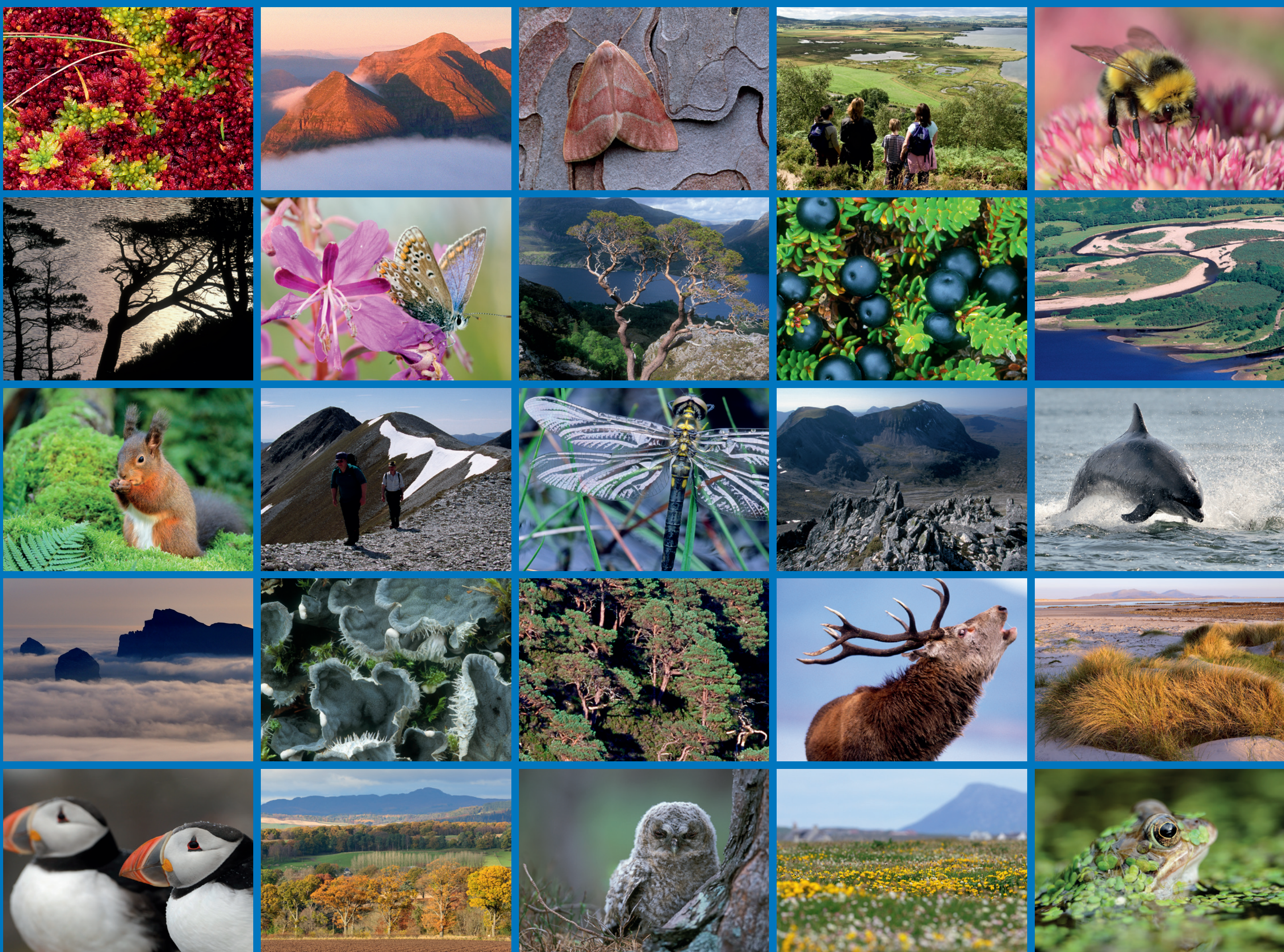
Scottish Natural Heritage
Commissioned Report No. 927

Morrich More coastal change analysis 1987 to 2015



COMMISSIONED REPORT

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Morrich More coastal change analysis 1987 to 2015

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Summary

Morrich More coastal change analysis 1987 to 2015

Commissioned Report No. 927
Project No: 016339
Contractor: Dr Thomas Dargie
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Keywords

Coastal habitat change; relative sea-level rise; lunar nodal cycle; saltmarsh; road impacts; coastal squeeze; ordination analysis.

Background

Morrich More is a unique UK coastal site created over 7000 years by isostatic rebound, producing a very extensive suite of emergent landforms. However, rising sea level and a likely slow-down of rebound in the Inner Moray Firth have led to a possible switch from emergent to submergent conditions. This would reflect Scotland-wide changes in relative sea-level rise (RSLR).

This project examines existing habitat survey information for Morrich More. It uses a combination of desk-study, permanent quadrat analysis, 2015 field checks of 1988 vegetation sample locations and tidal modelling to seek and explain change in habitat over time. Research concentrates on saltmarsh but also includes transition to dune, a scarce saltmarsh feature in Scotland which is frequent within this site as a small proportion of saltmarsh extent. Change is assessed as evidence of RSLR.

Main findings

The following conclusions summarise findings on habitat change at Morrich More.

- There is strong evidence of fresh groundwater forcing affecting the inner upper edge of saltmarsh where it is close to the remarkable dune slack complex of Morrich More. Well-developed brackish swamp is best developed in the north of the outer strandplain. Drier forms which are probably just beginning the transition to brackish swamp are now appearing inland of the Blue Pool area. Brackish swamp and transitions to dune slack are also present as part of a very clear wetness gradient identified in a separate set of saltmarsh permanent quadrats. Brackish swamp also occurs in saltmarsh fringing the centre of Inver Bay. It is not developed strongly in the Fendom area where it ought to occur due to dune slack proximity; this area of marsh is artificially drained by deep ditches, probably preventing swamp development.
- Tidal modelling suggests that the 18.61-year lunar nodal cycle is responsible for most recent sea-level change at Morrich More. Models adjusted to include eustatic sea-level

rise and isostatic fall modify the lunar nodal cycle signal slightly, but it remains the strongest component of sea-level change.

