Cundy, A. B. (2011). Recent estuarine sedimentation rates from shallow inter-tidal environments in western Scotland: implications for future sea-level trends and coastal wetland development. *Quaternary Science Reviews*, 30(1-2), 109-129.
https://doi.org/10.1016/j.quascirev.2010.08.002

Tessier, M., Vivier, J. P., Ouin, A., Gloaguen, J. C., & Lefeuvre, J. C. (2003). Vegetation dynamics and plant species interactions under grazed and ungrazed conditions in a western European salt marsh. *Acta Oecologica*, 24(2), 103-111.
https://doi.org/10.1016/S1146-609X(03)00049-3

Tinch, R., Ledoux, L. (2006). *Economics of Managed Realignment in the UK*.
Final Report to the Coastal Futures Project by Environmental Futures Limited. Available from:

https://www.researchgate.net/publication/228541694_Economics_of_Managed_Realignment_in_the_UK_Final_Report_to_the_Coastal_Futures_Project

Transport Scotland (2017) Scottish Trunk Road Infrastructure Project Evaluation - 3YA Evaluation Report for A876(T) Clackmannanshire Bridge, pp 73. Available from: https://www.transport.gov.scot/publication/scottish-trunk-road-infrastructure-project-evaluation-3ya-evaluation-report-for-a876-t-clackmannanshire-bridge/

Wade, K. S. (2018). The biodiversity, ecosystem functioning and value of restored salt marshes in the Eden Estuary, Scotland. PhD thesis, pp 292. Available from: https://research-repository.st-andrews.ac.uk/handle/10023/17541

WFD UKTAG. (2014). *UKTAG Transitional and Coastal Water Assessment Method: Angiosperms, Saltmarsh Tool*. Water Framework Directive—United Kingdom Advisory Group, Stirling.

9. Appendix 1 – Saltmarsh distribution maps

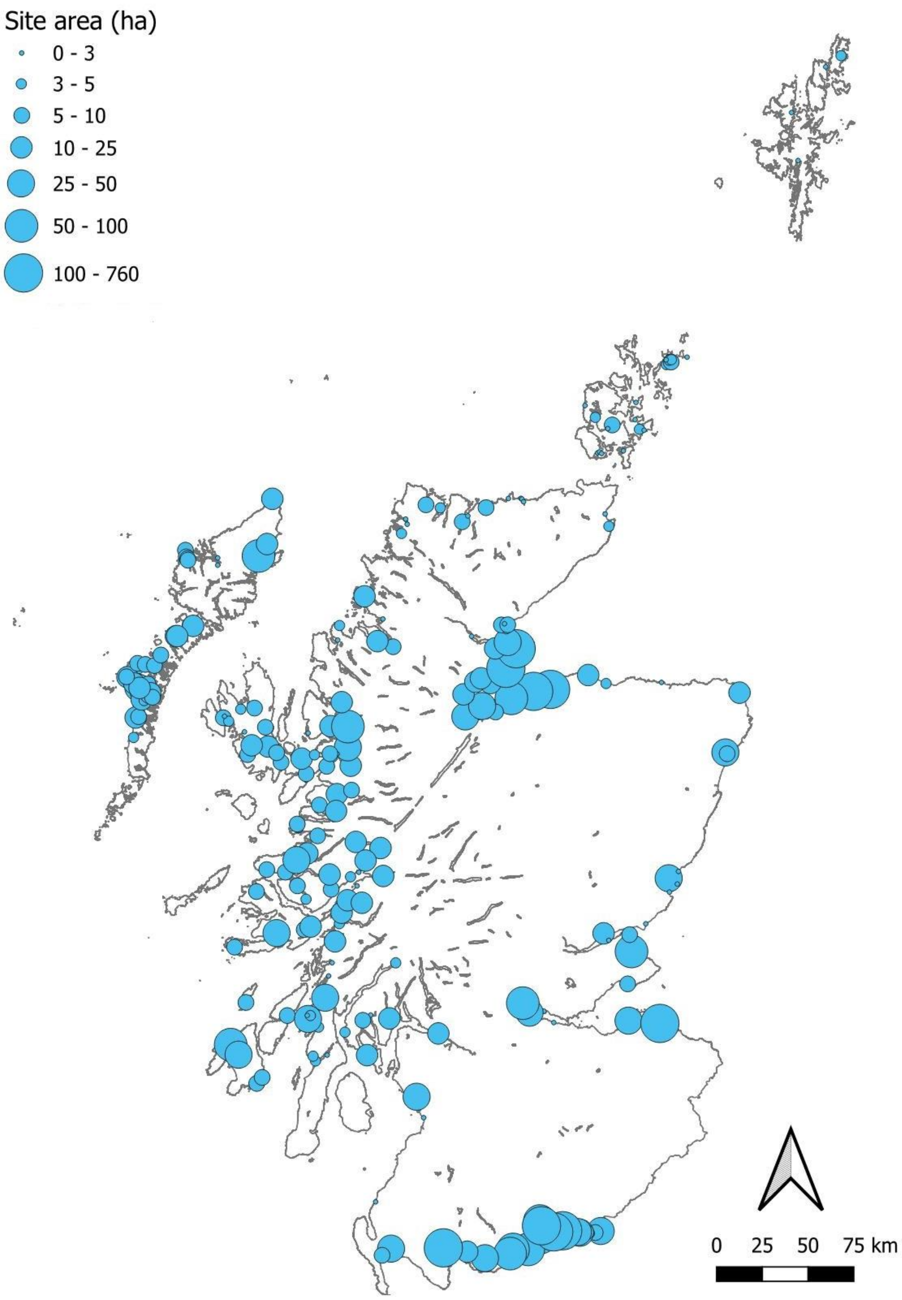

Figure A1-1: Saltmarsh site distribution by area size (ha) with a site defined as a distinctly named geographical region as shown in Figures 1 and 2; after Haynes (2016) GIS layer.

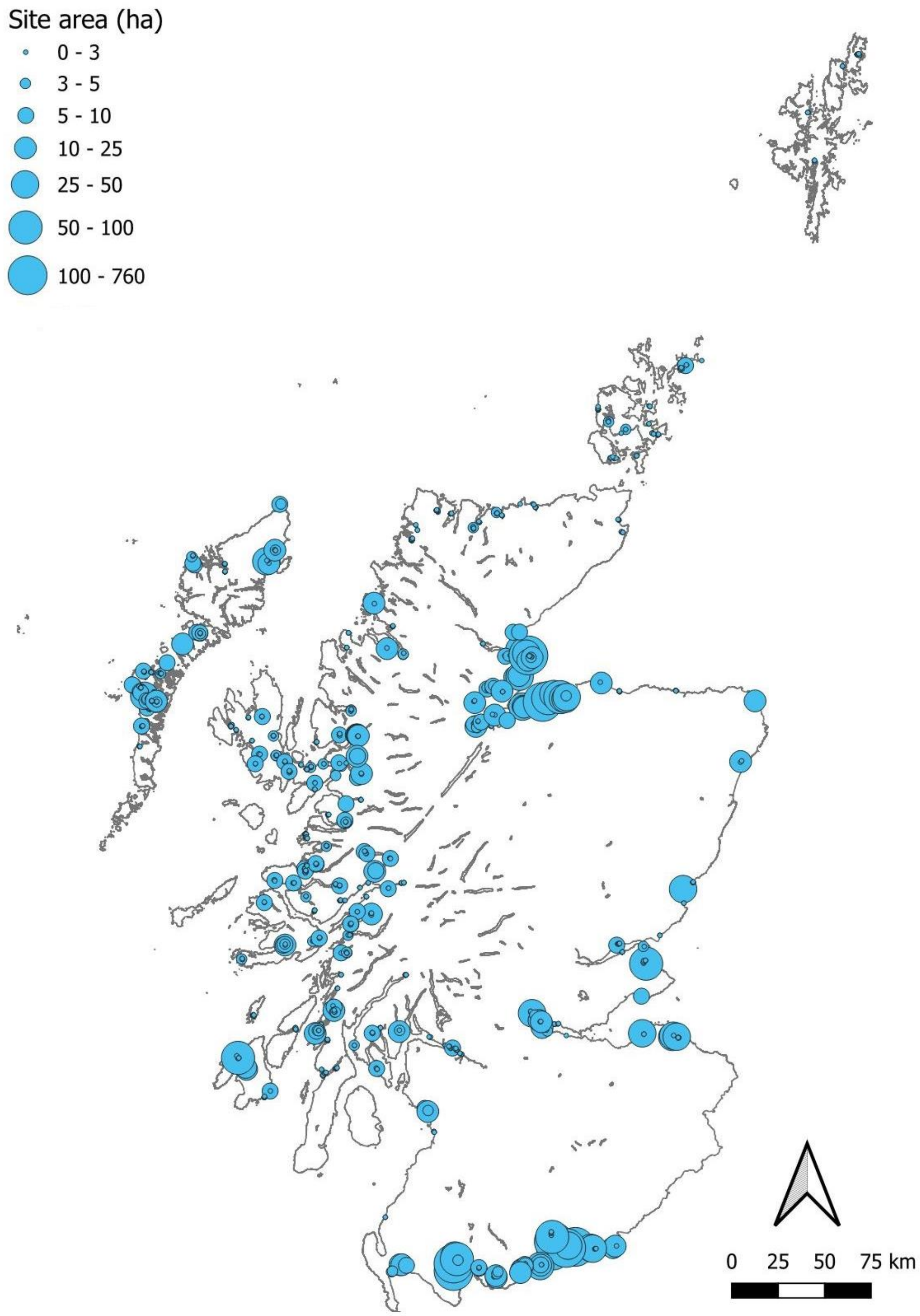

Figure A1-2: Saltmarsh site distribution by area size (ha) with a site defined as a connected and uninterrupted stretch of land as shown in Figure 3; after Haynes (2016) GIS layer.

Figure A1-3: Littoral saltmarsh distribution by area size (ha); after Haynes (2016) GIS layer.

