The application of an eroding coastal heritage site dataset to test models of coastal erosion susceptibility, and historic coastal change:

a case study from Sanday, Orkney

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1. Main Findings

Three coastal erosion models were tested against the SCHARP dataset of eroding coastal heritage sites (CESM, Dynamic Coast NCCA and vegetation edge analysis). The best performing model is a modified version of the CESM with the superficial deposit filter removed (showing an 87% agreement). This improves upon the original CESM which has an agreement of 39% between SCHARP sites and high or very high susceptibility to erosion. The next best performing model is the vegetation edge analysis, which displays a 70% agreement between the SCHARP sites and erosion of ≥ 5m (based on any time period studied). The Dynamic Coast NCCA has agreement of 48% between the SCHARP sites and erosion of ≥ 5m (based on any time period studied).

The CESM, Dynamic Coast NCCA and vegetation edge change lines are complimentary approaches, and when used together have enormous potential for management of coastal assets.

2. Glossary of Terms

CESM – Coastal Erosion Susceptibility Model. In this report, the term CESM incorporates the Underlying Physical Susceptibility Model (UPSM) also developed by James Fitton and team from the University of Glasgow.

MHWS, Mean High Water Spring– An average over time of the highest level that the spring tide reaches around the coastline.

Dynamic Coast Change Line – The movement landward or seaward of the MHWS between two periods of time.

Vegetation Edge – The seaward or coastal limit of terrestrial vegetation as interpreted from an OS map or aerial photography.

3. Rationale for Work

The Scottish coastline contains a wealth of archaeology and as such the areas and extent of erosion of the Scottish coastline is of high importance to archaeologists.

There is a need for a predictive tool to help prioritise stretches of coastline for new archaeological survey to be undertaken and to assist in modelling future change to vulnerable sites on eroding coastlines that have already been identified. Two recent models of coastal vulnerability and historic coastal change have great potential for archaeologists as a management tool for coastal heritage assets. The Coastal Erosion Susceptibility Model

(CESM)[1] is a result of PhD research by James Fitton and Scotland's National Coastal Change Assessment (NCCA)[2] has been developed by the Dynamic Coast project. Both models have been produced at a national scale, with the CESM having full coverage of Scotland, and the main focus of the NCCA being on areas of soft coast. A further model of vegetation edge change analysis has been undertaken as part of this study.

This study uses an empirical dataset of eroding coastal heritage sites documented by volunteers in the Scotland's Coastal Heritage at Risk Project (SCHARP) to test the performance of each model, using a small case study area of Sanday.

There is a potential limitation in testing the relationship between highly localised eroding sites (such as the SCHARP dataset) and the national level assessments of coastal erosion susceptibility. Nevertheless it is hoped that through ground truthing local data alongside national-level data, and through the use of complimentary methods such as vegetation edge change analysis, we can improve our awareness of the exposure of archaeology to coastal erosion and the range of local factors which contribute to vulnerability.

4. Case study area

Sanday is an island situated in the north east of Orkney. It has been chosen as a case study area to test the CESM model and Dynamic Coast change lines for the following reasons:

1. There are 25 SCHARP priority sites on the island which is a reasonably sized dataset to work with;
2. Orkney is an area of Scotland which is not currently showing good agreement between eroding priority sites and the original CESM model, and Sanday contains a range of coastal environments which are representative of the wider island archipelago;
3. The whole of Sanday's coastline is included in the Dynamic Coast NCCA;
4. The SCAPE team have good on-the-ground knowledge of the priority sites and coastal environment of Sanday;
5. It is a manageable size to test vegetation edge analysis.

5. Priority Sites on Sanday

There are a total of 25 SCHARP priority sites on Sanday (Table 1). A Priority Site is defined as an archaeological site which has been designated as a priority by SCAPE based on its high

[1] Fitton, J. M., Hanson, J. D., and Rennie, A. F. (2016) A national coastal erosion susceptibility model for Scotland, *Ocean & Coastal Management*, 132, 80-99.

[2] Fitton, J.M., Hansom, J.D., and Rennie, A.F. (2017) Dynamic Coast - National Coastal Change Assessment: Methodology, CRW2014/2. http://www.dynamiccoast.com/index.html

archaeological significance and risk of loss due to active erosion[3]. All priority sites are experiencing erosion and all have recent condition surveys carried out by volunteers and moderated by SCAPE. The data is point data, which in most cases is not representative of the area of the site. To compensate for this, a buffer of 25m has been created around each point to more realistically describe the site extent and to facilitate intersection with the models.

SCHARP ID	Site Name	Description
6710	Augmund Howe or Egmondshowe	Burial cairn
6736	Backaskaill	Broch
6681	Bay of Lopness/ Newark Settlement Mount	Coastal exposure, settlement remains
6750	Bay of Stove	Coastal exposure, settlement remains
6657	Buryan	Broch
6827	Cleat	Coastal exposure, settlement remains
12218	Crow Taing, Tofts Ness	Mound and coastal exposure
6770	Ebb of Seater	Coastal exposure, settlement remains
6689	Hangie Head, Tres Ness	Mound and coastal exposure
6725	Ladykirk*	Mound and coastal exposure
12495	Langamay, wall	Walls
6674	Lopness	Coastal exposure, settlement remains
6765	North Mire	Burial cairn
6817	Northskaill	Coastal exposure, settlement remains
12899	Ore Ledge Lopness	Broch (?)
6726	Ouse Point	Coastal exposure, building
6829	Peterkirk	Settlement mound and coastal exposure
6764	Pool	Coastal exposure, settlement remains
12492	Possible farm site, Langamay	Midden and walling
6806	Quoybanks, Scar	Site of boat burial
6793	Rethie Taing*	Possible chambered cairn
6802	Runna Clett	Mound and coastal exposure
6704	Russ Ness	Mound and coastal exposure
13134	The Grithies, Cata Sand**	Settlement
6803	Woo	Coastal exposure, settlement remains

Table 1:Priority sites of Sanday with brief description.

* There are issues with the heritage information from Ladykirk and Rethie Taing, so these have been excluded from the analysis.

** The Grithies is intertidal but has been retained in the analysis.

[3] Hambly, J. (2017) *A Review of Heritage at Risk from Coastal Processes in Scotland: Results from the Scotland's Coastal Heritage at Risk Project 2012-2016*. Unpublished SCAPE report. http://scharp.co.uk/media/medialibrary/2018/02/Review_of_Coastal_Heritage_at_Risk.pdf

6. Aims

The aims of this study are to explore and analyse the agreement between observed records of eroding coastal heritage sites on Sanday with:

1. The Coastal Erosion Susceptibility Model (CESM) developed by James Fitton;
2. Historic change lines produced by the Dynamic Coast NCCA;
3. Historic change lines computed from Vegetation Edge Analysis, undertaken as part of this study.

For each of the three models, the following steps were carried out:

1. Intersect priority sites with each model
2. Identify priority sites which agree/do not agree to each method
3. Account for agreement and non-agreement;

Finally, the performance of each model for locating coastlines on Sanday where sites at risk as a result of erosion are found is compared and discussed.

7. CESM

The CESM identifies areas of the coastline susceptible to erosion by aggregating susceptibility to four data layers: ground elevation, rock head elevation, distance from open coast and wave exposure. It also takes into account sediment supply and coastal defences. The results are presented by colour-coding from green to red across a 50m^2 raster from 'Very Low' to 'Very High' susceptibility to erosion (Table 2).

(dark green)	0-20	Very Low
(light green)	>20-40	Low
(yellow)	>40-60	Medium
(orange)	>60-80	High
(red)	>80-100	Very High

Table 2:CESM classifications

7.1 Methodology

Step 1: Using the 'Select by Attributes' tool, raster cells with a susceptibility of ≥60 (High) are isolated using the formula "CESM" >= 60.

Step 2: The highlighted attributes are exported to a new shapefile.

Step 3: Using the 'Select by Location' tool, priority sites (buffered by 25m) are intersected with the newly created CESM60 shapefile.

Step 4: Highlighted attributes are exported and added to the map as a new shapefile

7.2 Results

The above methodology was carried out to isolate coastal areas which indicate a high or very high susceptibility to erosion and to subsequently intersect the SCHARP priority sites with those coastal cells. Table 3 (below) identifies that 9 of 23 original Priority sites coincide with land which is expected to have a high or very high susceptibility to erosion (a CESM score >60).

SCHARP ID	Site Name	CESM cell value*	Notes on location/coastal environment
6681	Bay of Lopness/Newark Settlement Mound	85.7	Sand cliff
6750	Bay of Stove	64.2	Low lying or low cliff thin layer of till/subsoil over rock platform
12218	Crow Taing, Tofts Ness	89.2	Sand behind storm beach
12495	Langamay, wall	78.5	Sand
6817	Northskaill	92.8	Sand cliff
12899	Ore Ledge Lopness	71.4	Low lying or low cliff thin layer of till/subsoil over rock platform
6726	Ouse Point	85.7	Shingle spit
12492	Possible farm site, Langamay	85.7	Sand
6806	Quoybanks, Scar	75	Sand behind rock platform and storm beach

Table 3: 9 out of 23 SCHARP Priority Sites on Sanday agree with a CESM ≥60

* If buffered site intersects with more than one CESM cell, the highest CESM cell value is reported. This is also the case in subsequent tables.

Table 4 (below) considers the remaining sites which are not coincident with areas at high susceptibility to coastal erosion (i.e. CESM <60) and also notes their proximity to high susceptibility areas.