- The lunar nodal cycle signal has been detected as a major response of vegetation within permanent quadrat data. It is a clear signal over time within strong elevation and wetness gradients which structure Morrich More saltmarsh. This is the first time that a lunar nodal signal has been identified in UK and European saltmarsh vegetation science. Its strength suggests that this factor is much more important in saltmarsh development and change than its contribution to tidal range would indicate.
- 2015 was a lunar nodal minimum period with the tidal peak in October. 2015 observations will have been affected by higher average sea levels. Much of the 2015 evidence for a rising sea level in 1988 quadrat revisits is probably due to the lunar nodal effect.
- Vegetation trends (elevation and wetness) compared with tidal models suggest that an additional eustatic sea-level rise component is uncertain in vegetation signals. It might be present but it is small compared to the lunar nodal cycle and cannot be separated at present using vegetation data.
- Vegetation analysis has also detected a strong and locally extensive effect from a road constructed as part of a pipeline flowbundle launching corridor which was operational between 1990 and 2006. The road acted as a partial tidal barrier, interrupting tidal currents and sediment delivery across the outer strandplain between Blue Pool and Inver Bay, inside Patterson Island.
- A descriptive geographical model of Morrich More saltmarsh and foredune habitat change is developed which includes various lines of evidence established by this study. The model infers that all parts of the saltmarsh and foredune zone are experiencing change.

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Table of Contents **Page**

Acknowledgements

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1. INTRODUCTION

1.1 Background

The low-lying coastal plain of Morrich More (Ross-shire) has been advancing seawards for at least 7,000 years (Hansom 2003), extending more than 7 km from the foot of a raised Postglacial cliff line. The rear of the area has an altitude of 8 mOD and elevation falls very gently to its north-eastern edge at about 2 mOD. Morrich More is a large strandplain, a low-lying soft-coast system which captures and stabilises sediment as intergrading saltmarsh, strand and low frontal dune habitats within the intertidal and immediate supratidal zone. Isostatic rebound since 7000BP has produced alternating sequences of long (1 – 2.5 km) narrow wet depressions (former saltmarsh) and convex rises (former frontal dune). These are orientated at right angles to the seaward gradient, in a near-continuous sequence which forms a descending staircase falling about 6 m over 7 km towards the north-east. The current MHWS (1.98 mOD, Fitton *et al.* In prep.) delimits two offshore tidal islands, Innis Mhor and Patterson Island. It also demarcates an important tidal inlet between them called Blue Pool (Figure 1).

A long fetch down the Kyle of Sutherland exposes the north-western side of the strandplain to edge erosion. Predominant westerly winds here have also been sufficiently strong to develop a set of parabolic dunes, now mainly stabilised by forestry plantation. Sand originally derived from the parabolic dunes and other former frontal dunes extends across the centre of the site and has largely buried the chronosequence of gentle rises and hollows. The age order of habitats, geomorphology and soils is therefore best seen in the inner and outer parts of the site.

The erosional western shoreline carries sediment north-east where it accretes as a mix of dune, strand and sandy saltmarsh. A comparison of the coastal edge of Morrich More mapped in 1988 (Dargie 1989) and again in 2003 using DGPS (Dargie 2003) suggested that 72 ha of erosion (in the west, along the outer edge of Innis Mhor and within the Blue Pool area) resulted in the formation of 138 ha of new habitat, much of it saltmarsh inside Innis Mhor and around sheltered extremities of Patterson Island. In a maximum of 15 years, each 1 ha of erosion therefore produced 2 ha of new habitat within the outer strandplain. The frontal dunes in 1988 were particularly diverse and dominated by sea lyme-grass *Leymus arenarius*. These developed irregularly at first as nebkha dunes (steep-sided small dune hummocks) which formed clusters on the crest and the immediate rear of overwash fans. They then aggregated and evolved into large concentric dune-ridge rings. In places these rings in turn coalesced and were then fronted by parallel foredune lines developing seawards above the strand. Dune development in this manner involving *Leymus arenarius* (as opposed to *Ammophila arenaria*) is probably rare in Britain, particularly concentric ring structures.

Overall, the long-term effects of edge erosion and accretion over millennia have led to Morrich More migrating eastwards and seawards as a trapezoidal feature (Hansom 2003). Inver Bay has developed as an elongate estuary along the south-eastern side of the enlarging trapezium, maintained by freshwater flow via the Fendom Burn at its head and tidal currents at its mouth. The Fendom drainage system has been artificially improved within the last century by a network of deep cut drains running into the centre of the strandplain. The course of the Fendom Burn is artificially straightened for the head of its tidal sector.

Former saltmarsh elevated by isostatic uplift has developed into a very large expanse of accretionary dune slack (Figure 2). The extent of this is 458 ha based on 1988 mapping (Dargie 1989), plus 89 ha of transitional grassland marking upper saltmarsh in transition to dune slack and drier dune grassland. The transitional grassland is found on three sides of the slack expanse, above the largest extent of saltmarsh in the Highlands (505 ha based on

2003 mapping). The dune slack area is particularly significant in a UK context because it is larger than that for all of England (463 ha, based on data in Radley 1994) and is two-thirds of dune slack area in all of Wales (670 ha, Blackstock *et al*. 2010). It is extraordinary to find such an extent of slack in a single site and previous UK accounts of dune vegetation have not recognised the significance of Morrich More in this respect. The slack vegetation is a poor fit with most types described in the National Vegetation Classification (Rodwell 2000) and is notable for good chronosequences, large amounts of juniper *Juniperus communis* and short-distance variability closely related to height above the watertable (Dargie 1989).