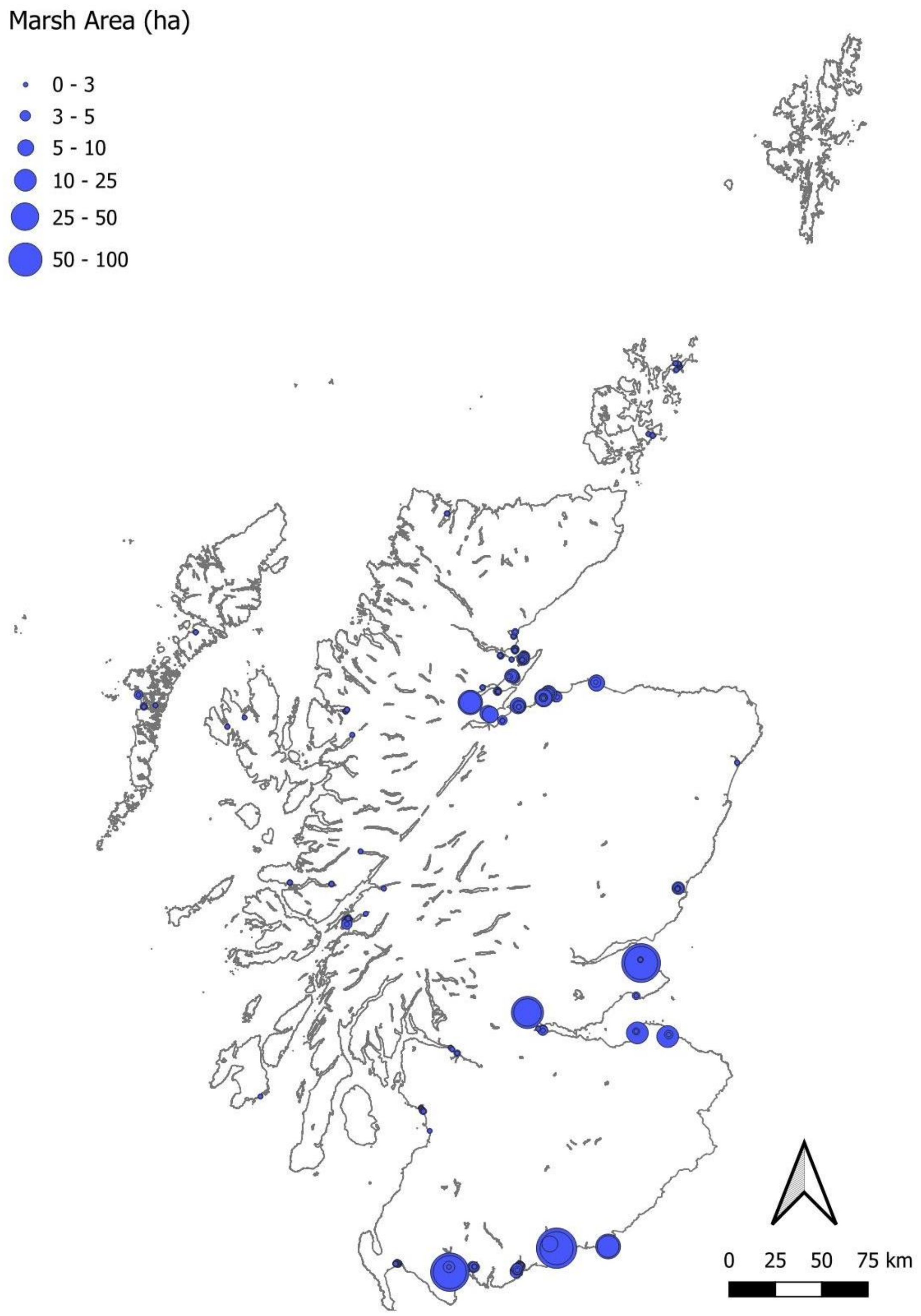

Figure A1-4: Pioneer saltmarsh distribution by area size (ha); after Haynes (2016) GIS layer.

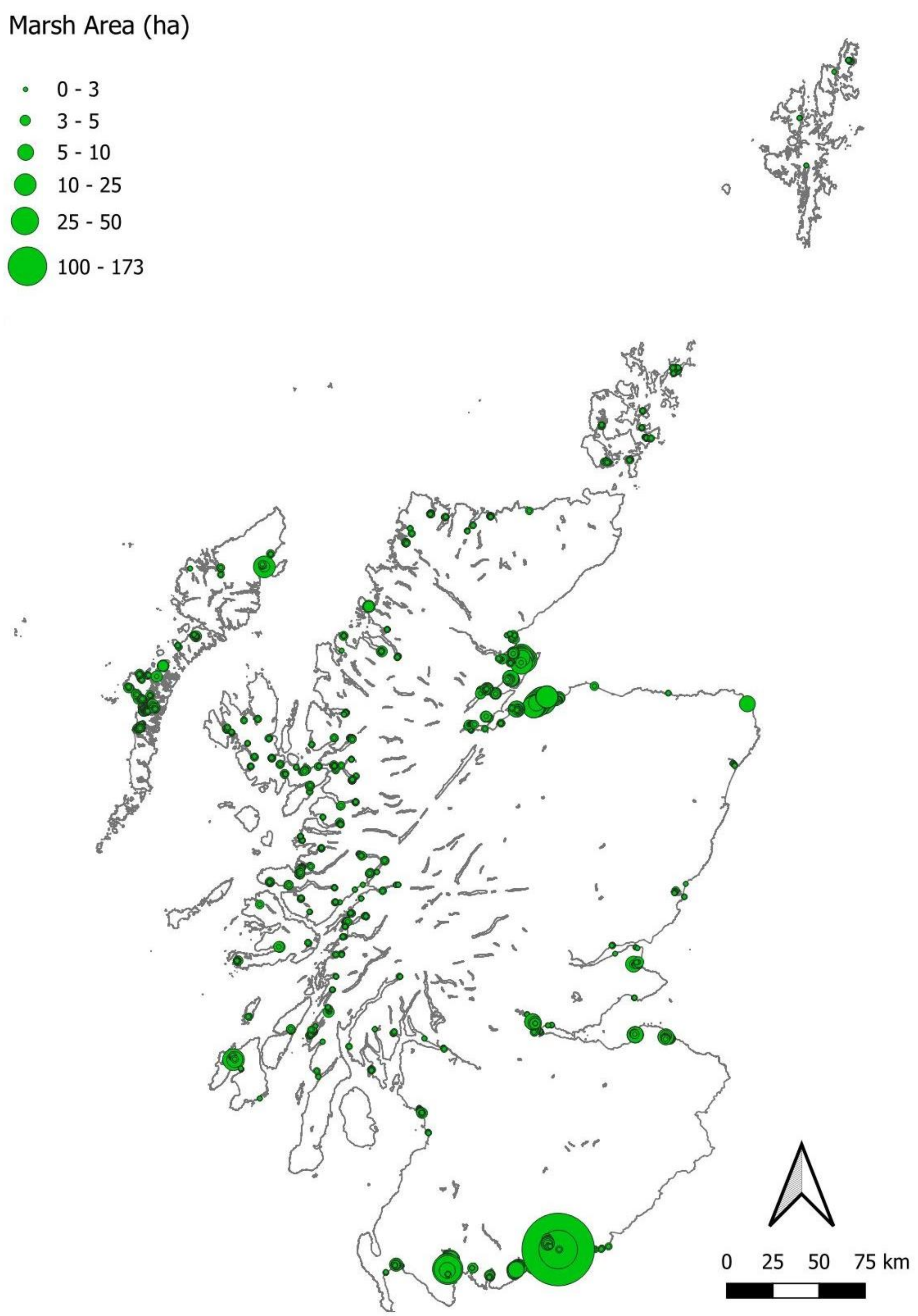

Figure A1-5: Lower and middle saltmarsh distribution by area size (ha); after Haynes (2016) GIS layer.

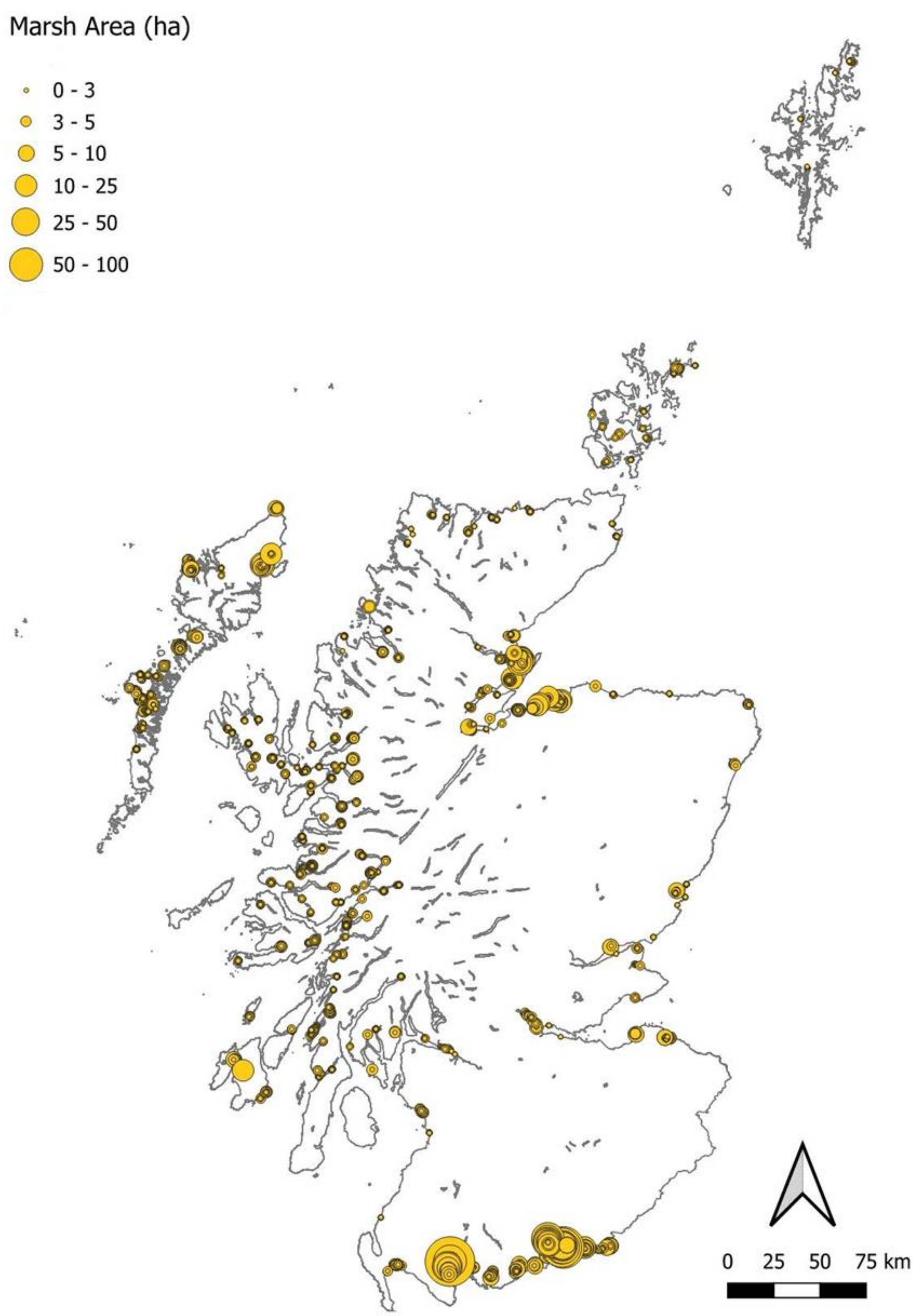

Figure A1-6: Upper saltmarsh distribution by area size (ha); after Haynes (2016) GIS layer.