SCHARP ID	Site Name	CESM cell value	NEAR Distance (m) to CESM ≥60	Closest CESM ≥60 cell value	Notes on location/coastal environment
6736	Backaskaill	0	35.83	75	Elevated bedrock at edge of sandy bay
6710	Augmund Howe or Egmondshowe	0	743.51	78.5	Low-lying rocky coast
6657	Buryan	0	75.00	85.7	Low lying or low cliff thin layer of till/subsoil over rock platform

SCHARP ID	Site Name	CESM cell value	NEAR Distance (m) to CESM ≥60	Closest CESM ≥60 cell value	Notes on location/coastal environment
6827	Cleat	0	89.02	78.5	Low lying or low cliff thin layer of till/subsoil over rock platform
6770	Ebb of Seater	0	10.00	75	Low lying or low cliff thin layer of till/subsoil over rock platform
6689	Hangie Head, Tres Ness	0	125.00	100	Low lying or low cliff thin layer of till/subsoil over rock platform
6674	Lopness	0	35.00	64.2	Low lying or low cliff thin layer of till/subsoil over rock platform
6765	North Mire	0	258.02	71.4	Low lying or low cliff thin layer of till/subsoil over rock platform
6829	Peterkirk	0	465.41	78.5	Low lying or low cliff thin layer of till/subsoil over rock platform
6764	Pool	0	82.70	71.4	Elevated bedrock at edge of sandy bay
6802	Runna Clett	0	16.00	85.7	Low lying or low cliff thin layer of till/subsoil over rock platform
6704	Russ Ness	57.1	678.28	92.8	Low lying, sandy
13134	The Grithies, Cata Sand	0*	38.32	96.4	Intertidal
6803	Woo	0	42.08	78.5	Low lying or low cliff thin layer of till/subsoil over rock platform

Table 4: 14 out of 23 SCHARP Priority Sites on Sanday do not agree with a CESM ≥60. The proximity of each buffered site to the closest CESM cell ≥60 has also been stated. *The Grithies does not intersect with the CESM model but the closest raster cell value has been stated.

Table 3 and 4 identify that only 39% of the priority sites are located on land that was identified as being at high or very high sensitivity by the CESM. Of the 14 sites which are not situated in a cell with a CESM score of ≥60, 12 are in a cell with a value of 0 (a very low susceptibility to erosion). One site, Russ Ness, is situated in a cell with a medium susceptibility of erosion, and one site, The Grithies, is located outside the model completely.

It is worthwhile to consider that the CESM was a national level assessment based on pre-existing data, some of which have limited confidence within the further reaches of Scotland's isles (this is discussed in section 8 of the report). As such the 61% of priority sites do not fall into the highest two categories of susceptibility but have some inherent resilience, as described by the CESM.

Many of the eroding sites out with the CESM ≥60 are located on low lying coastlines characterised by having a thin layer of till and/or subsoil over bedrock.

A typical example of an eroding site on this type of coastline is Cleat (SCHARP ID: 6827), in north east Sanday. This is a site which lies out with CESM ≥60 but is a priority site which has been documented as experiencing coastal erosion (Figure 1).

Figure 1:Photograph of priority site of Cleat [SCHARP ID: 6827] demonstrating the low-lying coastline with a thin layer of soft sediment on top of bedrock.

In this example of the coastal exposure of Cleat, the model suggests this part of the coast has a very low susceptibility to erosion, which disagrees with the erosional status of the archaeological site (Figure 2). However, the high level bedrock geology indicates inherent resilience which may be contributing to this lower CESM score, despite ground truth showing active erosion at the site.

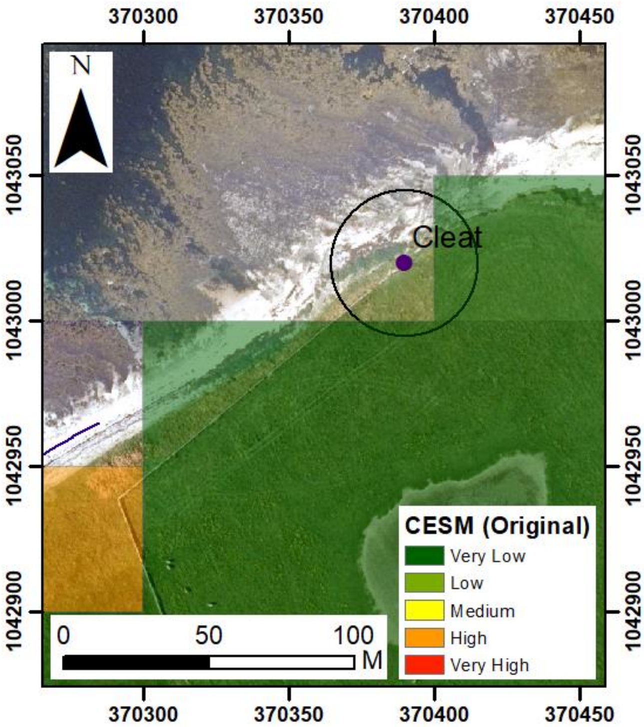

Figure 2: Location of Cleat with overlay of CESM. The site is intersecting with the model in an area of very low erosion susceptibility. The figure also demonstrates how the 25m buffer compensates for the resolution issues with the 50m raster.

8. CESM with Superficial Deposit Filter Removed

Of the 14 priority sites not located on CESM ≥60, ten are located on low lying coast edges characterised by thin deposits of till or subsoil over bedrock.

Within the CESM, rock head elevation, or the height of bedrock above MHWS is used as one of the variables to assess susceptibility to erosion. This is calculated by using the OS 50m DTM and subtracting the Advanced Superficial Thickness Model (ASTM) which used mapping and borehole records to calculate the thickness of Quaternary deposits. In the post-processing stages of the model creation it was thought that susceptibility to erosion was overstated, and therefore filters were added to refine the model[4]. The Superficial Deposit Filter reduces the susceptibility to erosion rating if rock head is at the surface and/or if rock head is > 6m above MHWS elevation.

The DTM that is used to calculate the ASTM has a resolution of 50m, which is coarse in respect to small scale sites, however borehole data could be even more sparsely distributed, and as such, the ASTM will be less well constrained in areas with low availability of borehole data. Borehole data is generally most dense in urban areas and less so in rural areas, which

[4] Fitton *et al.* 2016

is the case for the peripheral Scottish islands where there is limited development. Also, due to the thinness of superficial deposits around much of Sanday's coast, it is possible they are not captured in the ASTM. This means that even for sections of Sanday's coastline with thin superficial deposits that are eroding, the CESM assumes that rock head is at the surface and so is not erodible. If we disable the filter that reduces the susceptibility rating if rock head is at the surface, much more of Sanday's coastline should be categorised as susceptible. To test if this was the case and on the advice of James Fitton, we disabled the superficial deposit filter and re-ran the model.

8.1 Results

When the Superficial Deposit Model Filter is disabled, 20/23 sites agree with the CESM model (87%) and only 3 do not agree (Table 5 and Table 6 respectively).

SCHARP ID	Site Name	CESM cell value (not including superficial thickness score)
6710	Augmund Howe or Egmondshowe	71
6736	Backaskaill	67
6681	Bay of Lopness/Newark Settlement Mound	85
6750	Bay of Stove	64
6657	Buryan	92
6827	Cleat	85
12218	Crow Taing, Tofts Ness	89
6770	Ebb of Seater	67
6689	Hangie Head, Tres Ness	92
12495	Langamay, wall	78
6674	Lopness	85
6765	North Mire	71
6817	Northskaill	92
12899	Ore Ledge Lopness	71
6726	Ouse Point	85
6829	Peterkirk	60
12492	Possible farm site, Langamay	85
6806	Quoybanks, Scar	82
6802	Runna Clett	64
6803	Woo	71

Table 5: 20 of 23 SCHARP Priority Sites on Sanday agree with a CESM rating of ≥60 when the Superficial Deposit Filter is removed.

SCHARP ID	Site Name	CESM cell value	NEAR Distance (m) to CESM ≥60	Closest CESM ≥60 value (not including superficial thickness score)
6764	Pool	57	25.00	71
6704	Russ Ness	57	678.28	92
13134	The Grithies, Cata Sand	0*	38.32	96

Table 6: 3 of 23 SCHARP Priority Sites on Sanday do not agree with a CESM rating of ≥60, when the Superficial Deposit Filter is removed. * The Grithies does not intersect with the CESM model but the closest raster cell has a CESM (without superficial deposit filter) value of 96.

When the superficial deposit filter is removed, Cleat is now located on a raster with a very high susceptibility to erosion (Figure 3). This increase in high and very high susceptibility of erosion can be seen visually when comparing the two models (Figures 4 and 5).

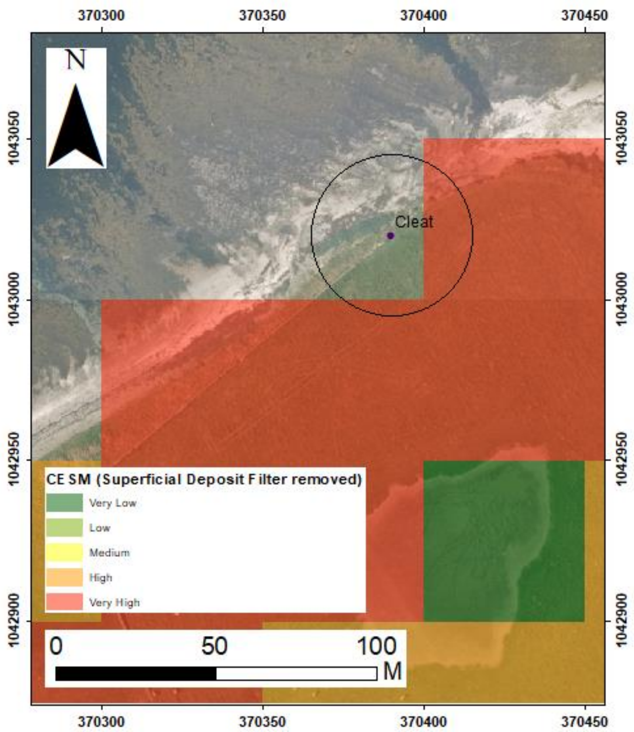

Figure 3: Location of Cleat with overlay of CESM with no superficial deposit filter. The site is intersecting with the model in an area of very high erosion susceptibility.