Habitat development reflects the geomorphological evolution of the site apart from the innermost sectors where agriculture, a golf course and a WWII airfield have modified the ground. A pipeline (flowbundle) launching corridor was constructed in 1990 and much of its 5 km length ran within Morrich More SSSI across saltmarsh. The corridor was 15 m wide and constructed of stone chunks laid over a fabric geotextile. The outer 5 m of width was raised by about 1 m above marsh level and used as a road. Stone plinths were installed for supporting 5 km lengths of pipe prior to launching to sea via a winch and temporary breach in frontal dunes. Culverted sections were installed in creeks and over a mudflat sector to maintain tidal flow. The corridor operated for about a decade but there were no launches after 2001. Culverts and stone in creeks and over mudflats were removed in 2006. At the same time, the height of the remaining corridor was reduced by stone removal to be level with adjacent saltmarsh. This avoided disturbance to compacted sediment under the weak fabric geotextile. Environmental monitoring was required for the corridor and adjacent ground, as a condition for planning consent. This mainly focussed on tidal and groundwater effects of the road as a partial tidal barrier, sediment redistribution around culverts, plus additional monitoring of saltmarsh vegetation and birds.

1.2 Purpose of the report

There is no other UK coastal site resembling Morrich More. The main factor responsible for its unique characteristics has been isostatic rebound, producing a very extensive suite of emergent landforms. However, rising sea level and a likely slow-down of rebound in the Inner Moray Firth has led to a possible switch from emergent to submergent conditions, reflecting Scotland-wide changes in relative sea-level rise (RSLR) (Rennie & Hansom 2011).

This project is a follow-up of an earlier case study featuring the Dornoch Firth, in which Morrich More was forecast to be exposed over coming decades to increased levels of erosion and flooding (DEFRA 2012). The earlier study considered erosion and frontal recession along the north-east frontal edge of Morrich More to be the most extensive erosion in the last 7,000 years. This geomorphological response was reworking eroded sediment towards the dune interior. An example of ecological adjustment was quoted as numerous examples observed in 2009 of pioneer saltmarsh species invading the lower edges of mature sand dune habitats.

If this geomorphological interpretation is correct, erosion is now occurring across parts of the site, particularly Innis Mhor, where long-standing accretion was the dominant process three decades ago. This might be the start of a new phase of landform development, marking the end of an 'isostatic honeymoon' for this part of the Scottish soft coast. Isostatic rebound (glacio-isostatic adjustment) around Scotland has a centre around Rannoch Moor and rates decrease outwards in the form of an elliptical dome. Estimated rates on the coast of this uplift dome are now considered to lag behind rates of RSLR in two separate recent studies (Rennie & Hansom 2011; Teasdale *et al.* 2011).

Whilst there is geomorphological evidence of increased erosional conditions on outer Morrich More, there has been no recent detailed scrutiny of consequent ecological change. The ecological response is therefore less clear. This project aims to establish if there is evidence of sea-level driven ecological change within existing site survey and monitoring information. Some of that information was summarised by Dargie (2007a) in a brief overview. Further review and analysis are applied here, up-dating data sets where necessary and adding new information where possible and relevant.

Any evidence for ecological change also needs to consider time lags within coastal systems, as part of changes in key drivers which might now be operating (sea-level change and increasing rainfall). The changes include geomorphological processes (erosion replacing longstanding accretion) and ecological responses (changes in habitat type and distribution, as well as changes within habitat type).

The lag between morphological and ecological change is poorly understood. Conceptually, several habitat responses are possible: loss and expansion (reflecting erosion and accretion), change in internal saltmarsh character, conversion of dune to saltmarsh in transition zones, even perhaps conversion of saltmarsh to dune following sediment accretion and reworking by wind as dune sand. Morrich More is particularly important for investigating potential changes because it contains diverse and extensive transition zones between saltmarsh and dune (Dargie 1989). These zones are likely to be sensitive to changes in key drivers. Overall, the site, in theory, is an unrivalled UK test bed for research into change as soft coast moves from emergent to submergent conditions.

1.3 Themes of interest

A meeting with SNH staff was held early in the project programme. This identified three themes of interest to SNH. These were:

i. Theme I: evidence in available habitat data for freshwater forcing of groundwater affecting the higher parts of saltmarsh. This is the result of fresh water from higher ground (dune slacks or other adjacent habitats) entering the upper inner parts of saltmarsh, either by groundwater seepage (flushing) or, rarely, overland flow. If this process becomes a constant or strong seasonal feature over time, it converts saltmarsh to dune slack or swamp. This process might be driven by increased rainfall;

ii. Theme II: evidence for RSLR in available habitat data of dune and saltmarsh erosion;

iii. Theme III: evidence of change in saltmarsh vegetation elevation resulting from RSLR, particularly the conversion of dune habitat to saltmarsh.

Together, if identified, evidence for these themes would imply 'coastal squeeze' of Morrich More saltmarsh, an area almost without sea walls or embankments which elsewhere act as the usual physical limit to saltmarsh movement inland as a response to rising sea level. An inner boundary of dune slack or swamp could have the same effect as a sea wall. In the long-term saltmarsh area could be reduced by removal along its outer edges via erosion, creating the squeeze effect. In addition, there would be modification of dune and saltmarsh character within those bounds.

A fourth additional theme was added later in the programme as interpretation of available site information evolved. Only one data set provided a detailed source of vegetation change over time, permanent quadrats installed in 1987 and recorded in 14 years between 1987 and 2013 (a 26-year period). This set provided a very clear understanding of two saltmarsh gradients (elevation and drainage) in work under Theme III. However, the quadrat layout in 1987 was designed to check for the effects of pipeline corridor construction on the vegetation of adjacent saltmarsh habitat. Further work was therefore needed to clarify potential road effects as a partial tidal barrier and its interactions with other factors affecting vegetation change. This was particularly important for use of the data set as a vegetation indicator of sea-level change over the past three decades. Road effects could complicate or completely obscure sea-level change information. The following theme was therefore added to the programme:

iv. Theme IV: Assessment of road corridor impacts on saltmarsh vegetation.

Figure 1. Satellite image of Morrich More strandplain
1 km national grid lines shown in faint yellow.
© Google Earth and Digital Globe, scene date 31 January 2009, mid- to high tide with supratidal ground frozen.
Key features in geomorphological development and dates from Hansom (2003), SSSI boundary courtesy of SNH (© Crown copyright and database right 2016. Ordnance Survey 100017908).