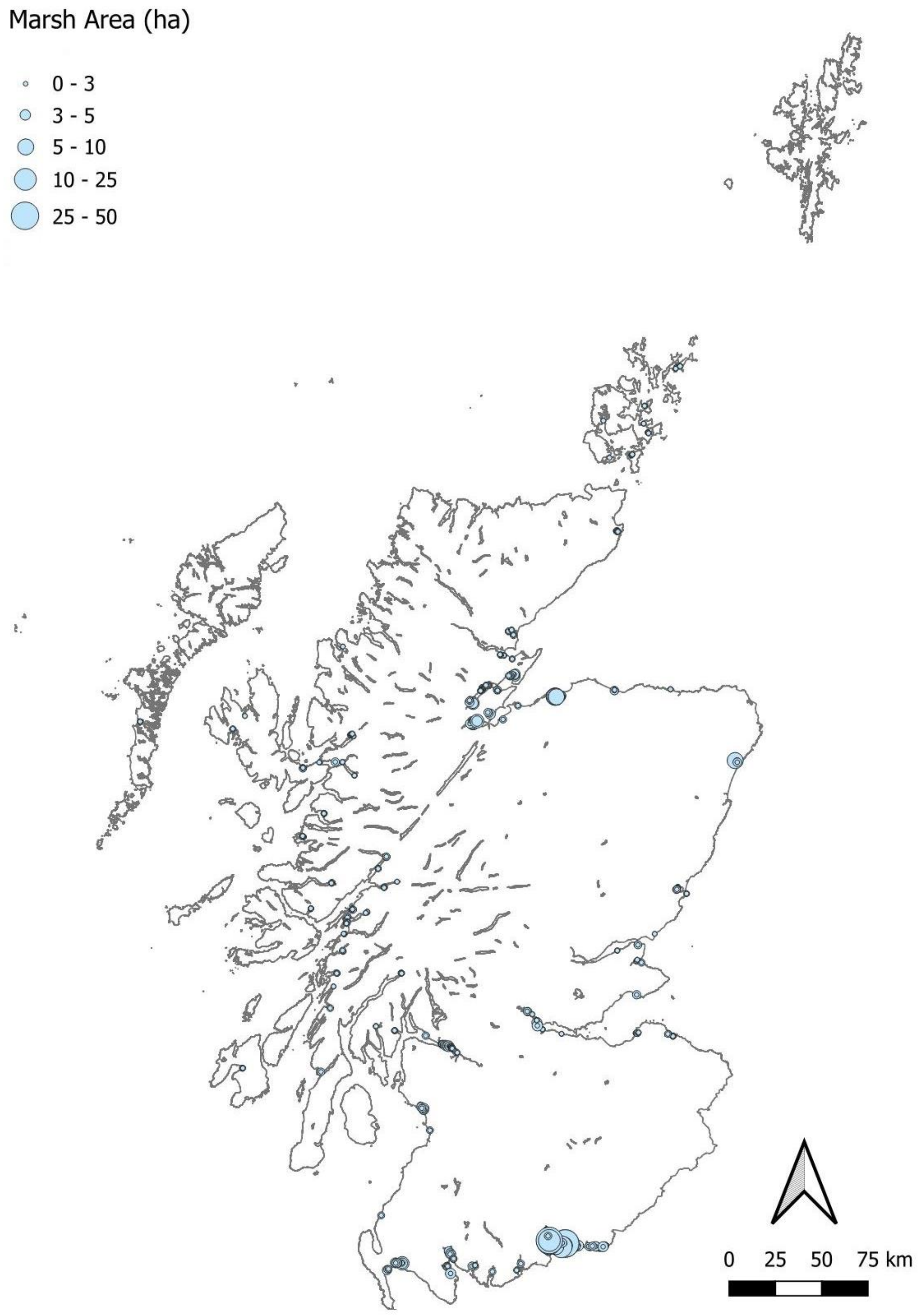

Figure A1-7: Strandline and disturbance saltmarsh distribution by area size (ha); after Haynes (2016) GIS layer.

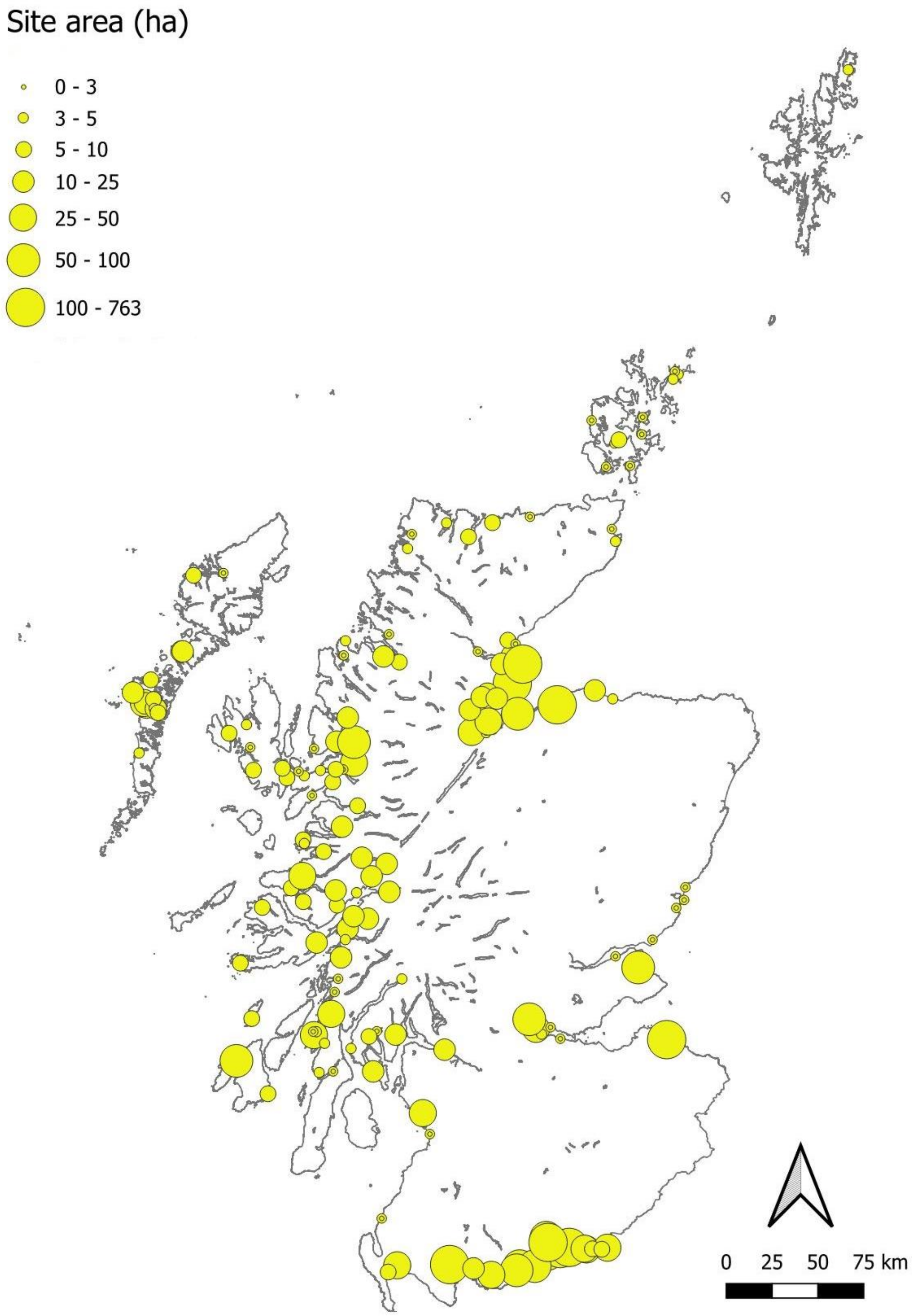

Figure A1-8: Sites - defined as distinctly named geographical regions – which failed the site condition monitoring (SCM) by area size (ha). Sites after Haynes (2016) GIS file, SCM assessment after Haynes (2016) report, Table 3-6.

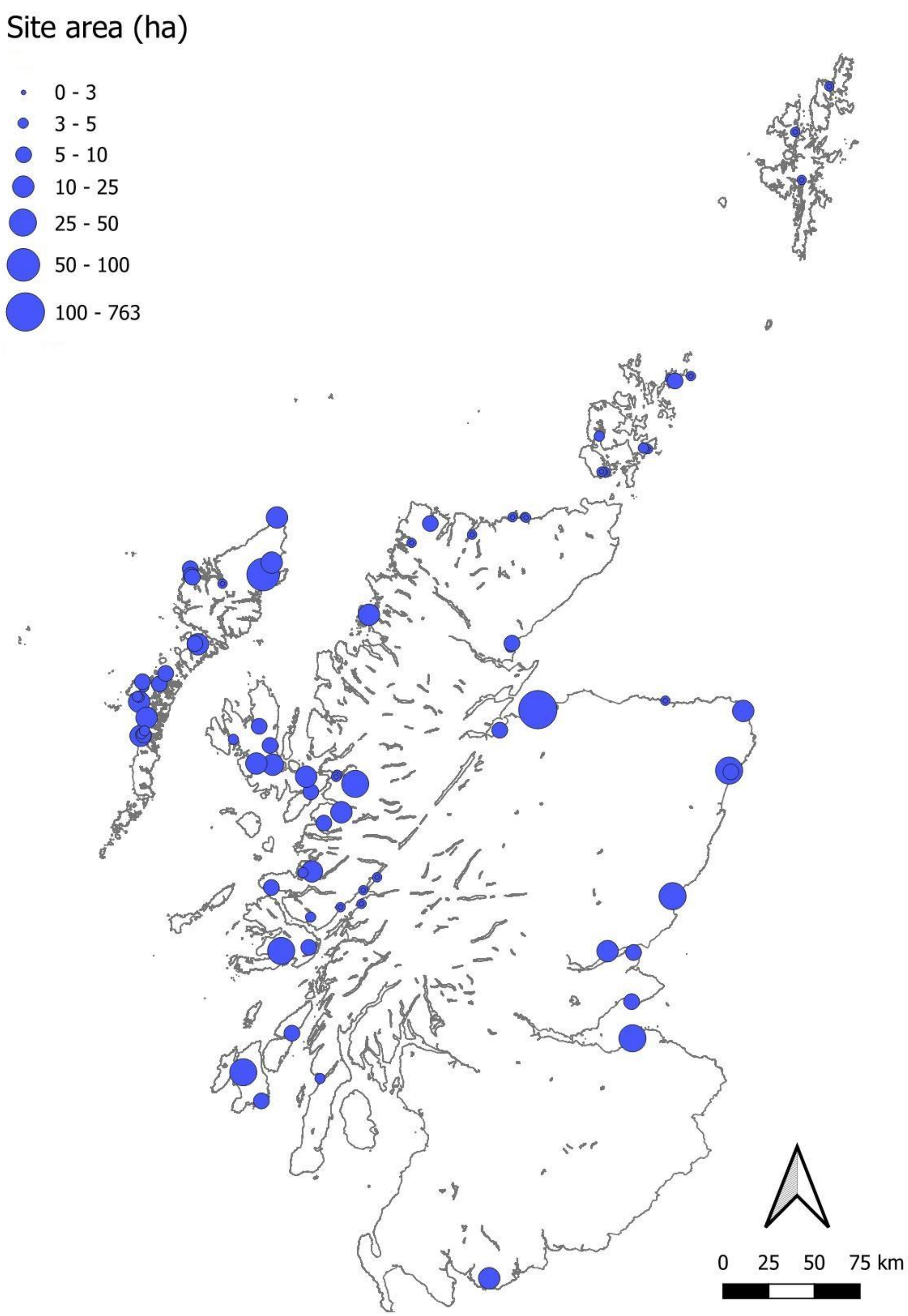

Figure A1-9: Sites - defined as distinctly named geographical regions – which passed the site condition monitoring (SCM) by area size (ha). Sites after Haynes (2016) GIS file, SCM assessment after Haynes (2016) report, Table 3-6.