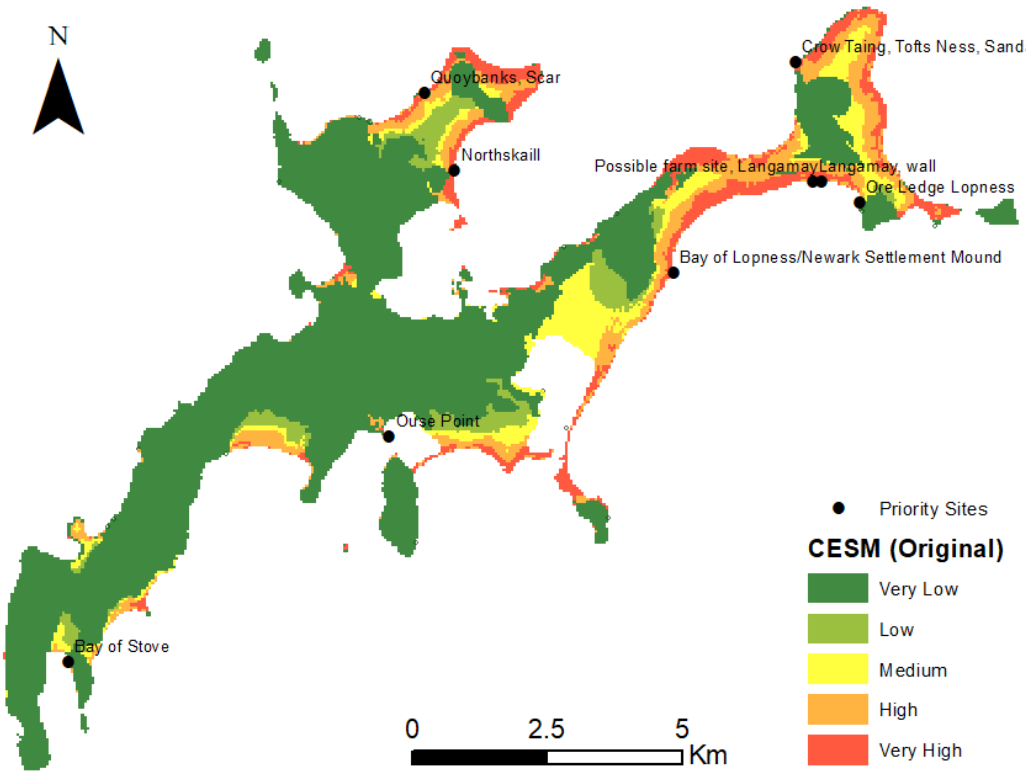

Figure 4: CESM for Sanday including the superficial deposit filter. 9 sites are intersecting with CESM ≥60.

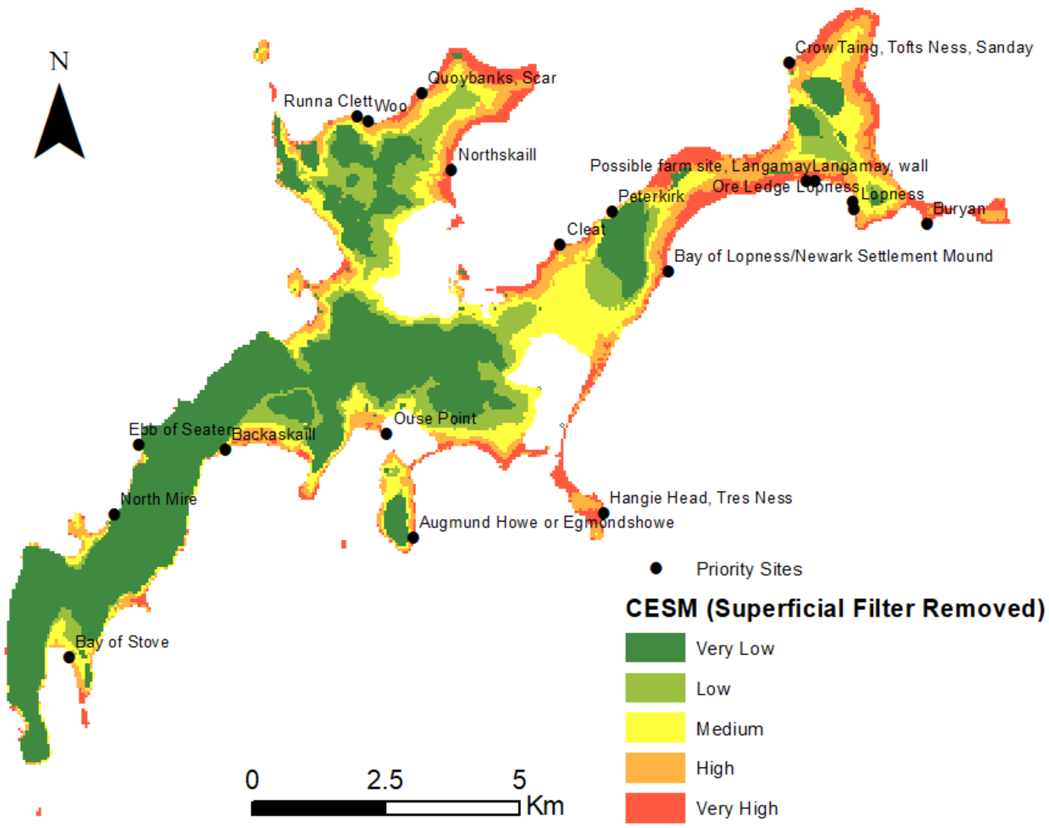

Figure 5: CESM for Sanday with superficial deposit filter removed. 20 sites are intersecting with CESM ≥60.

8.2 Discussion

Due to the lower accuracy of the ASTM in rural areas attributed to sparse borehole data as well as the thin superficial deposits characteristic of Sanday, there was potential that erosion was understated in the final model output and it was deemed acceptable to run the model without the superficial deposit filter in place. The removal of the superficial deposit filter significantly improves agreement between priority sites and the CESM; however there is a risk that this simple change to the model could now be overstating susceptibility of the coast edge. For example, if there was a significant increase in the proportion of the coastline with high susceptibility; we would expect a corresponding increase in agreement with eroding sites. The proportion of priority sites intersecting with CESM ≥60 with the filter removed increases from 39% to 87%. This suggests a strong relationship between observed erosion and modelled susceptibility to erosion in this iteration of the model. By removing the filter, the total length of coastline recording CESM ≥60 increases from 44.5% to 76.9%.

9. Dynamic Coast Phase 1

Dynamic Coast's National Coastal Change Assessment has digitized Mean High-Water Spring (MHWS) lines from 1890s, 1970s and modern maps for the 20% of Scotland's coastline classified as 'soft' to use as a proxy to identify where historic erosion or accretion has occurred[5].

Two change lines have been computed; the first showing the change between MHWS from the 1890s to 1970s, and the second showing the change between 1970s and modern.

For this study we clipped the MHWS Change Lines for the island of Sanday. Figures 6 and 7 show the two change lines for the island.