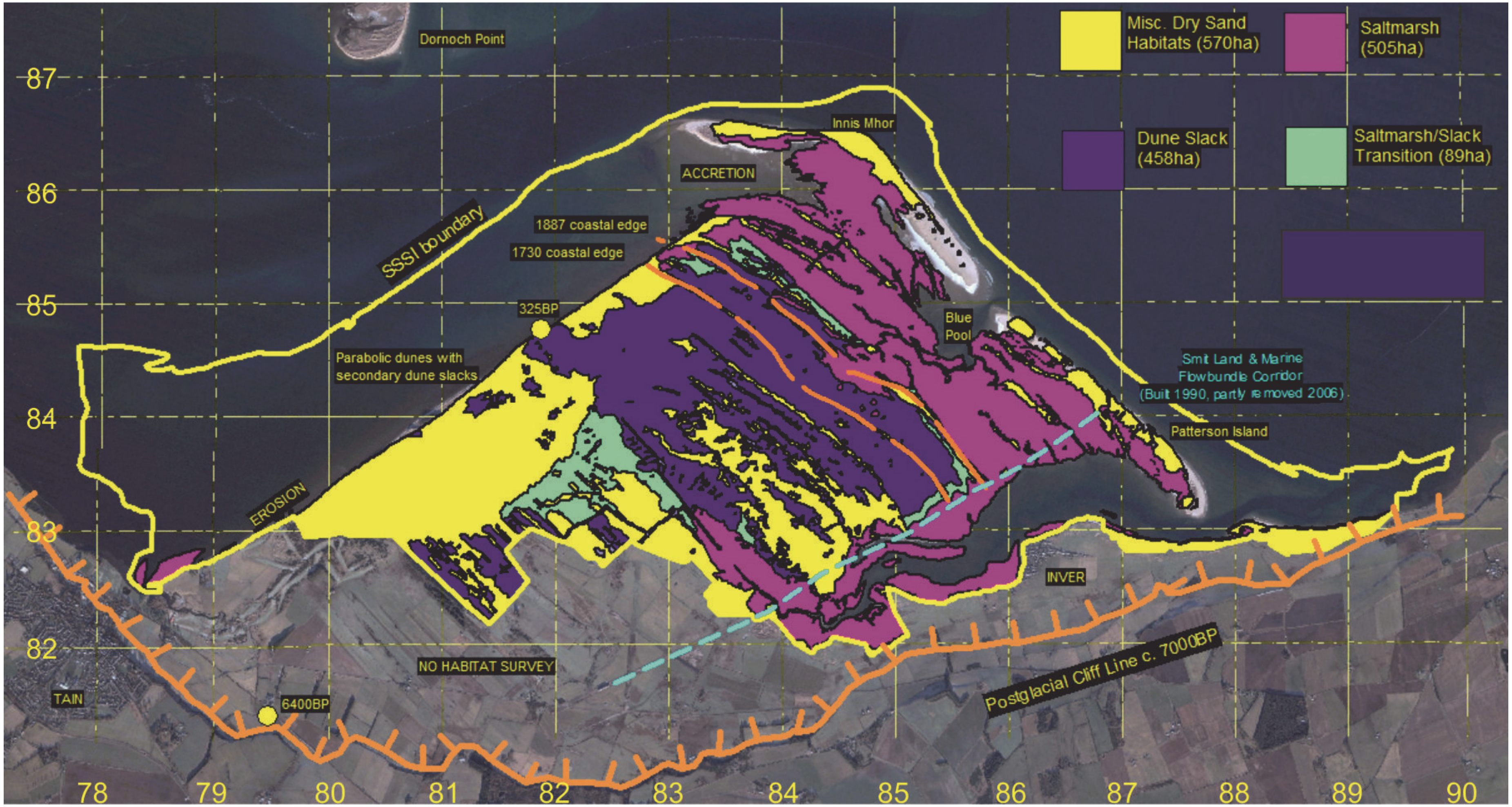


Figure 2. Morrich More SSSI habitats superimposed on satellite image of Morrich More strandplain

1 km national grid lines shown in faint yellow.

© Google Earth and Digital Globe, scene date 31 January 2009, mid- to high tide with supratidal ground frozen.

Sources: SNH Sand Dune Vegetation Survey of Scotland, Dargie (1989), Dargie (2003). Key features in geomorphological development and dates from Hansom (2003), SSSI boundary courtesy of SNH (© Crown copyright and database right 2016. Ordnance Survey 100017908).

1.3.1 Theme I: Freshwater forcing

The best ecological evidence of freshwater forcing is the new development and/or an increased extent of brackish and fresh wetland conditions along the inner edge of saltmarsh, including examples of upper saltmarsh being converted to dune slack or brackish swamp since the habitat survey in 1988. These changes are not necessarily the result of RSLR. Indeed, they must have occurred throughout emergent times to form the very large Morrich More expanses of accretionary dune slack from former saltmarsh. The continuation of this process is important for the site but the threat of 'squeeze' upon the saltmarsh component of site features is also key. A search for increasingly brackish conditions along the inner edge of saltmarsh is therefore one part of this work.

1.3.2 Theme II: Saltmarsh and dune erosion

Evidence of saltmarsh and dune loss is to be made using existing site information and relevant digital data sources. Likewise, information on accretion is needed as an indication of continued soft sediment capture, both as new dune and new saltmarsh. The balance between erosion and accretion, if that can be estimated, is particularly important.

1.3.3 Theme III: Changing saltmarsh elevation and conversion of dune to saltmarsh

Site vegetation maps, old quadrat location re-visits and permanent quadrat data are to be considered as evidence of change and potential support for RSLR. A RSLR scenario includes alteration to lower saltmarsh types and the conversion of former dune to saltmarsh, following submergence. If emergent conditions are still dominant within this site, there will be little or no evidence of saltmarsh altering to higher types or changing to dune habitat.

1.3.4 Theme IV: Assessment of road corridor impacts on saltmarsh vegetation

Permanent quadrat analysis results are examined for evidence of pipeline road corridor impacts on saltmarsh vegetation. The road corridor operated between 1990 (year of construction) and 2006 (year of restoration). Permanent quadrat sets are available for 1987, 1991 to 2001 inclusive, 2006 and 2013. The effects of the road on vegetation as a partial tidal barrier is assessed, particularly its potential to obscure trends driven by submergence or emergence.