10. Appendix 2 – Map of saltmarsh restoration sites

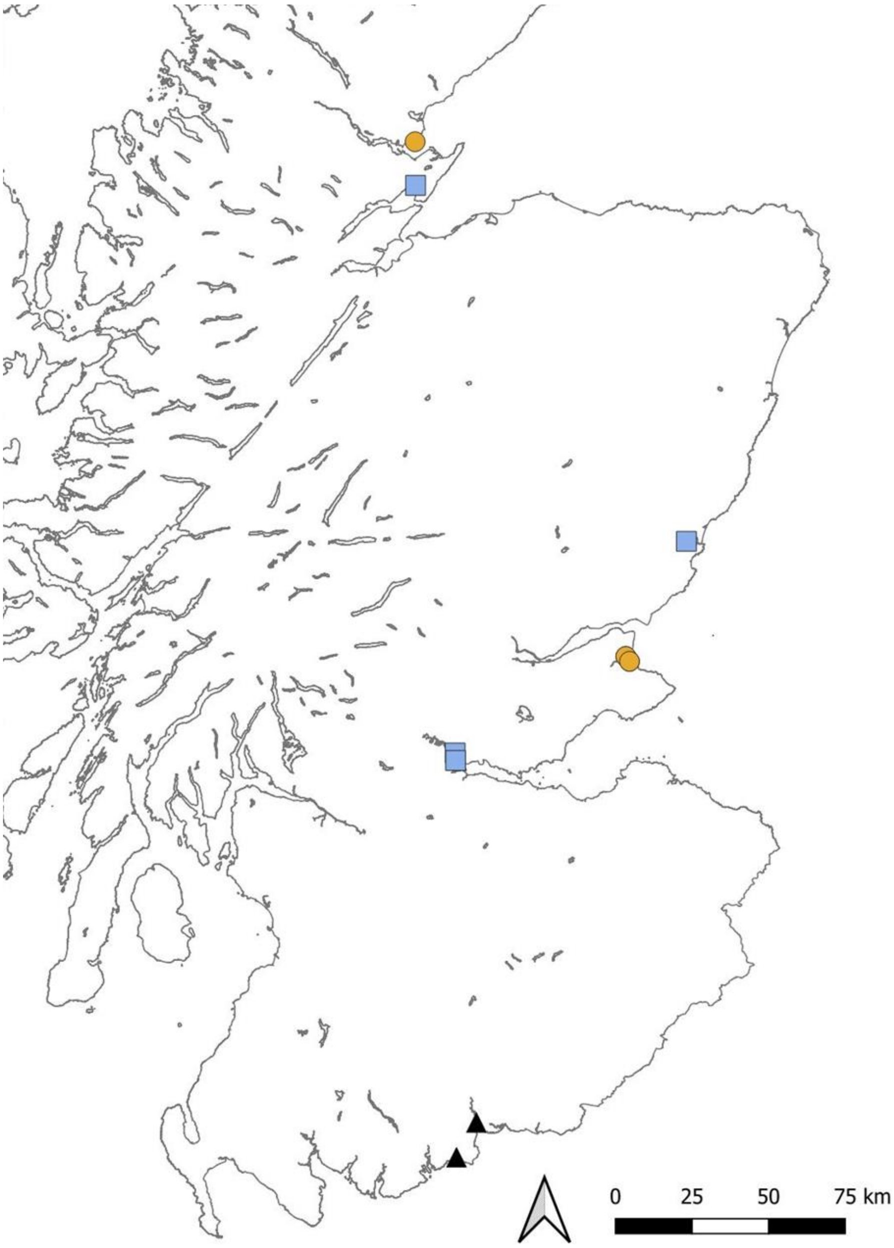

Figure A2-1. Locations of restoration sites; blue squares = managed realignment (MR), orange circles = transplanting and wave protection, black triangles = grazing management.

11. Appendix 3 – Maps with identified sites for potential saltmarsh restoration

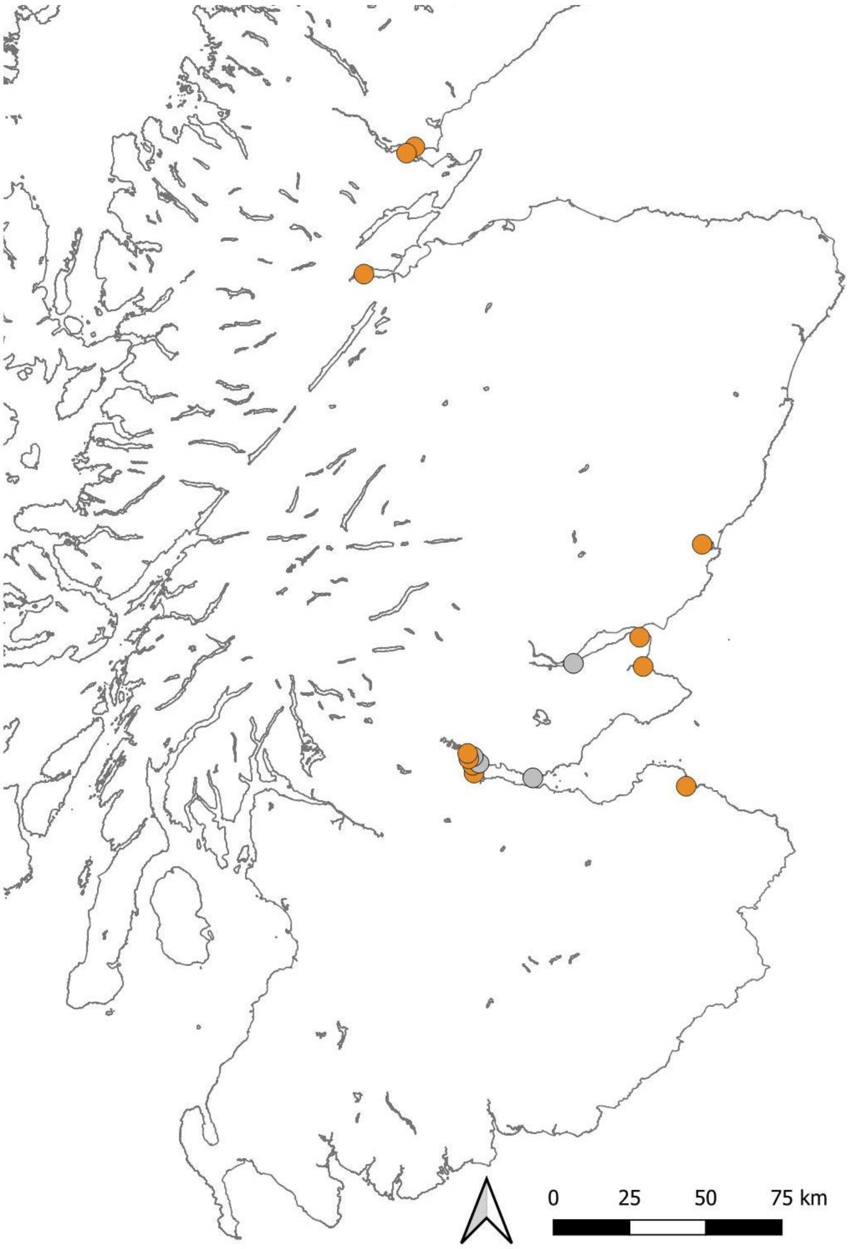

Figure A3-1: Map with sites for potential saltmarsh restoration identified by Austin et al. (2022). Sites with grey circles were considered less suitable due to infrastructure present and lack of established saltmarsh nearby.