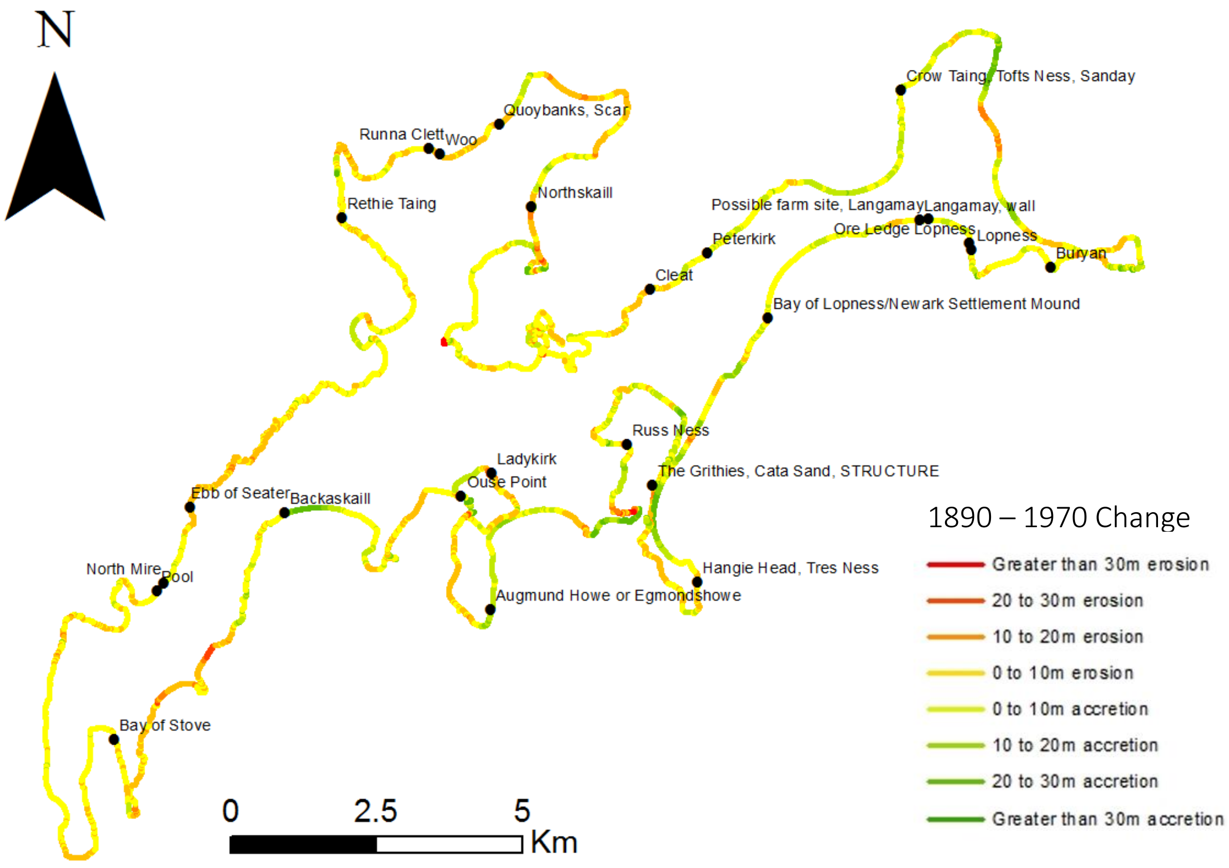

Figure 6: MHWS Change 1890-1970

[5] Fitton *et al.*, 2017

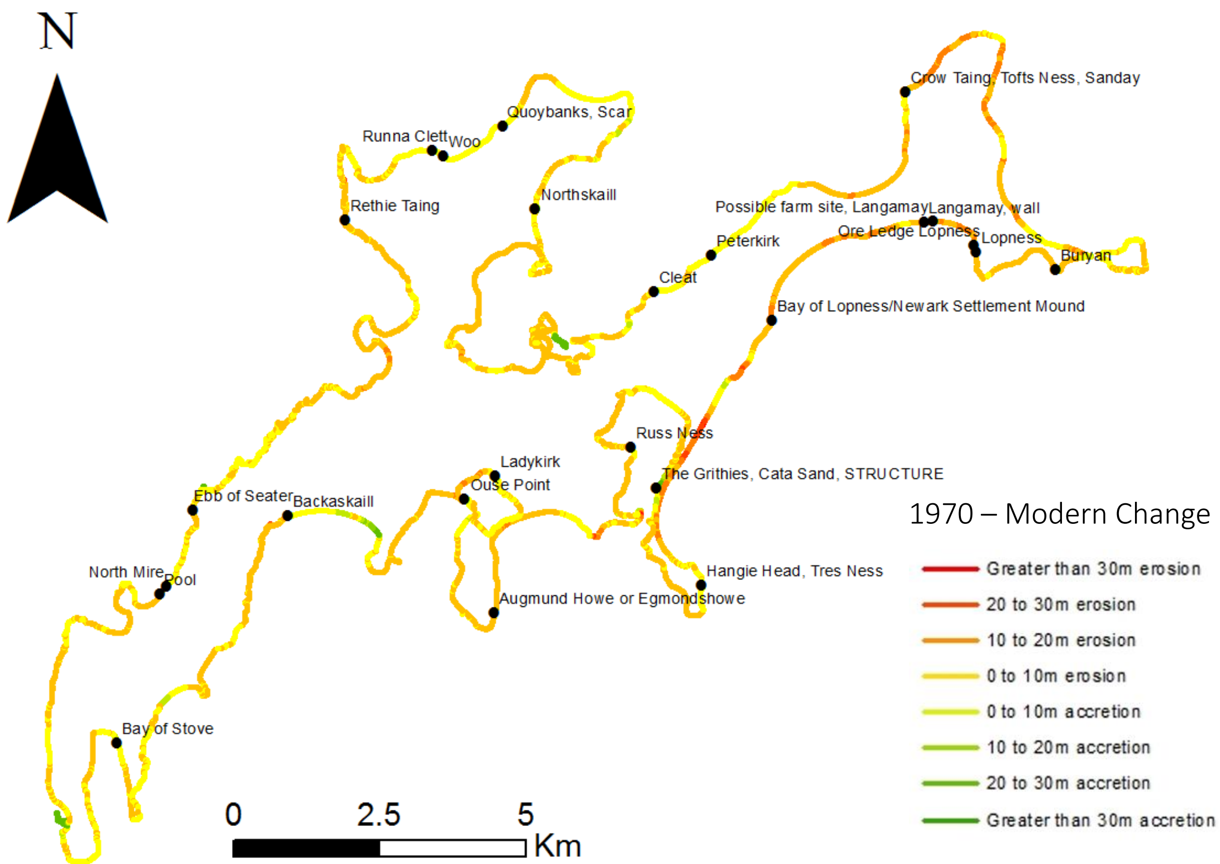

Figure 7: MHWS Change 1970-Modern

9.1 Intersection of priority sites with Dynamic Coast change lines showing accretion and erosion

9.1.1 Methodology

In an initial study it was found that SCHARP priority sites were as likely to intersect with an accreting Dynamic Coast change line as an eroding Dynamic Coast change line, so in the Sanday study, we initially also looked at the relationship between priority sites with both accreting and eroding change lines.

Using the 'Select by Attributes' function in ArcGIS, erosion and accretion greater than a range of thresholds were extracted to create a separate polyline. This was then intersected with the SCHARP priority site data to identify how many of the priority sites intersected the Dynamic Coast data line.

The thresholds chosen to intersect with the buffered priority sites were:

- >0 m erosion/accretion
- ≥1m erosion/accretion
- ≥5m erosion/accretion
- ≥10m erosion/accretion

This was repeated for both the 1890-1970 change line and the 1970-modern change line.

9.1.2 Results

	Coastline (m)	Coastline (%)	Number of Priority Sites	Number of Sites (%)
1890-1970 Change	116,539	100	21	100
Accretion				
>0m	82,112	70	**17**	**81**
≥ 1m	80,862	69	16	76
≥5m	54,310	47	13	62
≥ 10m	26,910	23	10	48
Erosion				
> 0m	34,427	30	**12**	**57**
≥ 1m	33,194	28	12	57
≥5m	14,155	12	7	33
≥ 10m	3,785	3	1	5
1970-Modern Change	118,216	100	24	100
Accretion				
>0m	44,356	38	**12**	**50**
≥ 1m	41,056	35	12	50
≥5m	9,097	8	5	21
≥ 10m	3,809	3	2	8
Erosion				
>0m	73,840	62	**16**	**67**
≥ 1m	70,199	59	16	67
≥5m	21,620	18	5	21
≥ 10m	7,470	6	3	13

Table 7: Number of sites showing accretion or erosion for a range of thresholds and the length of coastline experiencing erosion and accretion at each threshold. Note the high % of accretion between 1890 and 1970.

The results for Sanday were similar to the results for the whole of Scotland. Priority sites were more likely to intersect with accreting coastlines on the 1890-1970 change line and slightly more likely to intersect with eroding coasts on the 1970-modern change line.

	1890 - 1970		1970 - modern	
	Scotland	Sanday	Scotland	Sanday
Priority sites accreting	48 (36%)	17 (81%)	42 (34%)	12 (50%)
Priority sites eroding	39 (32%)	12 (57%)	48 (39%)	16 (67%)

Table 8: Comparison of number of all Scotland and Sanday priority sites intersecting with accreting and eroding coasts according to Dynamic Coast change lines for 1890-1970 and 1970-modern (some plot on both accreting and eroding change lines).

Next, a ≥5m threshold was chosen for accretion and erosion change lines. This is because the 1890s and 1970s MHWS line drawn on the map translates to *c.* 10m wide on the ground. Therefore, a line showing less than 5m of change either side of the mid-point of the line may not be showing actual change.

Accretion ≥5m		Erosion ≥5m	
1890-1970	1970-modern	1890-1970	1970-modern
Augmund Howe or Egmondshowe	Ouse Point	Bay of Lopness/Newark Settlement Mound	Bay of Lopness/Newark Settlement Mound
Backaskaill	Quoybanks, Scar	Cleat	Crow Taing
Bay of Lopness/Newark Settlement Mound	Runna Clett	Ebb of Seater	Langamay, wall
Buryan	The Grithies	Northskaill	Lopness
Langamay, wall	Woo	Quoybanks, Scar	Possible farm site Langamay
Lopness		Runna Clett	
North Mire		Woo	
Ore Ledge Lopness			
Ouse Point			
Peterkirk			
Pool			
Possible farm site, Langamay			
Rethie Taing			
Russ Ness			
13 (62%)	5 (21%)	7 (33%)	5 (21%)

Table 9: Sanday priority sites intersecting with accreting and eroding coasts showing ≥5m change according to Dynamic Coast change lines for 1890-1970 and 1970-modern.

When a ≥5m threshold is applied, 11 unique sites, or 48% of Sanday's priority sites, intersect with eroding coastlines in either period. Seventeen or 74% intersect with an accreting coastline of either period.

9.1.3 Discussion

Priority sites agreeing with accreting coastlines are not necessarily problematical because in a dynamic coastal system cycles of erosion and accretion may naturally occur. The Langamay sites are good examples of this, located in a dynamic sandy bay. However, the character of much of the coastline identified as accreting is of bedrock platform close to the surface covered by thin superficial deposits, and it is hard to see how these coastlines could accrete.

There are limitations to the use of MHWS as a proxy for coastal change:

1) a MHWS line will not capture all fluctuations of a dynamic coastline and are a simplified proxy for a complicated coastal system. They are also not located directly at the vegetation edge, which could be showing different behaviours to what is recorded at the MHWS;

2) some of the modern MHWS lines for Sanday have not been updated by the Ordnance Survey but instead have been interpreted by eye during the change line creation as part of the NCCA.

9.2 Proximity of priority sites with change lines showing erosion only

In a further stage of analysis, we explored the relationship between priority sites and Dynamic Coast change lines showing only erosion by calculating the proximity of priority sites to the ≥5m change lines in order to better understand the extent of 'near misses' .

9.2.1 Methodology

Using the 'NEAR' tool in ArcGIS, the nearest distance from the 25m buffered sites to any erosion ≥5m on either change line were calculated.