1.4 Author’s coastal habitat experience

The author is a habitats ecologist with 25 years of experience in survey using the UK National Vegetation Classification. His coastal interest started with photogrammetric mapping of sand dune vegetation change in 1969. He produced the first detailed account of Morrich More vegetation (Dargie 1989), has written Joint Nature Conservation Committee dune inventories for Scotland and Wales, as well as producing the Sand Dune Vegetation Survey of Scotland for Scottish Natural Heritage. He has also undertaken large NVC saltmarsh surveys of macrotidal estuaries and coast for other national conservation agencies (Severn, Dee, North Lincolnshire).

2. METHODS

2.1 Themes of interest and available data

Existing Morrich More environmental information was collated for the three initial themes of interest. This included unpublished monitoring documents supplied to The Highland Council and SNH under planning conditions for the pipeline corridor (CEMP 1991; AURIS 1992a, b, 1993a, b, 1994a, b; RSK Environment Ltd. 1995, 1996, 1997, 1998, 1999, 2000, 2001, 2002). Hydrology, tide, permanent vegetation quadrats and annual bird surveys were the focus of monitoring. Most reports are at least ten years old and were reviewed for SNH in Dargie (2007a). A re-survey of permanent quadrats established in 1987 was funded by the corridor developer in 2006, at the time of restoration. A more recent 2013 re-survey of permanent quadrats has also been produced (Dargie 2013).

Digital datasets covering Morrich More SSSI were also supplied by SNH: LiDAR elevation data (2012 1m pixel image data, date of overflight uncertain but between September 2011 and March 2012, assumed here to be 2012); ortho-rectified colour aerial photography flown 12 May 2009 (source: copyright GetMapping, provided under One Scotland Mapping Agreement OSMA), and site NVC GIS data produced as part of the SNH-SEPA Saltmarsh Survey of Scotland (SSS) (Haynes 2016). Morrich More saltmarsh was surveyed in August 2011 as part of the SSS. Digital vegetation boundary data for a 1988 NVC survey of Morrich More SSSI (Dargie 1989) was already available to the author of this report. Satellite imagery available using Google Earth was also consulted.

2.2 Theme I: Freshwater forcing

Evidence of continued or increasing freshwater influence along the inner edge of saltmarsh would be the continued presence or an increase in area over time of NVC saltmarsh categories reflecting brackish conditions, found in the highest parts of a saltmarsh unaffected by coastal defences inland. These conditions are the result of freshwater drainage on to upper saltmarsh, from fresh groundwater at a higher elevation inland. The potential for freshwater forcing at Morrich More is strong due to the proximity of the very extensive dune slacks inland at a higher level. The fresh groundwater flow on to saltmarsh is possible in three directions (north-east, south-east and south-west), given the distribution of saltmarsh around three sides of the main dune slack expanse (Figure 2).

Two brackish saltmarsh types are recognised in the UK National Vegetation Classification (NVC) (Rodwell 2000): the SM19 *Blysmus rufus* and SM20 *Eleocharis uniglumis* saltmarsh communities. Both nominate species have a northern and western distribution in the UK and probably have much of their occurrence in Scotland. Both species occur on Morrich More, with *Blysmus rufus* much more frequent in quadrat records collected in 1988 (Dargie 1989). The 1988 survey recorded many small occurrences of SM19, as well as brackish vegetation dominated by either *E. quinqueflora* or *E. palustris* (mapped as S19 swamp). No SM20 was recorded in 1988 and *E. uniglumis* was only recorded in a single 1988 saltmarsh quadrat (of 217 recorded). Comparison with Saltmarsh Survey of Scotland mapping (Haynes 2016), provides potential for assessing change over a 23-year period (1988 to 2011).

The 1988 mapping results were compared in GIS and in the field with the August 2011 survey, checking map accuracy with other data sources, particularly the 2009 GetMapping orthophotography.

Results are given in section 3.1.

2.3 Theme II: Saltmarsh and dune erosion

Edge erosion and accretion of saltmarsh and dune were investigated by Dargie (2003) and those findings were updated qualitatively by visual comparison with GetMapping 2009 orthophotography and more recent satellite imagery available in Google Earth for 2015.

Saltmarsh loss due to creek edge erosion has resulted in the loss of a few vegetation permanent quadrats over time (2 out of 11 in the Blue Pool area, 3 out of 86 around the pipeline road corridor). This might be an important process, partly driven by RSLR if that is occurring. It is not investigated in this report because the required data (large scale digital imagery) and photogrammetric analytical resources were not available.

A major sea surge event occurred in the Moray Firth on the 14/15 December 2012, causing major damage to exposed harbour infrastructure, including Portmahomack (adjacent to Morrich More). Erosion and overwash fan extents were recorded by the author on a single site visit to the outer strandplain in July 2013. These records were also referred to in discussing erosion and the redistribution of sediment.

Results are given in section 3.2.

2.4 Theme III: Changing saltmarsh elevation and conversion of dune to saltmarsh

This theme was examined in two ways. The first approach sought evidence for long term change in saltmarsh permanent quadrat data, using ordination analysis, again looking for trends indicating recent submergence. Permanent quadrat information was available as paper records from annual surveys of saltmarsh on the northern side of Inver Bay and the Blue Pool area of the outer Morrich More (CEMP 1991; AURIS 1992a, b; 1993a, b; 1994a, b; RSK Environment Ltd. 1995, 1996, 1997, 1998, 1999, 2000, 2001, 2002). A total of 83 quadrats had records for 1987 (October/November) and 1991 to 2001 (recorded in July or early August). A further nine quadrats located in the Blue Pool area were recorded in all years except 1987. A further survey in 2006, simple paper quadrat records, was given to SNH in 2006 by the pipeline corridor developer at the end of corridor restoration. A later survey (Dargie 2013) was also available. The location of permanent quadrats is shown in Figure 3. There was therefore potential information on vegetation change between 1987 and 2013, including 11 years of uninterrupted annual survey (1991 to 2001).

All field records were made using the non-linear Domin cover-abundance scale. The paper records and 2013 results were collated into a single spreadsheet and then converted for this project to percentage cover using a transformation published by Currall (1987) ('Domin 2.6' variant). The resulting data matrix contained 1279 quadrats and 54 species.