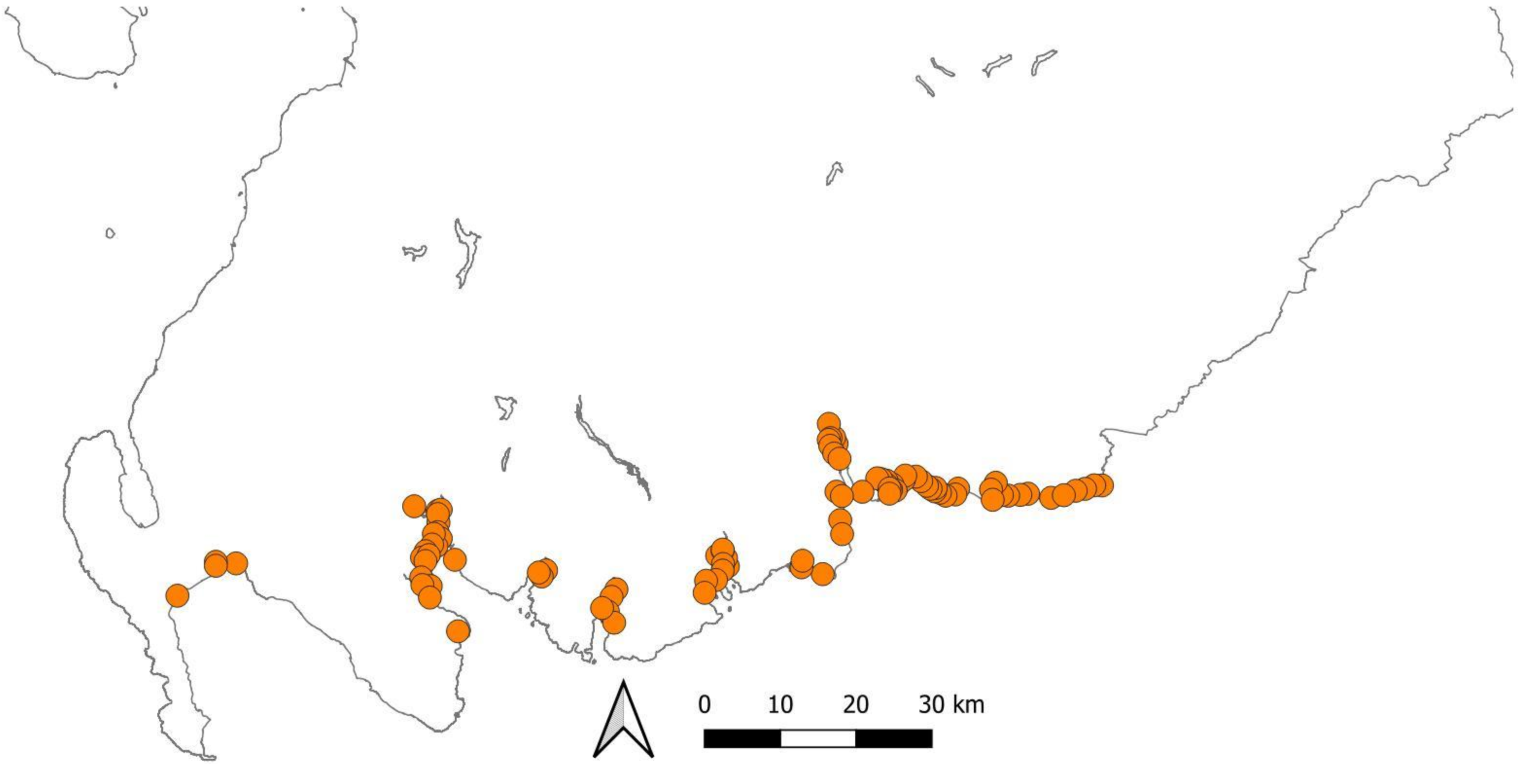

Figure A3-2: Map with sites for potential saltmarsh restoration on the Solway Firth identified by Griffin et al. (2023).

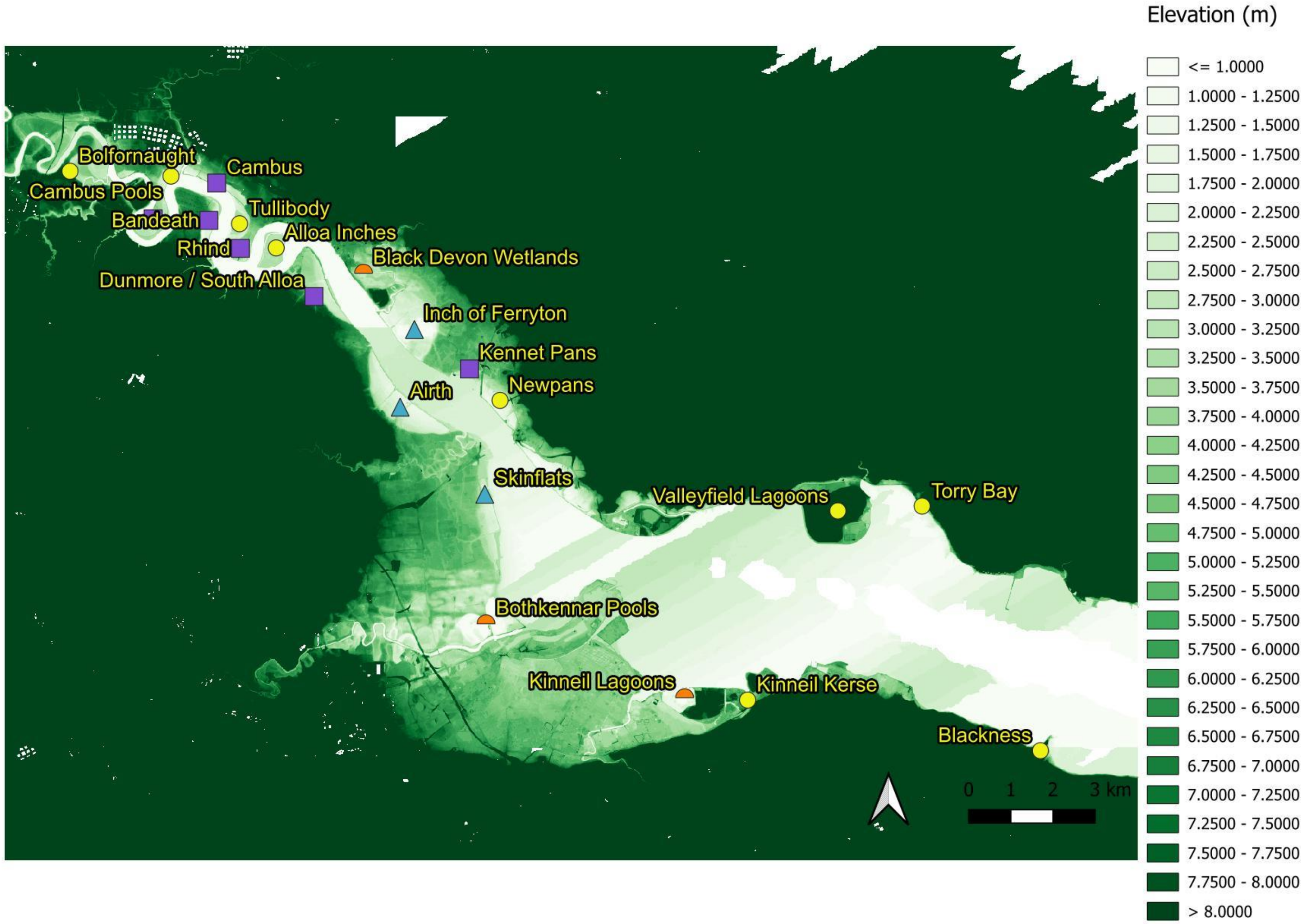

Figure A3-3: All 21 sites considered in the Inner Forth Futurescapes Feasibility Study (RSPB, 2012). Yellow circles = sites not considered further, turquoise triangles = sites over 100 ha and 'environmentally advantageously' for MR, purple square = sites between 7 and 50 ha and 'environmentally advantageous' for MR, orange half circle = sites with habitat creation opportunities but also with potential for the development of visitor facilities.

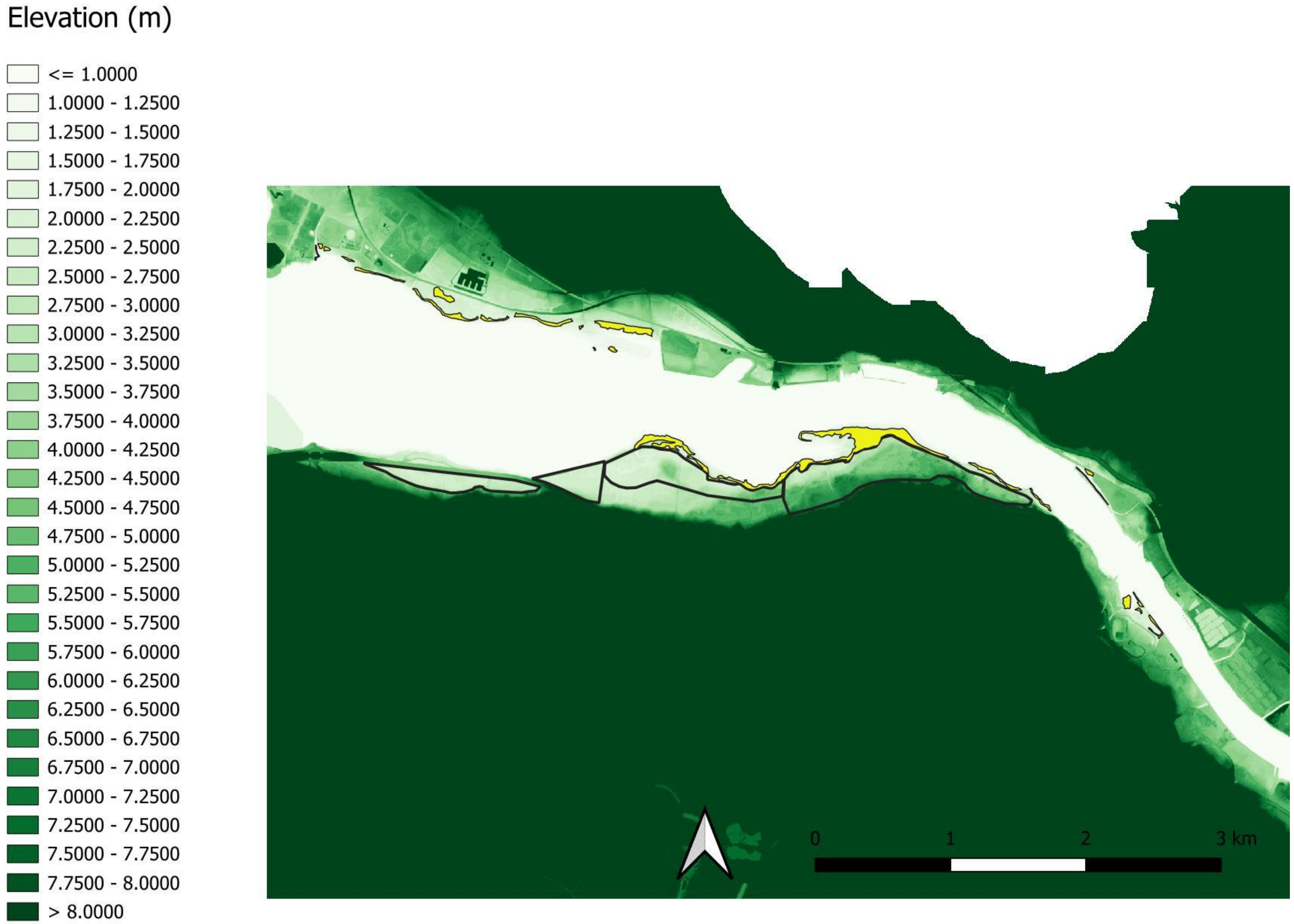

Figure A3-4: Potential Inner Clyde South MR sites (black outline) after Hansom et al. (2017) with existing saltmarsh (yellow polygons) after Haynes (2016) GIS file.