9.2.2 Results

SCHARP ID	Site	NEAR Distance (m) to 1890-1970 erosion ≥ 5 m	NEAR Distance (m) to 1970-modern erosion ≥ 5 m
6710	Augmund Howe or Egmondshowe	21.43	342.89
6736	Backaskaill	311.12	571.57
6681	Bay of Lopness/Newark Settlement Mound	0	0
6750	Bay of Stove	388.15	419.12
6657	Buryan	21.60	426.83
6827	Cleat	288.00	0
12218	Crow Taing, Tofts Ness	0	1266.38
6770	Ebb of Seater	18.09	0
6689	Hangie Head, Tres Ness	413.51	123.42
12495	Langamay, wall	0	1414.24
6674	Lopness	0	396.09
6765	North Mire	873.65	696.78
6817	Northskaill	592.15	0
12899	Ore Ledge Lopness	52.48	510.50

SCHARP ID	Site	NEAR Distance (m) to 1890-1970 erosion ≥ 5 m	NEAR Distance (m) to 1970-modern erosion ≥ 5 m
6726	Ouse Point	104.59	11.05
6829	Peterkirk	1255.82	888.39
6764	Pool	736.20	604.79
12492	Possible farm site, Langamay	0	1303.00
6806	Quoybanks, Scar	913.69	0
6802	Runna Clett	1268.42	0
6704	Russ Ness	30.88	551.53
13134	The Grithies	86.01	32.45
6803	Woo	1444.34	0

Table 10: Buffered priority sites showing closest section of coast with ≥5m erosion per MHWS change lines. '0' indicates the site intersects with the MHWS line.

The results of the NEAR analysis shows that 6 sites are located <25m from a change line showing ≥5m erosion from either period, and 6 are located >100m from a change line showing ≥5m erosion from either period. The spread and range of distance values highlights the limitations of using MHWS change lines as a proxy for coastal erosion when looking at specific assets located on the coast edge, because the MHWS line may be situated lower down the shore than the eroding land edge (identified by the vegetation edge analysis).

10. Vegetation Edge Analysis

The analysis carried out thus far suggests that changes in the MHWS shoreline is an imperfect proxy for changes at the coast edge on Sanday. Following discussion with the Dynamic Coast team, we applied vegetation edge analysis to Sanday as part of the development of this complementary method to the MHWS change analysis of Dynamic Coast Phase 1.

The potential advantages of this method are:

- The vegetation edge is a readily identifiable feature which is in close proximity to archaeological sites when erosional events compromise the archaeology. Whilst it can vary seasonally, when it is erosional these fluctuations are often absent or spatially limited;
- ability to identify areas which have eroded by both wave action, but also wind erosion, and therefore it can better reflect multiple threats;
- the potential of this method for greater spatial and temporal resolution as more aerial imagery becomes available, at lower costs than the photogrammetric production of MHWS line which are more expensive.

The limitations of this method are:

- access to aerial photography
- interpretation of vegetation edge from maps and aerial imagery;
- seasonality of vegetation;

10.1 Methodology

Three vegetation edge coastlines were digitised for Sanday. The 1900 vegetation edge was digitised from OS historic maps (used within the Dynamic Coast project), while the vegetation edges in 2005 and 2014 were digitised from aerial photography. These were dictated by the availability of data sets. A 1970s vegetation edge would have been very useful, but the OS maps were too uncertain and the aerial photography not available within the timescales of this project.

Maps/Aerial Photography used:

- 1:2500 County Series 1st Revision (1900), 1:2500 County Series 1st Edition (1879)
- 2005-2006 Pan Government Agreement aerial images supplied by SNH
- 2014 Aerial Photography provided by Edina Digimap ©GetMapping Plc

Three separate vegetation edge change lines were created: 1900-2014; 1900-2005 and 2005-2014. The methodology follows that for the creation of the 1900-2014 vegetation edge change set out below:

Step 1: The vegetation edge as interpreted on both the OS maps and aerial photography was digitised as two separate vegetation edge lines at a scale of 1:800.

Step 2: All individual polyline attributes which make up the outline for a vegetation line were merged to create one polyline.

Step 3: Points were created along each of the lines at an interval of 10m.

Step 4: The NEAR tool was used to calculate the distance between the two nearest points on each of the lines [NEAR_DIST].

Step 5: An inland polygon was created of the 1900 line

Step 6: Where the 2014 points intersect with the 1900 inland polygon, they are representing areas of erosion and the NEAR_DIST value is multiplied by -1 [DIST_V].

Step 7: The 2014 vegetation edge line is used to create points along it at 5m intervals.

Step 8: The 2014 vegetation edge line is split into sections based on the 5m point data.

Step 9: The split-up line is joined back to the 10m point data and the DIST_V value is symbolised.

Step 10: The resulting line shows change in the coastline between 1900 and 2014.

The same methodology was applied to create vegetation edge changes lines for 1900-2005 and 2005-2014.

10.2 Results of vegetation edge change lines

	Vegetation Edge Change 1900-2014	Vegetation Edge Change 1900-2005	Vegetation Edge Change 2005-2014	MHWS Change Line 1890-1970	MHWS Change Line 1970-Modern
Total Length of Line	119,325m (100%)	127,702m (100%)	119,325m (100%)	116,539m (100%)	118,216m (100%)
Length showing erosion > 0m	62,070m (52%)	72,618m (57%)	54,913m (46%)	34,427m (30%)	73,840m (62%)
Length showing erosion ≥5m	35,042m (29%)	48,004m (38%)	12,580m (11%)	13,785m (12%)	21,025m (18%)

Table 11: Vegetation edge change lines compared to MHWS change lines

Vegetation edge analysis indicates that around half (52%) of Sanday’s coast shows any erosion between 1900 -2014, and this figure remains quite consistent for the two selected time periods (57% in 1900-2005 and 46% in 2005-2014). If we consider only change of ≥5m, vegetation edge analysis shows 29% of Sanday's coastline is eroding by ≥5m between 1900 and 2014 (Figure 8). Broken down into the two time periods, 38% of Sanday's coastline eroded by ≥5m between 1900-2005 (Figure 9) and 11% between 2005-2014 (Figure 10). The fall in % may be partly attributed to the much shorter time interval covered in the latter period.