Analysis used ordination methods in the PC-ORD ecological multivariate analysis package Version 2.19 (McCune & Mefford 2011), with techniques explained in detail in McCune & Grace (2002). The clearest results came from Detrended Correspondence Analysis (DCA). The same underlying trends were quite similar in other methods (NMDS Non-metric Multidimensional Scaling, RA Reciprocal Averaging, Bray & Curtis Ordination, PCoA Principal Coordinates Analysis). To avoid repetition, only DCA results are discussed here. The LiDAR elevation of each quadrat was extracted from supplied data to assist ordination interpretation.

Figure 3. Location of permanent quadrat transects above and below stone flowbundle pipeline corridor, monitored between 1987 and 2013 (1987, 1991 – 2001, 2006, 2013).

Background satellite image of part of Morrich More strandplain, scene date 2012. Map source: Dargie (2013) (© Google Earth and SIO, Boreas Ecology).

The second line of investigation (results in section 3.3.2) re-visited the locations of quadrat records made in the 1988 NVC survey. Quadrat locations in 1988 were carefully marked on large-scale panchromatic aerial photographs (1:2500, enlarged from 1: 5000 originals flown in 1987 by the Natural Environment Research Council (NERC)). Species details were recorded on field sheets. All this information was still available. Re-visits were made to all 1988 saltmarsh records plus dune quadrats located on the outer strandplain (a total of 217 saltmarsh and 133 dune records). In most cases it was easy to relocate the marked 1988 quadrat position and the species list and cover (Domin scale) recorded in 1988 were quickly compared with 2015 conditions, concentrating on species with high cover values in 1988 and 2015. A subjective assessment of likely change was made, with most locations showing little or no obvious change. A rigorous analysis of change would have required re-recording of each quadrat, followed by ordination analysis. Time was not available to do this (for example, re-recording all saltmarsh quadrats would require a minimum of 20 days). The simple re-visit procedure occupied more than half of all field visit time.

Results are given in section 3.3.

2.5 Theme IV: Assessment of road corridor impacts on saltmarsh vegetation

The flowbundle pipeline corridor in place between 1990 and 2006 included a raised road as a possible partial tidal barrier. Its potential for altering tidal patterns for significant parts of Morrich More (particularly around Inver Bay) is investigated by reviewing 10 years of monitoring reports and then further analysis of Detrended Correspondence Analysis (DCA) output derived from permanent quadrats placed north and south of the pipeline corridor. Tidal modelling is used to construct several models of sea-level change for the period 1987 to 2013, summarising these as graphs showing trends over time. One model includes adjustment for possible road effects, based on monitoring observations.

Subset analysis is then used to compare trends over time in two saltmarsh vegetation gradients extracted from DCA ordination in Theme III: elevation and drainage. Quadrat subsets relate to road (above: north-of-road, below: south-of-road, Blue Pool samples as ‘controls’), elevation (upper marsh >1.98 mOD, lower marsh ≤1.98 mOD) and estuarine position (outer and inner strandplain). Graphical analysis (smoothing splines) is used to compare different subsets, as well as comparing subsets with different tidal models.

Results are given in section 3.4.

2.6 Other general methods

2.6.1 Access

Fieldwork was essential to check available data in relation to themes of interest. Most of Morrich More SSSI is a military site (Tain Air Weapons Range), with restricted access. Permission to use the range was agreed with local Ministry of Defence (MoD) staff. Vehicle use on tracks was allowed on a single day in early August 2015, combined with the start of Site Condition Monitoring by SNH (Geomorphology). Thereafter access was only allowed on a bicycle (confined to tracks) or on foot from a locked gate at the site entrance, when the military site was not in use (i.e. no red flags flying). Apart from the one vehicle day, this effectively limited fieldwork for this project to weekends except for saltmarsh on the south side of Inver Bay, in the south of the SSSI and not on MoD land. The outer limits of saltmarsh are 3.1 to 5.5 km distance from the locked gate entrance. A total of 14 field days was required to check various aspects of data quality.

2.6.2 GIS, remote sensing and statistical analysis software

All GIS analysis was undertaken using MapInfo Professional. Abstraction of LiDAR elevation data for points and lines used the ENVI remote sensing software package. Statistical analysis used the PC-ORD package, supplemented with the PAST (PAleontological STatistics) Version 2.17 (2012) package (Hammer *et al.* 2001).

As an example of LiDAR use, elevations extracted for the 92 saltmarsh permanent quadrats are shown as a frequency histogram in Figure 4.

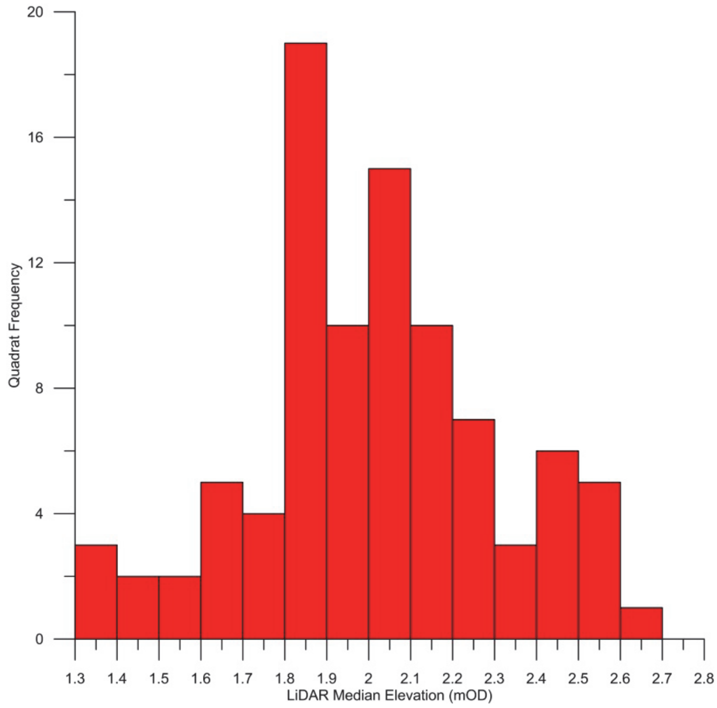


Figure 4. LiDAR elevation frequencies of 92 saltmarsh permanent quadrats

2.6.3 Field data checking and capture

GIS data for field checking and locating were exported to a Magellan Mobile Mapper equipped with PocketGIS. This allowed precise field navigation to points of interest, with additional capture of points, lines and attributes where necessary. The DGPS component of this facility is accurate to +/- 1m for XY coordinates.