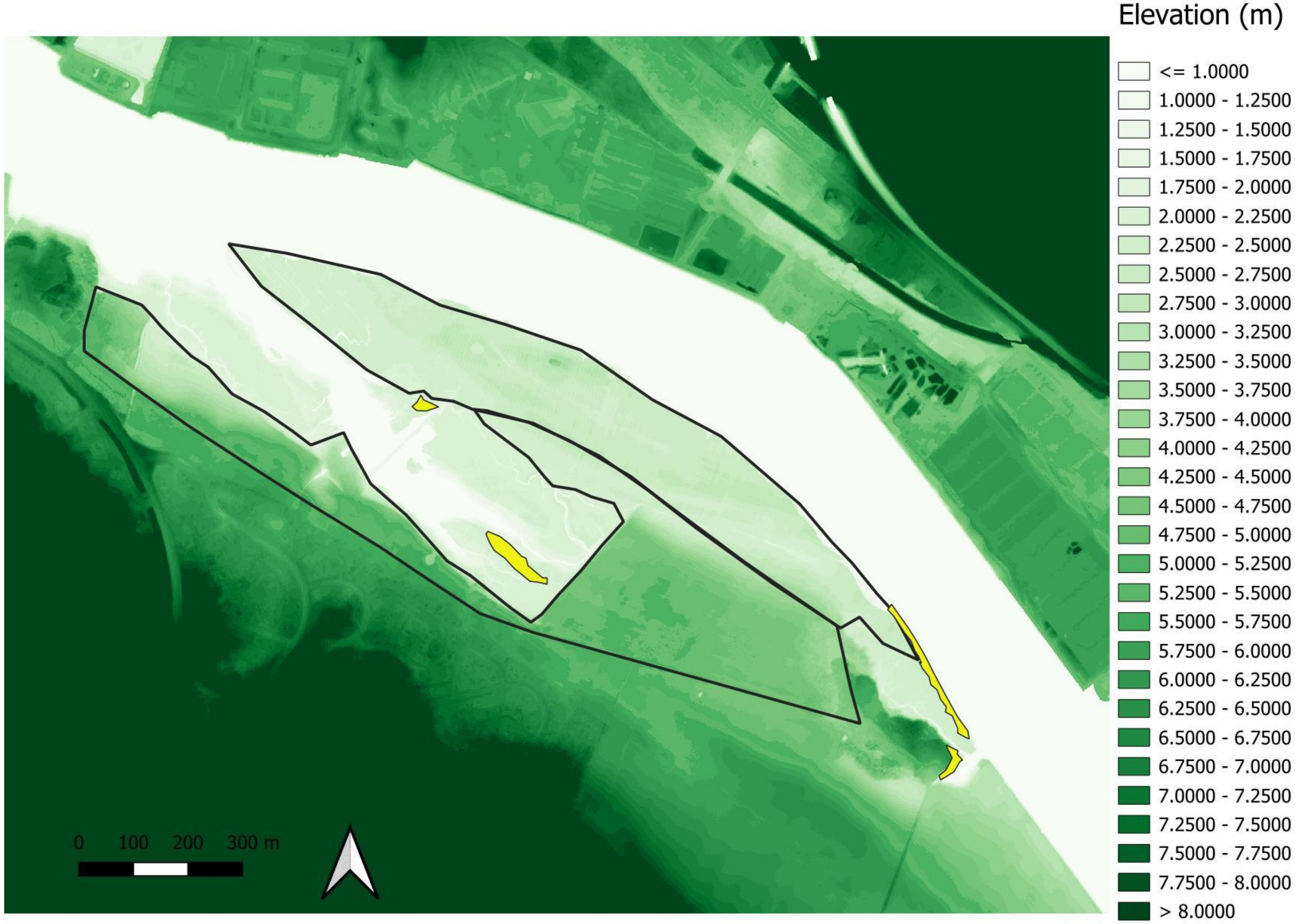

Figure A3-5: Potential Inner Clyde Newshot Island MR sites (black outline) after Hansom et al. (2017) with existing saltmarsh (yellow polygons) after Haynes (2016) GIS file.

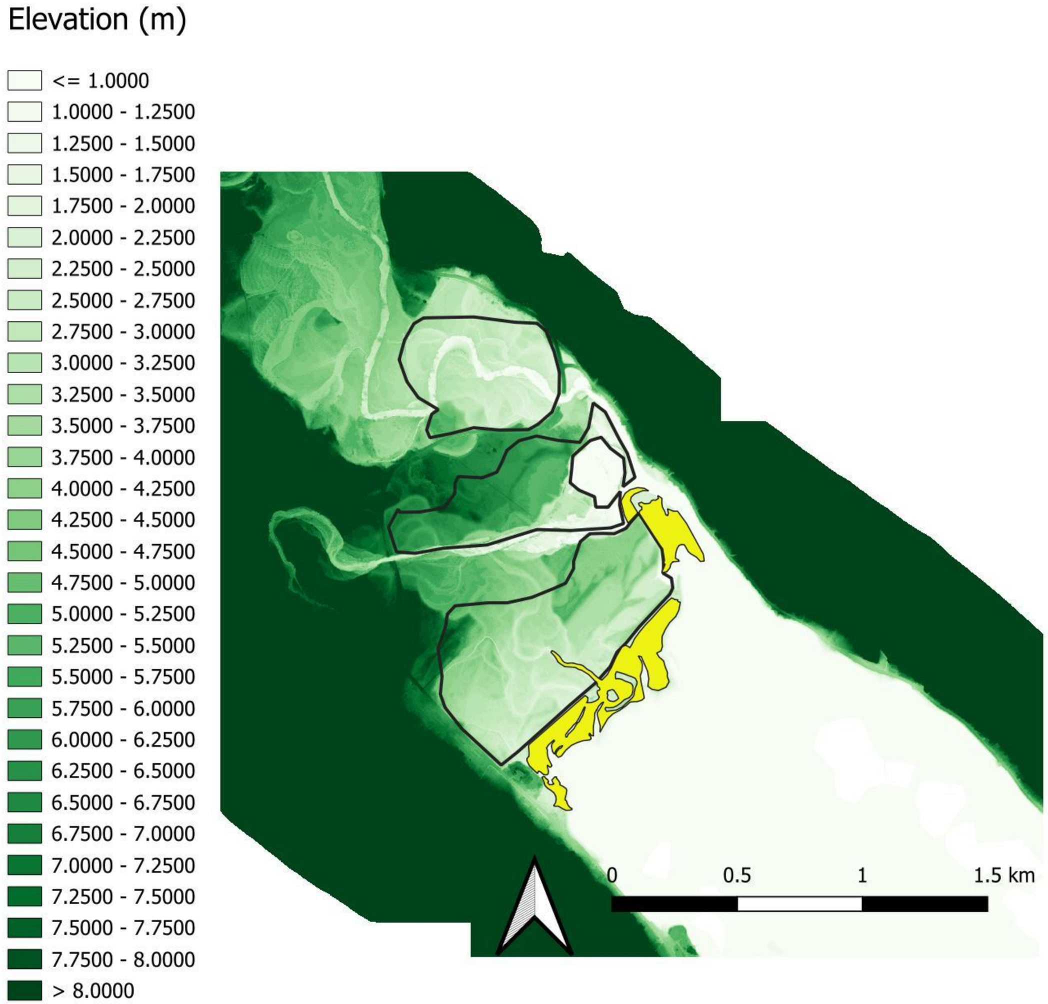

Figure A3-6: Potential Inner Clyde Holy Loch MR sites (black outline) after Hansom et al. (2017) with existing saltmarsh (yellow polygons) after Haynes (2016) GIS file.

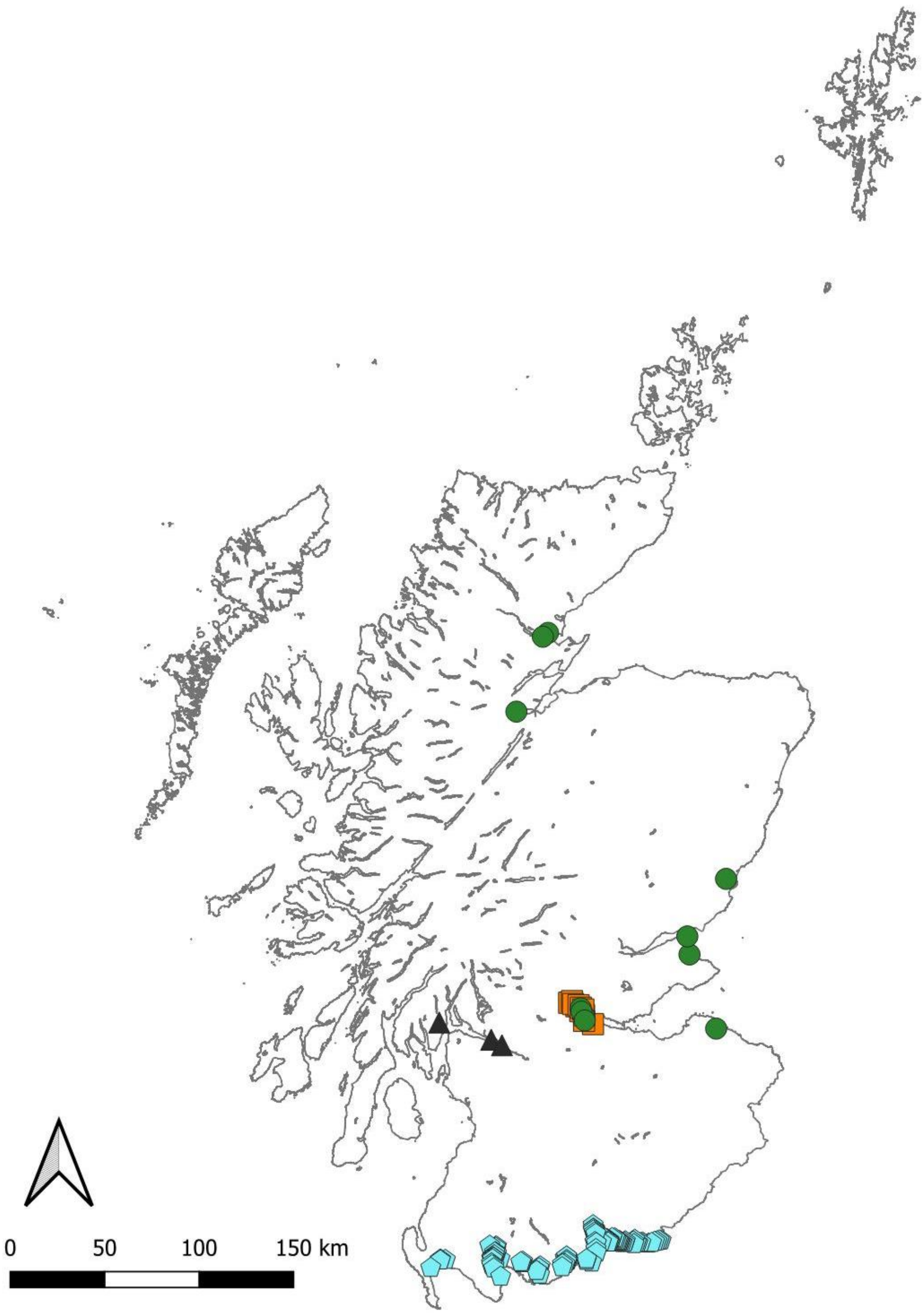

Figure A3-7: Map showing all identified and suitable potential saltmarsh restoration sites from RSPB (2012, orange squares), Hansom et al. (2017, black triangles), Austin et al. (2022, green circles) and Griffin (2023, pale blue pentagons).