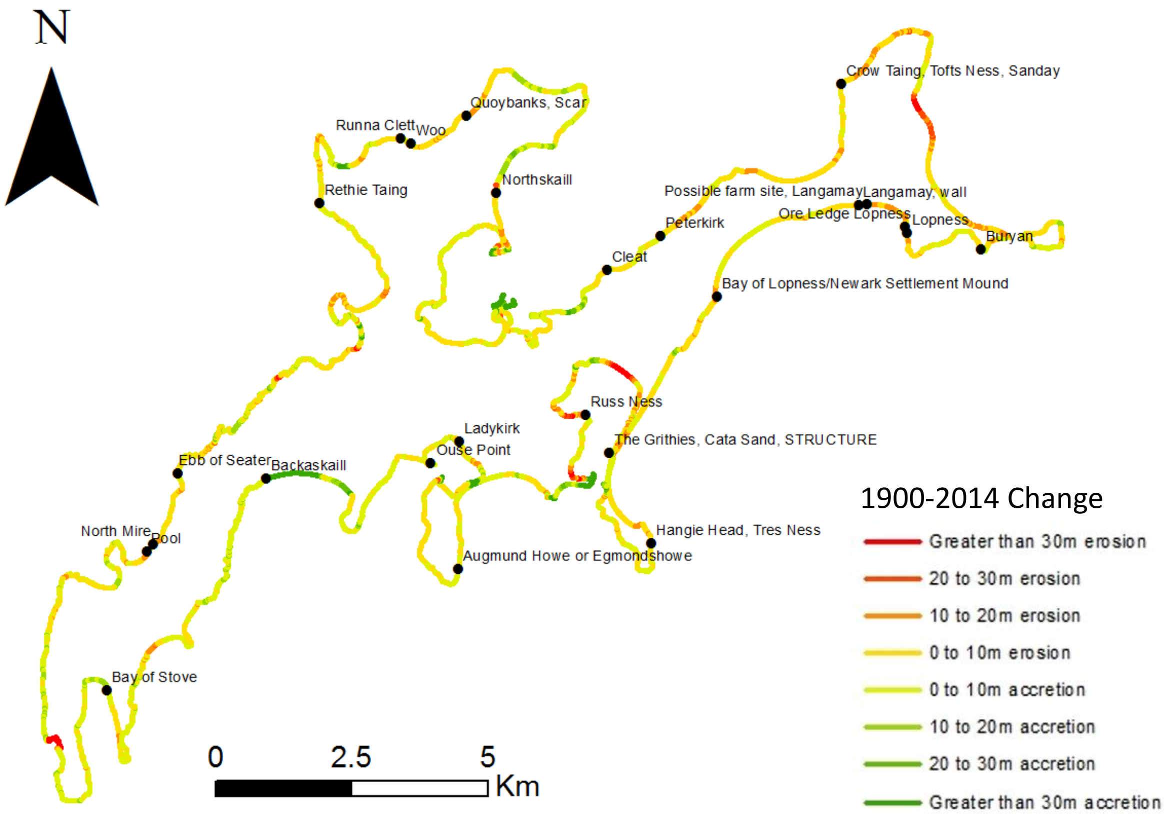

Figure 8: Vegetation Edge Change 1900-2014

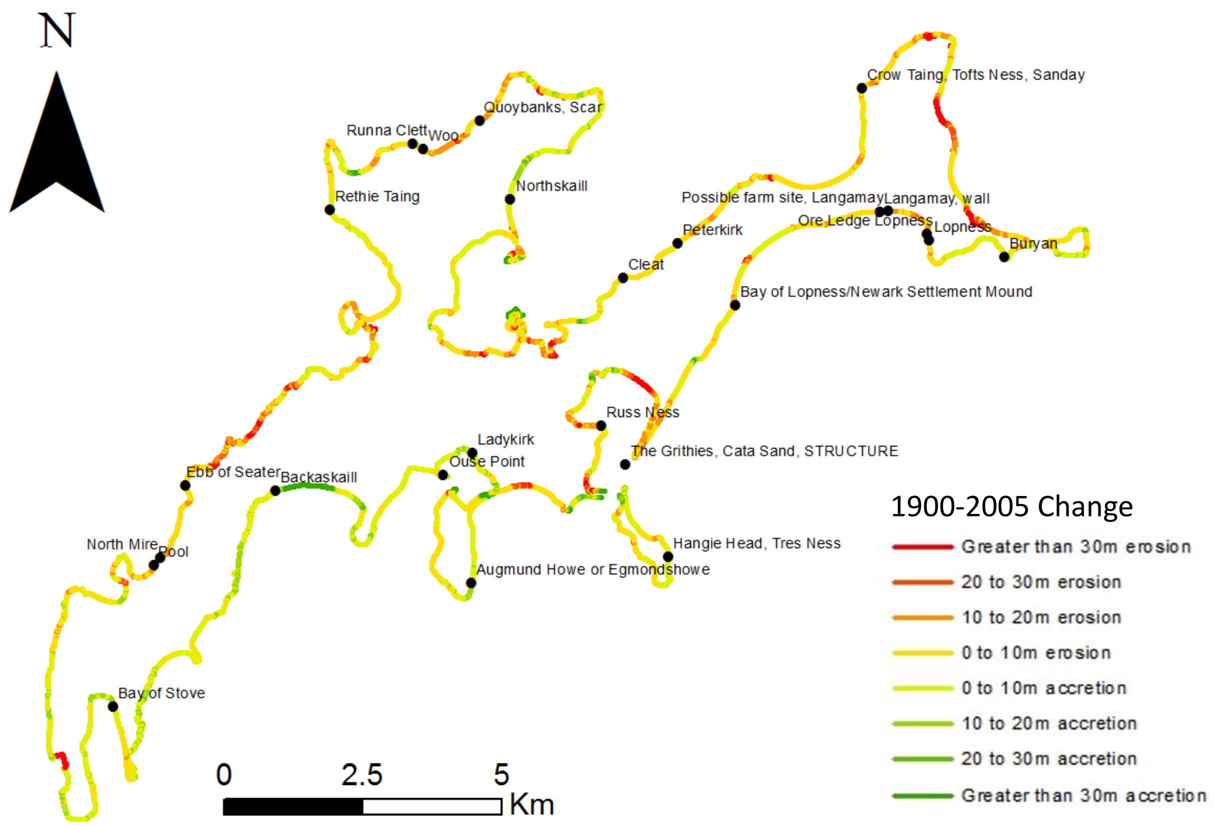

Figure 9: Vegetation Edge Change 1900 – 2005

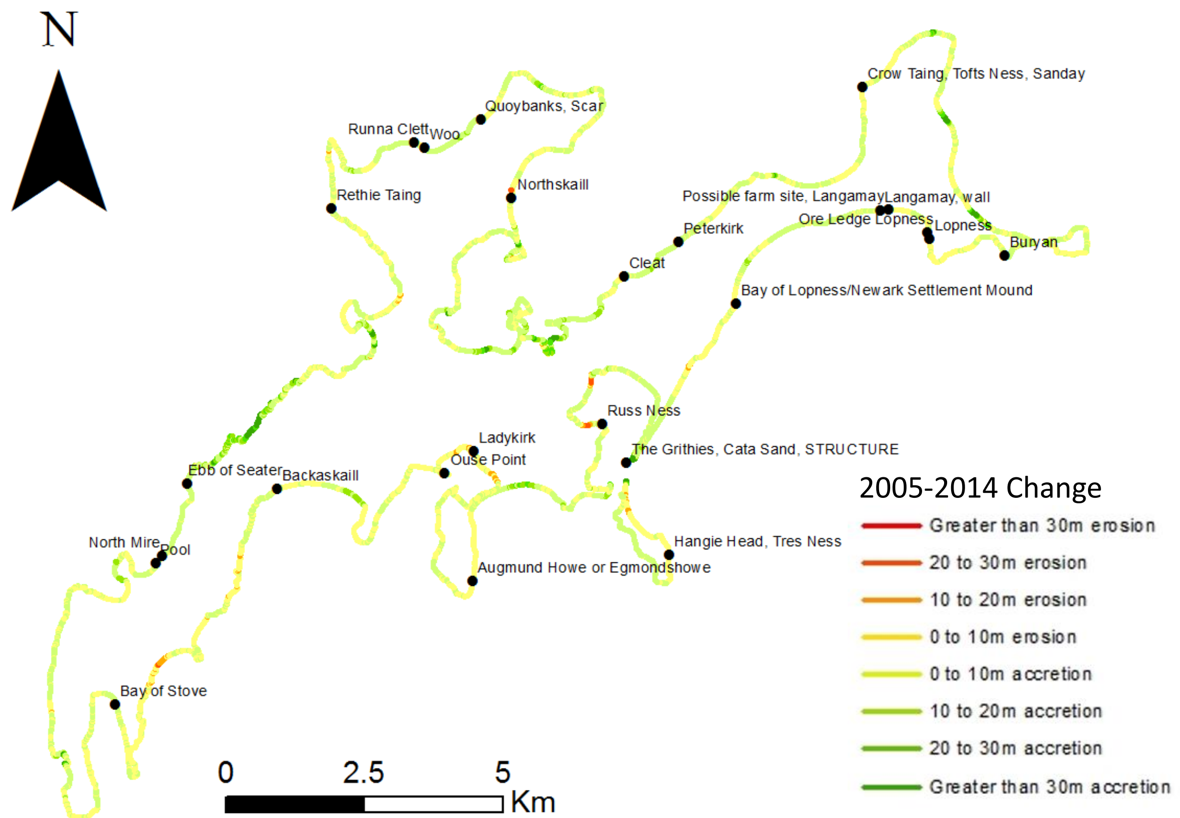

Figure 10: Vegetation Edge Change 2005 - 2014

Although it is not possible to compare vegetation edge change analysis directly with Dynamic Coast MHWS change lines because of the differing time periods considered, some observations can be made. Trends of erosion in the vegetation edge change lines run counter to those shown in the Dynamic Coast change lines. The % of the coast eroding in the vegetation edge analysis is higher in 1900-2005 than in 2005-2014. This is not surprising given the much shorter time interval in the later period. Dynamic Coast analysis shows the % of Sanday's coast eroding between 1890-1970 is lower than over the shorter time period between 1970-modern.

10.3 Discussion

One of the causes of the much lower % of erosion in the Dynamic Coast change lines between 1890 and 1970 compared to the vegetation edge analysis could be due to the issues already discussed; there may be an error associated with the position of the MHWS line but in addition, the MHWS position may not be describing the same processes as the vegetation edge analysis is capturing.

There is also an additional factor which could explain the counter trends between the change lines. Any assessment based on periodic data points may be influenced by antecedent conditions, thus unless the analysis takes very regular measurements it is always imperfect summary or sample of the past changes. It is highly likely that the vegetation edge analysis has captured the impact of the 2005 extreme weather event experienced in January 2005 in parts of Scotland including the Northern and Western Isles. The impact of this event on vegetation edge in the 2005 aerial photography is obvious and appears to have exacerbated erosion predominantly in the western and northern coastlines. The 2005 vegetation edge is clearly landward of the usual vegetation edge due to erosion or concealment beneath sand or storm beach. Therefore, when comparing 1900 to 2005, erosion may be elevated because of the influence of the 2005 data. If aerial photography from 2004 were used to generate the vegetation edge line, we could expect the erosion to be less. When comparing the 2005 and 2014 vegetation edge, the % of eroding coast is much lower because the vegetation edge line in 2014 is further seaward than in 2005-06. This is reflecting the recovery or re-vegetation of areas which have been affected by 2005 storm. Therefore, a trend of accretion will be observed within this time period, even in areas of overall net erosion.

These results underlie the strong influence of extreme weather events upon coastal change and need for caution when calculating rates of coastal change in selected time periods. The short time that has elapsed between the aerial photography shows that dynamic change in the coastline occurs within short time scales. Within a longer time span, there could be multiple cycles of erosion and recovery of coastal vegetation. Thus regular surveys are necessary to avoid any possible sampling bias.

10.4 Results of intersections of priority sites with vegetation edge change lines

Every priority site on Sanday except for the Grithies, which is intertidal, intersects with vegetation edge change lines.

	DC 1890 – 1970		DC 1970 – modern		VE 1900-2005		VE 2005-2014		VE 1900-2014	
	No.	%	No.	%	No.	%	No.	%	No.	%
Priority sites eroding ≥0m	12	55%	16	67%	19	83%	16	70%	18	78%
Priority sites eroding ≥5m	7	32%	5	21%	13	57%	5	22%	9	39%

Table 12: Comparison of the numbers and percentages of priority sites intersecting with each period change line for ≥0m and ≥5m erosion thresholds for Dynamic Coast and Vegetation Edge.

The results show that overall, in every time period, significantly more of the SCHARP priority sites are captured by the vegetation edge change lines showing erosion than are captured by the Dynamic Coast MHWS change lines showing erosion (Table 12).