3. RESULTS

3.1 Theme I: Freshwater forcing

In 2015 field checks were made of saltmarsh vegetation boundaries from the1988 NVC survey (Dargie 1989) and the Saltmarsh Survey of Scotland (SSS) (Haynes 2016) which surveyed Morrich More 8-11 August 2011. An overlay analysis in GIS suggested many large and small changes but a single day of fieldwork suggested that most such change was probably false and further scrutiny of data was required.

Varied planimetric errors were found in 1988 mapping when compared with GetMapping orthophotographs (12 May 2009) in GIS. This was due to use of non-rectified aerial photography. These errors were considered too large to attempt a formal overlay with SSS GIS data. Clear warnings of such errors were given in Dargie (1989).

The SSS 2011 NVC mapping of saltmarsh was checked carefully in the field and by overlay over 2009 GetMapping orthophotography. One relevant polygon was noted as incorrectly identified (acidic dune slack, not SM20 saltmarsh, NH 83846 85023). Several polygons coded as one vegetation type could have been better described using mosaics to cover several types varying with repeated changes in elevation due to microtopography and zonation around large primary pans, an important feature of the outer Morrich More strandplain. Secondary saltmarsh pans were also inconsistently recorded as a polygon feature. Boundaries were generally very good in terms of planimetry but in several cases the edges of creeks were ignored (including lower saltmarsh within the creek edges). Polygons with major creeks could have been split. The oversimplification of polygon attributes and use of over-large polygons was sufficient to limit the use of SSS mapping in assessing vegetation change. However, SSS mapping was considered accurate for extracting 2015-checked polygons containing SM19 and SM20 upper saltmarsh communities (Figure 5).

The mapped SSS waterlogged habitats total 23.3 ha in extent, as SM20 dominant or in mosaic, and a small area of SM19 in mosaic. Waterlogging is located on the upper edge of saltmarsh and closely corresponds with transitional habitat mapped in 1988 (Dargie 1989). No SM20 vegetation was recorded in 1988 and this comparatively large extent has developed in less than 30 years. The SM20 area above Inver Bay (grid reference 285340 883110) in Figure 5 has developed in a large area of water ponding on the northern side of the pipeline corridor and is an example of drainage obstruction interacting with freshwater forcing. Fieldwork in 2015 also noted the strong development of swampy ground immediately north-east of dunes at grid reference 285500 884000, in the same frontal position as the more mature examples to the north-west in Figure 5. This area to the south-east of Blue Pool might develop into SM19 or SM20 habitat quite quickly.

Overall, there is good evidence in SSS results that freshwater forcing is occurring widely around the upper edge of saltmarsh, especially immediately inland from Blue Pool where it is well developed to the north-west. These occurrences are mainly in a NW-SE band recorded as 1988 transitional grassland, immediately seaward of dry dune and dune slack. There is also further corroborative evidence of waterlogging within saltmarsh permanent quadrats located here (section 3.3.1.3). There is also evidence of a recent increase in freshwater forcing in section 3.3.3.6, in permanent quadrat time sequences.

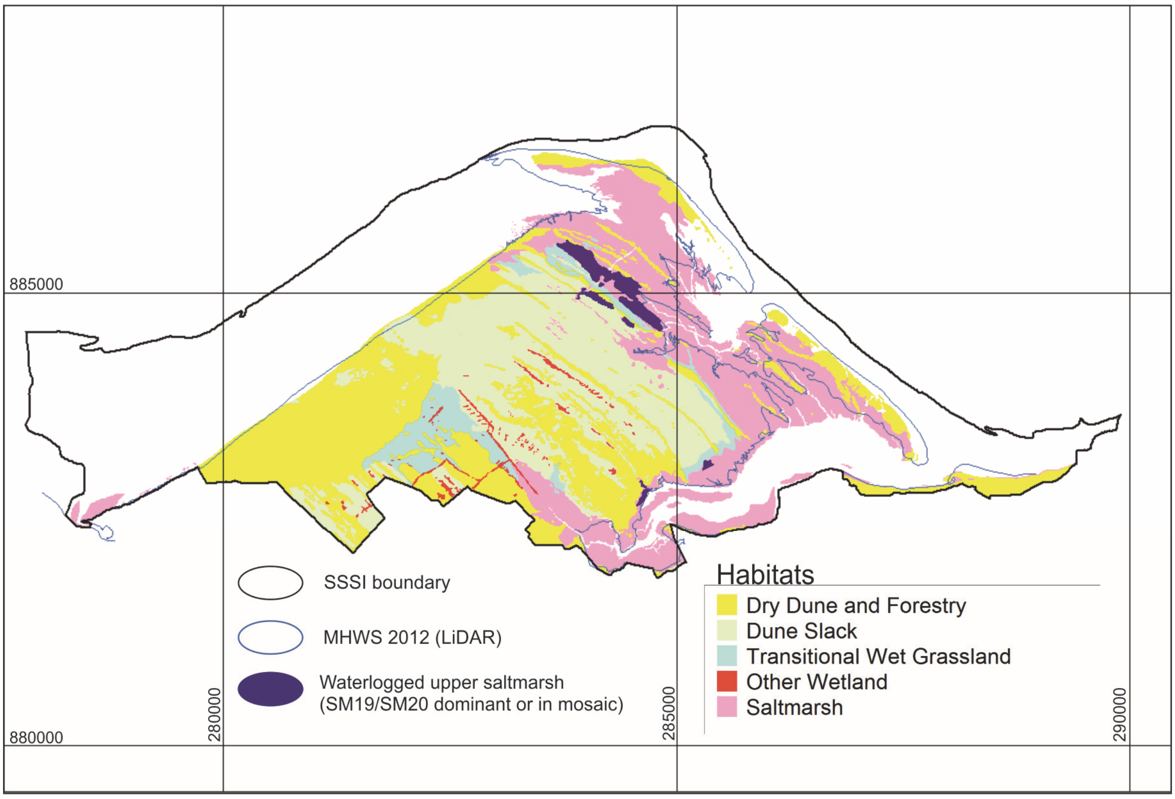


Figure 5. SM19 and SM20 waterlogged upper saltmarsh habitats mapped by the Saltmarsh Survey of Scotland in 2011.