12. Appendix 4 – Austin et al. (2022) sites identified with saltmarsh restoration potential.

Table A4-1: Overview of sites with saltmarsh restoration potential identified by Austin et al. (2022). *not mapped by Haynes (2016). Current saltmarsh extent taken from Austin et al. (2022); therefore unclear whether it refers to all areas surveyed by Haynes (2016) or only the saltmarsh NVC communities.

Site name	Current Saltmarsh extent (km^2)	Predicted low-mid marsh extent (km^2)	Predicted high marsh extent (km^2)	Predicted total saltmarsh (km^2)	Suitability for MR	Reasoning
Baldrium, Dornoch Firth	<0.0003*	0.06	0.23	0.3	Highly suitable	Saltmarsh present, no infrastructure
Ardmore, Dornoch Firth	<0.0003*	0.06	0.05	0.1	Highly suitable	Saltmarsh present, no infrastructure
Montrose, Montrose Basin	0.17	0.58	0.88	1.47	Highly suitable	Saltmarsh present, no infrastructure
Skinflats, Firth of Forth	0.1	0.22	0.22	0.44	Highly suitable	Saltmarsh present, no infrastructure
Inch of Ferryton, Firth of Forth	<0.0003*	0.17	0.05	0.22	Highly suitable	Saltmarsh present, no infrastructure

Tyninghame	0.4	0.69	0.44	1.13	Highly suitable	Saltmarsh present, no infrastructure
Dunmore, Firth of Forth	0.14	0.47	0.26	0.73	Highly suitable	Saltmarsh present, infrastructure (town present) would not be affected by MR
Eden Estuary	0.03	0.19	0.24	0.43	Highly suitable	Saltmarsh present, infrastructure (road present) would not be affected by MR
Kirkhill, Moray Firth	0.34	0.26	1.36	1.63	Highly suitable	Saltmarsh present, infrastructure (rail lines present) would not be affected by MR
Tayport, Tay Estuary	0.06	0.13	0.11	0.25	Suitable	Saltmarsh present, significant engineering effort would be required
Carron Pools, Firth of Forth	0.19	0.85	0.93	1.78	Suitable	Saltmarsh present, significant engineering effort would be required
Newburgh, Newburgh Estuary	0	0.46	0.32	0.78	Less Suitable	No saltmarsh present, brackish Phragmites marsh likely to form
Inverkeithing, Firth of Forth	0	0.02	0.16	0.19	Less Suitable	No saltmarsh present, significant engineering effort would be required

Longannet, Firth of Forth	0	0.1	0.12	0.22	Less Suitable	No saltmarsh present, remediation of contaminated land would have to take place first
Hawkhill, Firth of Forth	<0.0003*	0.12	0.13	0.26	Not suitable	Saltmarsh present but presence of power grid infrastructure would prohibit MR
Total	**1.43**	**3.39**	**4.44**	**9.93**		

13. Appendix 5 – Maps with data availability for blue carbon calculations

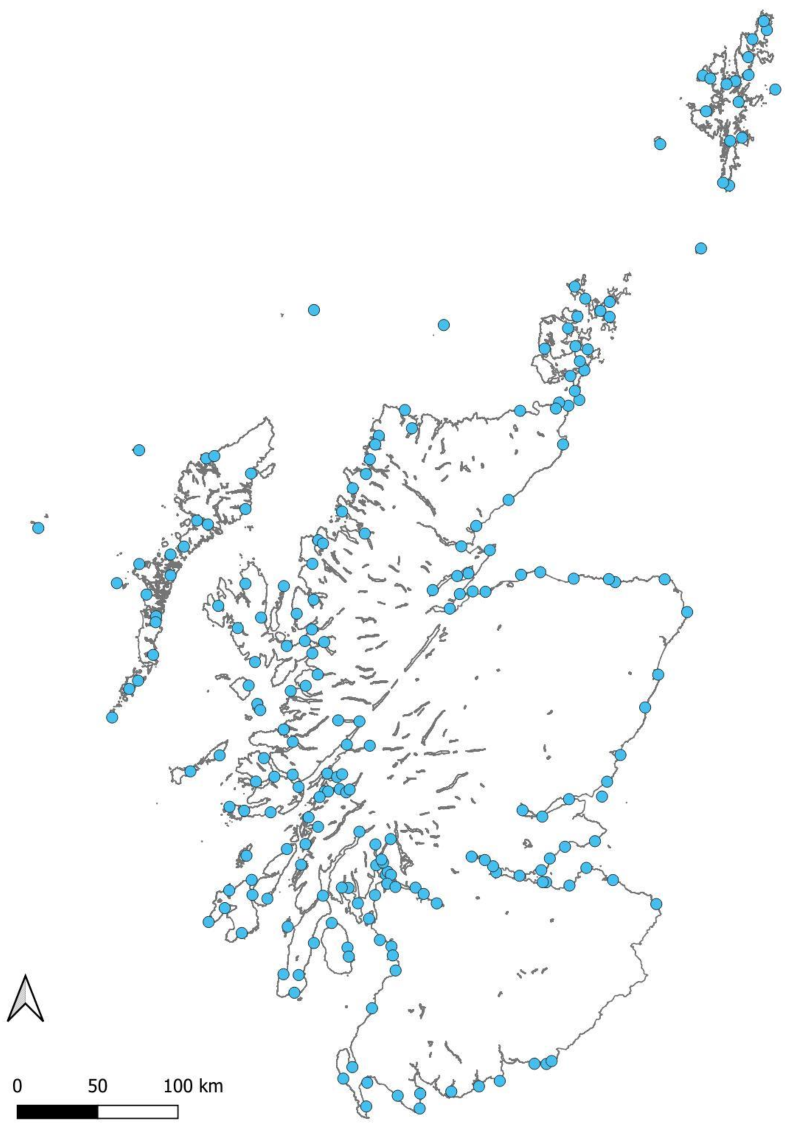

Figure A5-1: Locations with tidal range data available from EasyTide (Admiralty).

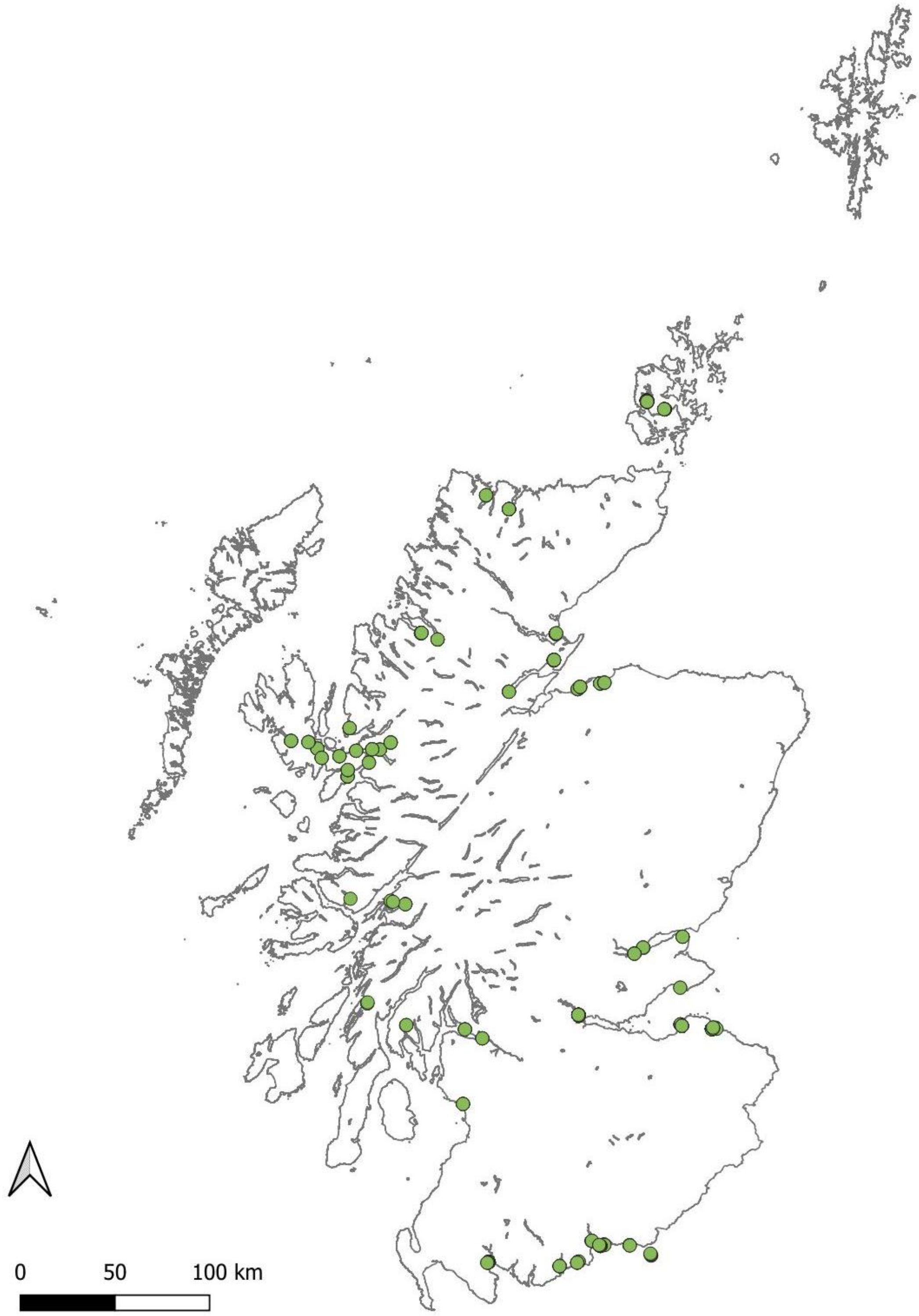

Figure A5-2: Locations with data for bulk density and carbon content for surficial (10 cm) samples.