Priority Sites ≥ 5 m Erosion		
VE 1900-2005	VE 2005-2014	VE 1900-2014
	Augmund Howe or Egmondshowe (6710)	
	Backaskaill (6736)	
Bay of Lopness/Newark Settlement Mound (6681)	Bay of Lopness/Newark Settlement Mound (6681)	Bay of Lopness/Newark Settlement Mound (6681)
Cleat (6827)		Cleat (6827)
Ebb of Seater (6770)		Ebb of Seater (6770)
	Hangie Head, Tres Ness (6689)	
Langamay, wall (12495)		Langamay wall (12495)
Lopness (6674)		Lopness (6674)
Northskaill (6817)	Northskaill (6817)	Northskaill (6817)
Peterkirk (6829)		
Pool (6764)		Pool (6764)
Possible farm site, Langamay (12492)		Possible farm site, Langamay (12492)
Quoybanks, Scar (6806)		Quoybanks, Scar (6806)
Runna Clett (6802)		
Russ Ness (6704)		
Woo (6803)		

Table 13: SCHARP priority sites intersecting with vegetation edge eroding coastlines ≥5 m for each time period.

Bay of Lopness, Newark settlement mound and Northskaill settlement mound are the two examples of priority sites which show erosion for all vegetation edge change lines (Figures 11 and 12). Both are located in unstable blown sand coast edges.

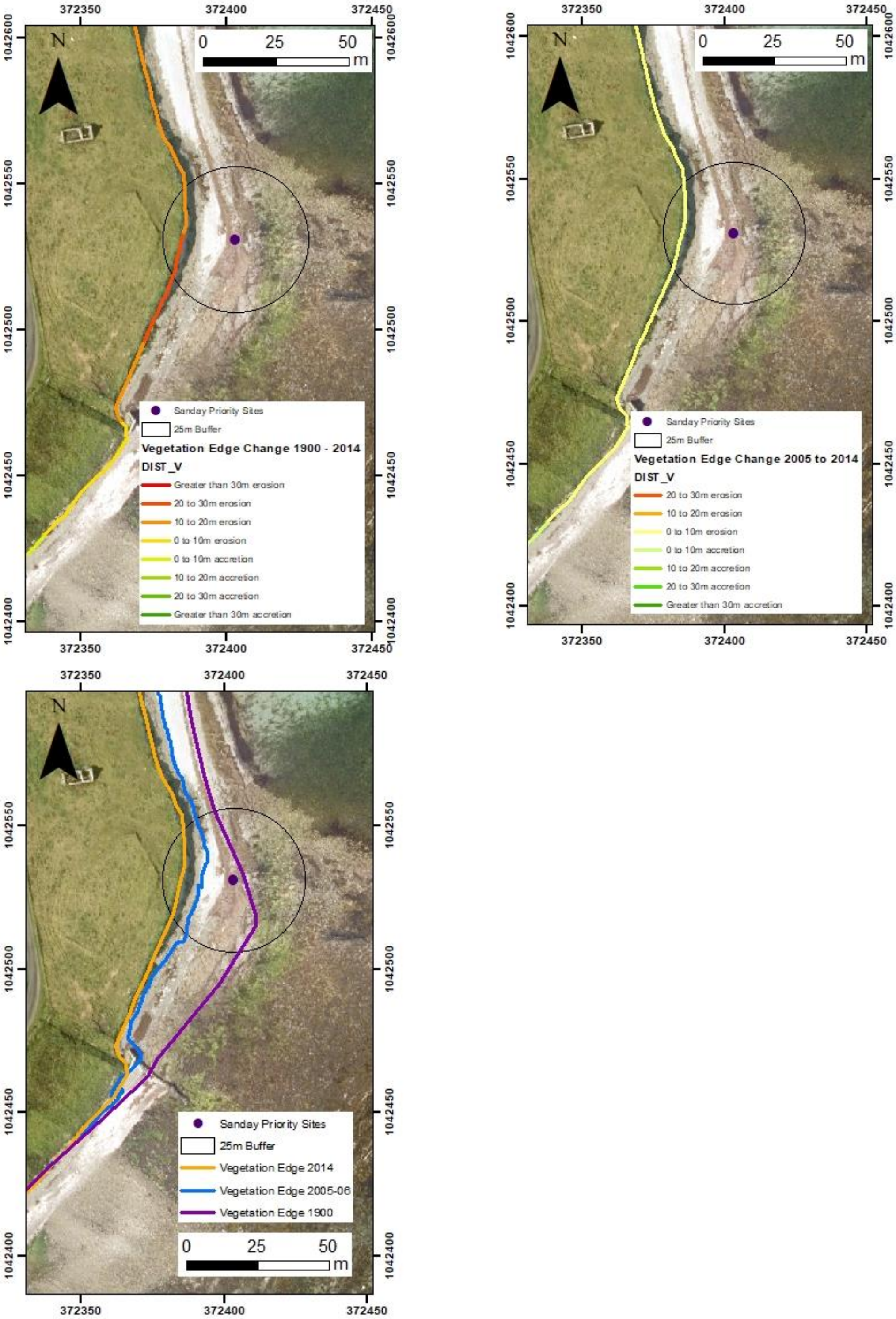

Figure 11: Bay of Lopness (SCHARP ID: 6681) showing erosion between 1900, 2005/06 and 2014.

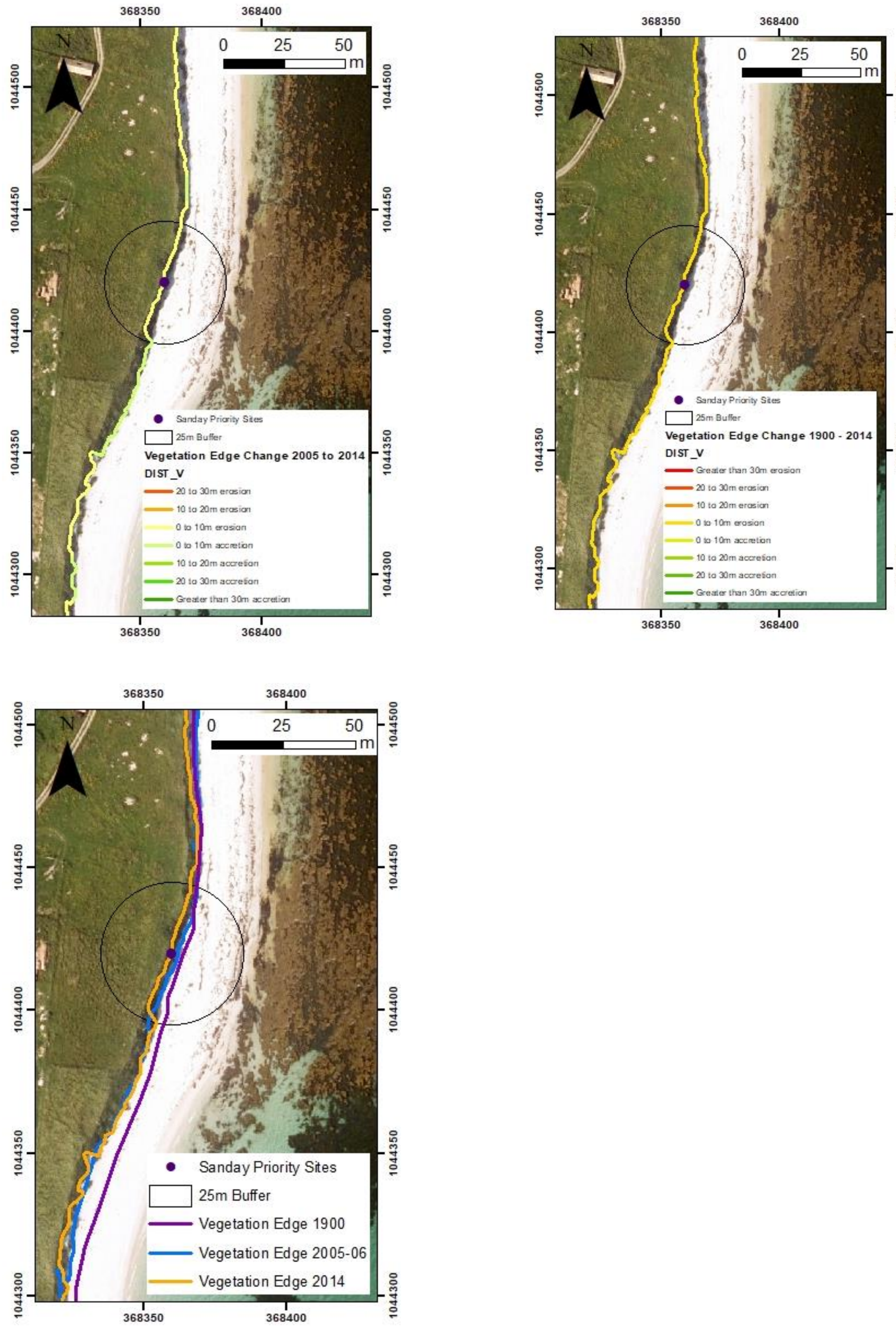

Figure 12: Northskaill (SCHARP ID: 6817) showing erosion between 1900, 2005/06 and 2014.

When a ≥5 m threshold is applied, 16 unique priority sites (70%) intersect with Vegetation Edge change lines of ≥5m erosion from any time period and 11 out of 23 unique priority sites (48%) intersect with Dynamic Coast change lines of ≥5m erosion from any time period (Table 14).

The Vegetation Edge change lines, therefore, more successfully reflect the observed erosional status of the validation dataset.

Vegetation Edge ≥ 5 m Erosion	Dynamic Coast MHWS ≥ 5 m Erosion
Augmund Howe or Egmondshowe (6710)	
Backaskaill (6736)	
Bay of Lopness/Newark Settlement Mound (6681)	Bay of Lopness/Newark Settlement Mound (6681)
Cleat (6827)	Cleat (6827)
	Crow Taing (12218)
Ebb of Seater (6770)	Ebb of Seater (6770)
Hangie Head, Tres Ness (6689)	
Langamay, wall (12495)	Langamay, wall (12495)
Lopness (6674)	Lopness (6674)
Northskaill (6817)	Northskaill (6817)
Peterkirk (6829)	
Pool (6764)	
Possible farm site, Langamay (12492)	Possible farm site Langamay (12492)
Quoybanks, Scar (6806)	Quoybanks, Scar (6806)
Runna Clett (6802)	Runna Clett (6802)
Russ Ness (6704)	
Woo (6803)	Woo (6803)

Table 14: Comparison between Dynamic Coast MHWS and Vegetation Edge of unique SCHARP sites intersecting with eroding coastlines ≥ 5 m from any change line period.