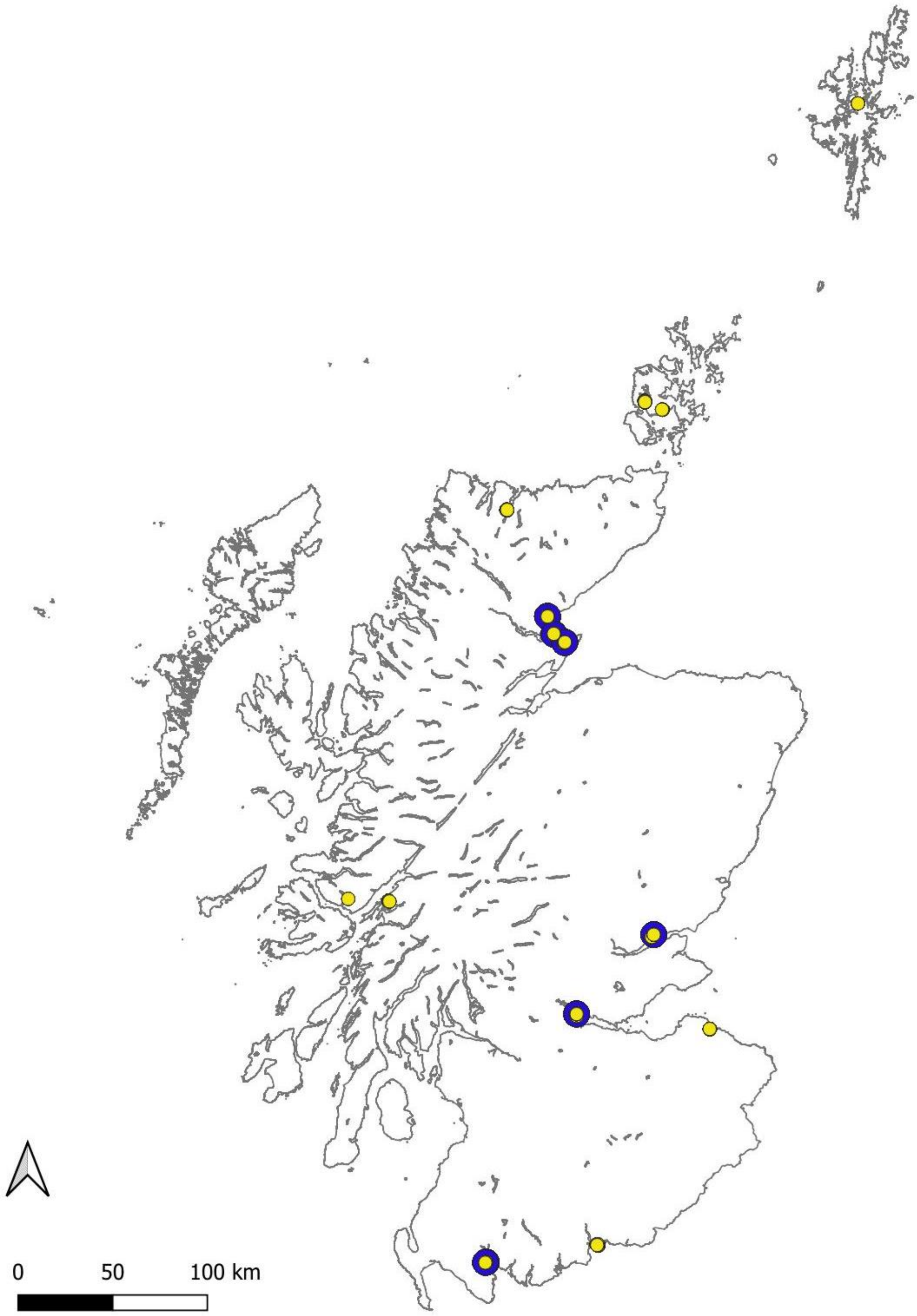

Figure A5-3: Locations with data for bulk density and carbon content for full depth samples. Yellow circle = narrow (3 cm) core; blue circle = wide (6 cm core).

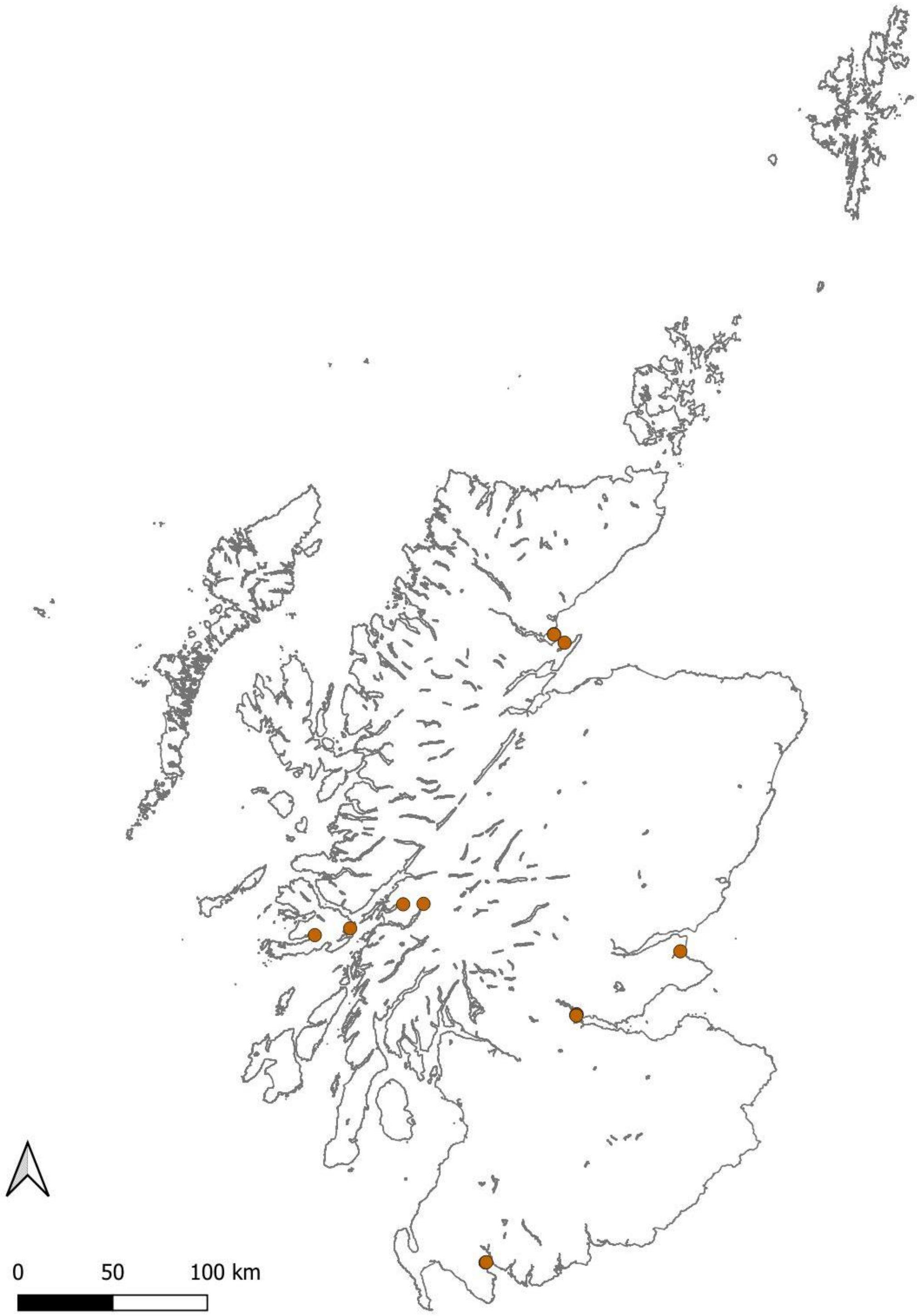

Figure A5-4: Locations with data for sediment accretion.

14. Appendix 6 – Data tables with marsh specific OC stock and accretion rates

Table A6-1: Examples of modelled surficial (10 cm) marsh OC stock highlighting the differences between different modelling approaches.

Marsh ID	Surficial OC stock (t) by Smeaton et al. (2021)	Surficial OC stock (t) by Smeaton et al. (2022a)	Difference between Smeaton et al. (2021) and (2022a) in %
Beauly Firth	2,886.0	4,577.3	58.6
Benbecula Airport - Gramsdale 1	846.0	898.5	6.2
Benbecula Airport - Gramsdale 2	255.5	278.4	8.9
Berneray	473.0	473.2	0.0
Blackness and Blackburn	2.8	4.7	67.2
Bonar Bridge	22.6	30.9	37.2
Bridge of Waithe and Cummi Ness	239.6	255.5	6.6
Bridgend Flats	2,310.2	2,182.0	-5.5
Broadford Bay	265.7	316.2	19.0
Browhouses	605.2	583.1	-3.7
Bunacaimb	364.2	347.5	-4.6
Caerlaverock	44,541.9	29,548.9	-33.7

Table A6-2: Saltmarsh soil OC (t) and standard deviation (SD) as reported by Smeaton et al. (2023).

Marsh ID	Saltmarsh Soil OC (t)	SD	% of SD of the Soil OC
Bridge of Waithe	1,698.9	1,034.4	60.9
Waulkmill Bay	1,314.3	768.8	58.5
Kyle of Tongue	3,308.9	1,908.6	57.7
Cambusmore Lodge	1,471.1	699.4	47.5
Dornoch Point	9,099.8	5,101.1	56.1
Morrich More	110,423.2	82,691.2	74.9
Loch Laich	437.6	95.9	21.9
Tay	1,741.3	950.2	54.6
Forth (Alloa)	2,174.9	1,022.8	47.0
Skinflats	8,235.3	4,114.2	50.0
Tyninghame	5,570.4	4,455.8	80.0
Wigtown Bay	62,293.6	28,120.4	45.1
Caerlaverock	47,830.5	27,478.7	57.5

Table A6-3: Sediment accretion rates per saltmarsh. Teasdale reported two numbers based on 1963 Weapons-test fallout (left) and 1986 Chernobyl accident (right).

Study	Marsh ID	Sediment Accretion Rates (mm yr^{-1})	SD
Miller et al. (2023)	Dornoch Point - Low-Mid Marsh	1.8	0.1
Miller et al. (2023)	Dornoch Point High Marsh	0.9	0.2
Miller et al. (2023)	Morrich More High Marsh	0.6	0.3
Miller et al. (2023)	Skinflats Low-Mid Marsh	4.6	1
Miller et al. (2023)	Skinflats High Marsh	2.4	1.2
Miller et al. (2023)	Wigtown Low-Mid Marsh	7.4	n/a
Miller et al. (2023)	Wigtown High Marsh	4.3	n/a
Teasdale et al. (2011)	Loch Scridain	1.8 / 1.8	n/a
Teasdale et al. (2011)	Loch Don	2.3 / 2.5	n/a
Teasdale et al. (2011)	Loch Creran	2.7 / 3.5	n/a
Teasdale et al. (2011)	Loch Etive	2.5 / 2.5	n/a
Masselink & Jones (2024)	Bothkennar Fields / Skinflats	2.15	0.97

Contact

enquiries@ceh.ac.uk

@UK_CEH

ceh.ac.uk

Bangor

UK Centre for Ecology & Hydrology
Environment Centre Wales
Deiniol Road
Bangor
Gwynedd
LL57 2UW

+44 (0)1248 374500

Edinburgh

UK Centre for Ecology & Hydrology
Bush Estate
Penicuik
Midlothian
EH26 0QB

+44 (0)131 4454343

Lancaster

UK Centre for Ecology & Hydrology
Lancaster Environment Centre
Library Avenue
Bailrigg
Lancaster
LA1 4AP

+44 (0)1524 595800

Wallingford (Headquarters)

UK Centre for Ecology & Hydrology
Maclean Building
Benson Lane
Crowmarsh Gifford
Wallingford
Oxfordshire
OX10 8BB

+44 (0)1491 838800

UK Centre for Ecology & Hydrology