11. Comparison of Results

CESM≥60	CESM≥60 with superficial deposit filter disabled	Veg Edge ≥5m erosion unique sites any period	DC MHWS ≥ 5m erosion unique sites any period
	Augmund Howe or Egmondshowe	Augmund Howe or Egmondshowe	
	Backaskaill	Backaskaill	
Bay of Lopness/Newark Settlement Mound	Bay of Lopness/Newark Settlement Mound	Bay of Lopness/Newark Settlement Mound	Bay of Lopness/Newark Settlement Mound
Bay of Stove	Bay of Stove		
	Buryan		
	Cleat	Cleat	Cleat
Crow Taing, Tofts Ness	Crow Taing, Tofts Ness		Crow Taing, Tofts Ness
	Ebb of Seater	Ebb of Seater	Ebb of Seater
	Hangie Head, Tres Ness	Hangie Head, Tres Ness	
Langamay, wall	Langamay, wall	Langamay, wall	Langamay, wall
	Lopness	Lopness	Lopness
	North Mire		
Northskaill	Northskaill	Northskaill	Northskaill
Ore Ledge Lopness	Ore Ledge Lopness		
Ouse Point	Ouse Point		
	Peterkirk	Peterkirk	
		Pool	
Possible farm site, Langamay	Possible farm site, Langamay	Possible farm site, Langamay	Possible farm site Langamay
Quoybanks, Scar	Quoybanks, Scar	Quoybanks, Scar	Quoybanks, Scar
	Runna Clett	Runna Clett	Runna Clett
		Russ Ness	
	Woo	Woo	Woo
39% (9)	87% (20)	70% (16)	48% (11)

Table 15: Results of intersection of each modelled method with priority sites on Sanday

Table 15 summarises the performance of each model in their agreement with empirical records of coastally eroding archaeological sites on Sanday. The threshold of ≥5m has been applied to change lines so that vegetation edge can be compared with Dynamic Coast.

- The poorest agreement is with CESM high and very high susceptibility (39% agreement). This may be due to the limitations of the superficial thickness deposit filter as discussed previously, as well as difficulty with applying a relatively coarse 50m resolution raster model to local scale sites.
- The best agreement is between the priority sites and the CESM ≥ 60 with the superficial deposit filter disabled (87% agreement). However, this may be due to this iteration of the model overstating the erodibility of the coast edge.

- Vegetation edge appears to be performing significantly better than MHWS in agreement between priority sites and eroding coastlines. This is mostly likely due to the close (physical and process) proximity of vegetation edge and eroding archaeological sites. It may also be due to historic mapping discrepancies in the position of the MHWS for Sanday. The position of the MHWS line in the intertidal zone also reduces the capability to intersect with coast edge assets, in all but the most extreme cases of erosion.

12. Conclusions

- The best agreement between a single model and the priority SCHARP sites is the CESM with the superficial deposit filter removed (87% agreement). This improved upon the original CESM which had an agreement of 39% between SCHARP sites and high or very high susceptibility to erosion. The only difference between the two models is the removal of the superficial deposit filter.

- The next best agreement is between the priority SCHARP sites and the vegetation edge analysis, which displays a 70% agreement between the SCHARP sites and erosion of ≥ 5m (based on any time period studied).

Additional general conclusions drawn from the study are that:

- The anomalously high accretion on Sanday between 1890 and 1970 shown on Dynamic Coast change lines may point to issues with the mapped position of historic MHWS in this region.
- Vegetation edge analysis is good at identifying impacts of weather events and the vegetation edge change lines describe well how coastlines can erode and recover over short periods, however the methodology implemented in this study would currently be challenging to replicate on a national scale.
- The Coastal Erosion Susceptibility Model and Dynamic Coast/Vegetation Edge change lines are complimentary approaches, and together have enormous potential for management of coastal assets. The CESM identifies susceptible coastlines at a national and regional scale, and comparisons of vegetation change lines describe and help us understand more local changes over different time periods.
  The next step is to build upon these strategic cornerstone projects to achieve refinements that improve their performance, spatially and temporally.

13. Recommendations for Future Work

1. Differentiation of site extents for future analysis

Creation of polygon boundaries for priority sites to refine each individual archaeological extent would improve the fidelity of the predictions (i.e. is the site the size of a single building or potentially a much larger collection of archaeological buildings/finds).

2. Obtain 1970s Aerial Photography for Vegetation Analysis

Vegetation Analysis of 1970s Aerial photography was not possible within the time frame of this study. Aerial photography does exist for this time and is held in physical storage at National Collection of Aerial Photography (NCAP).

Finding Aid Reference	Bar Code	Sortie	Date
SCOT FD_S_HY_64_74-00	SB_004543	OS/71/0384	19/07/1971
SCOT FD_S_HY_64_74-00	SB_004470	OS/71/0250	29/05/1971
SCOT FD_S_HY_63_73-00	SB_004467	OS/71/0092	24/04/1971
SCOT OS_05_02	SB_004510	OS/71/0486	29/05/1971

Table 16: NCAP records of 1971 aerial sorties for Sanday

Ideally, a further vegetation edge change line would be created using the aerial photography from 1971. This would allow a much better comparison between the Dynamic Coast change lines and the Vegetation Edge change lines.

3. Further investigate the effect of the superficial deposit filter

A lack of time meant that we were not able to explore refinements that could be made to the CESM to improve its performance (for Sanday).

4. Apply this study to another region

Scotland’s coastline is very variable and no one area is typical of another. We should repeat this analysis for a different case study region.

5. Vegetation edge capture and Streamlining of vegetation edge digitisation

The development of a semi-automated or more time efficient manual extraction of vegetation edge from aerial imagery would greatly enhance the predictability of archaeological exposure models. Whilst the pixel size of free satellite imagery limits the utility, commercial providers are able to offer satellite imagery of sub-metre scale which may offer opportunities for future vegetation edge analysis. The author also notes broader developments regarding NDVI and NDWI within (and beyond) the Dynamic Coast project.

A database of historic and recent vegetation edge surveys can also be updated via ground survey. Both the Sharp and Dynamic Coast teams are using GPS surveys to update the position in numerous areas. This is a complimentary technique which should be continued.

6. Reverse engineer the analysis

Use the different models to identify areas of coastline where eroding sites should be present and carry out a survey to test this on the ground. In this study, we have used SCHARP priority sites as a validation dataset because we have up to date condition surveys and know these sites are definitely experiencing significant erosion. However, there are many more coastal heritage sites that may be eroding that we have not included because of lack of recent condition surveys.

14. References

Fitton, J.M., Hansom, J.D., and Rennie, A.F. (2017) Dynamic Coast - National Coastal Change Assessment: Methodology, CRW2014/2. http://www.dynamiccoast.com/files/reports/NCCA%20-%20Methodology.pdf (Accessed 11 April 2019)

Fitton, J. M., Hanson, J. D., and Rennie, A. F. (2016) A national coastal erosion susceptibility model for Scotland, *Ocean & Coastal Management*, 132, 80-99.

Hambly, J. (2017) *A Review of Heritage at Risk from Coastal Processes in Scotland: Results from the Scotland's Coastal Heritage at Risk Project 2012-2016*. Unpublished SCAPE report. http://scharp.co.uk/media/medialibrary/2018/02/Review_of_Coastal_Heritage_at_Risk.pdf (Accessed 21 Jan 2019)

Moore, H. and Wilson, G. (1999) Orkney Coastal Survey 1999: Sanday & North Ronaldsay. Unpublished report. Historic Scotland

APPENDIX A: Confidence/Error of digitised vegetation edge line

Interpretation of Vegetation Edge

When interpreting the vegetation edge from OS maps, there is not one single line which is defined as "vegetation edge", but instead the edge of vegetation is denoted by numerous different polylines such as rocky cliffs, upper and lower slope lines, the MHWS line if it hugs the coastline and in some cases field boundaries which extend right to the coast edge. As a result, there is a certain level of interpretation of vegetation edge from the OS maps which needs to be undertaken, and this remains a limitation of digitising vegetation edge from OS maps.

Scale of digitisation

When digitising the vegetation edge line, the scale of the maps was kept in the region of 1:800 as this was deemed a suitable scale to capture the vegetation edge. Setting the maps at a larger scale would mean a more detailed vegetation edge line; however this could result in artificial erosion or accretion as the OS maps do not have the same level of detail. If when digitising the map is set to too small a scale, the digitised line could miss out on detail that would be depicted in the OS maps and could miss areas of genuine erosion/accretion.

Seasonality implications for aerial survey imagery

The method of digitising vegetation edge from aerial photography may be affected by seasonal differences in vegetation cover. If, for example, the 1970s OS map is based from photography flown in winter, and the 2014 aerial survey photographs were collected in August then there could be increased vegetation at the coast edge in the later photographs purely due to seasonal variation. This could have the effect of indicating accretion where there is none or masking the effects of erosion.

The three sets of photography used in this analysis were not acquired at the same time of year. The 2005 imagery was collected on 26th April, the 2006 imagery was collected on 23rd September, and the 2014 imagery was collected on 5th August. This same limitation could be present when comparing vegetation edge of OS maps as they may have been mapped at different times of the year, and unless aerial photography can be obtained on the same day over a number of years there will always be the potential limitation of seasonality.

5m Significance Threshold on vegetation change lines

In this analysis we have focused on erosion changes >5m so they can be compared to the Dynamic Coast MHWS change lines and to exclude potential small scale calculations of erosion which may be due to scale issues and interpretation of the vegetation edge.