Grid lines are spaced at 5 km intervals. Sources: SNH Sand Dune Vegetation Survey of Scotland; SNH-SEPA Saltmarsh Survey of Scotland. SSSI boundary courtesy of SNH (© Crown copyright and database right 2016. Ordnance Survey 100017908).

3.2 Theme II: Saltmarsh and dune erosion

Edge erosion and accretion on Morrich More between 1988 and 2003 were studied by Dargie (2003). Figure 6 maps edge loss between 1988 and 2003, which was widespread. Erosion along the long (6 km) western shore has been occurring for at least centuries and is an important component of the site's erosional and accretionary history. Sediment accretion (Figure 7) has more than compensated for losses, producing a very large expanse of new saltmarsh habitat inside Innis Mhor. The area was largely intertidal sandflat in 1988 and was named Whiteness Sands. As reported in section 1.1, edge loss totalled 72 ha, most of it in the west, along the outer edge of Innis Mhor and within the Blue Pool area. However, the sediment generated by erosion then formed 138 ha of new habitat, much of it saltmarsh inside Innis Mhor and around the extremities of Patterson Island. Over a maximum period of 15 years (starting summer 1988, extending to summer 2003) each 1 ha of mainly dune erosion produced 2 ha of new habitat within the outer strandplain. This net gain is mainly the result of erosion of dunes which are taller than the thickness of new saltmarsh habitat. Speculating, this positive habitat balance resulting from erosion has probably been the main way in which the strandplain has evolved over 7,000 years.

There is localised sediment accretion in the west of the northern Morrich More shore (Figure 7). This is anomalous upon an eroding shoreline. It marks sediment accreting behind several short lengths of low intertidal breakwaters installed in the early 1990s to protect adjacent golf course property, defended before this by unsightly heaps of rubble.

Erosion since 2003 has seen the narrow neck of Innis Mhor broken to form two intertidal islands. Rapid foredune modification is occurring, with very strong edge retreat which has pitched two military vehicle targets on to the beach, one before 2012 (DEFRA 2012) and the other between 2012 and 2015. There is certainly the strong impression that erosion at Innis Mhor is now proceeding faster than in the period 1988 to 2003. There has been edge retreat too at Patterson Island, but much less than at Innis Mhor. Comparing 1987 aerial photography with a 2015 Google Earth image shows most of the Patterson dune topography formed by 1988 still in place. Aerial photography (1987) and satellite images (2006 and 2009) suggest that rapid change is only occurring in the Innis Mhor area. There is much less coastal change towards Patterson Island.

The outer strandplain suffered a storm surge on the 14/15 December 2012, with major overwash. Unpublished field mapping by the author in July 2013, of Morrich More overwash fans and edge retreat, estimated 50 ha of saltmarsh affected by washover sand. This had resulted in 6-7 ha of dune and saltmarsh loss, with about 45 ha of saltmarsh covered in thinner new sand, allowing rapid re-growth of vegetation from seed and buried stems. High vegetation cover here was patchy in distribution but considerable recovery had occurred in seven months. There was little visible evidence of the storm surge event in saltmarsh observed in 2015, with high vegetation cover in most locations which had been affected by thinner sand burial. These observations suggest that much saltmarsh is resilient to a major sea surge and re-develops quickly via rapid plant succession within one growing season.

Erosion by edge retreat within Inver Bay is relatively slight and sediment generation by saltmarsh creek migration is probably more important, particularly at its head in the Fendom area. In 2015 observations were compared with the 1988 vegetation map (Dargie 1989) and loss was noted for the most eastern 1988 patches of low saltmarsh (SM1 *Zostera noltii* and SM3 *Ruppia maritima*) on the south side of Inver Bay, as well as the loss of all the lowest extent of this habitat west of the village of Inver. Restricted access meant that equivalent checks could not be made on the northern side of Inver Bay, within Tain Air Weapons Range. Re-visits to 1988 quadrat locations recorded three saltmarsh quadrats lost to frontal edge retreat and four to creek erosion (Table 1). These losses were balanced by accretion in which dune habitat has now formed, together with the very large expanse of new saltmarsh inside Innis Mhor since 1988. Re-visits to 133 dune quadrats (Table 2) recorded six quadrats eroded by dune frontal erosion (five in the Innis Mhor area) and one lost to creek erosion at Fendom. As with saltmarsh, these losses are balanced by sand accretion with dry dune succession since 1988 (8 quadrats). An important feature of dune quadrat change is the formation of extensive semi-fixed dune (Category 4 in Table 2, 44 quadrats) where in 1988 there was SD5 and SD6 mobile dune with much bare sand. Moss cover is now high here, much of it made up of *Syntrichia ruralis*. These vegetation changes point to a reduction in sand supply from the beach zone, despite that zone being closer following dune edge retreat. There is still active sand blow – the presence of *S. ruralis* indicates modest regular sand burial and is a species capable of growing upwards through sand inundation of up to 3 cm per year (Birse *et a*l. 1957; Ranwell 1972; Packham & Willis 1997).

In summary, the erosion and accretion study shows that the loss of high-sided dunes since 1988 has been more than balanced by accretion and new habitat development, particularly as saltmarsh. There is even the suggestion that for each 1 ha of dune habitat loss between 1988 and 2003 there was a 2 ha gain of saltmarsh. Coastal erosion is now occurring rapidly at Innis Mhor but decreases rapidly south-eastwards towards Patterson Island. Major beach sediment change has probably occurred, with reduced sand delivery into the foredune zone. In 2015 this had semi-fixed dunes, in contrast to mobile dune habitat in 1988. The habitat response to erosion and accretion seems to be dynamic and self-adjusting, showing much resilience. The habitats of the outer strandplain have not been overwhelmed by a clear recent increase in erosion, which is mainly restricted to the Innis Mhor area.

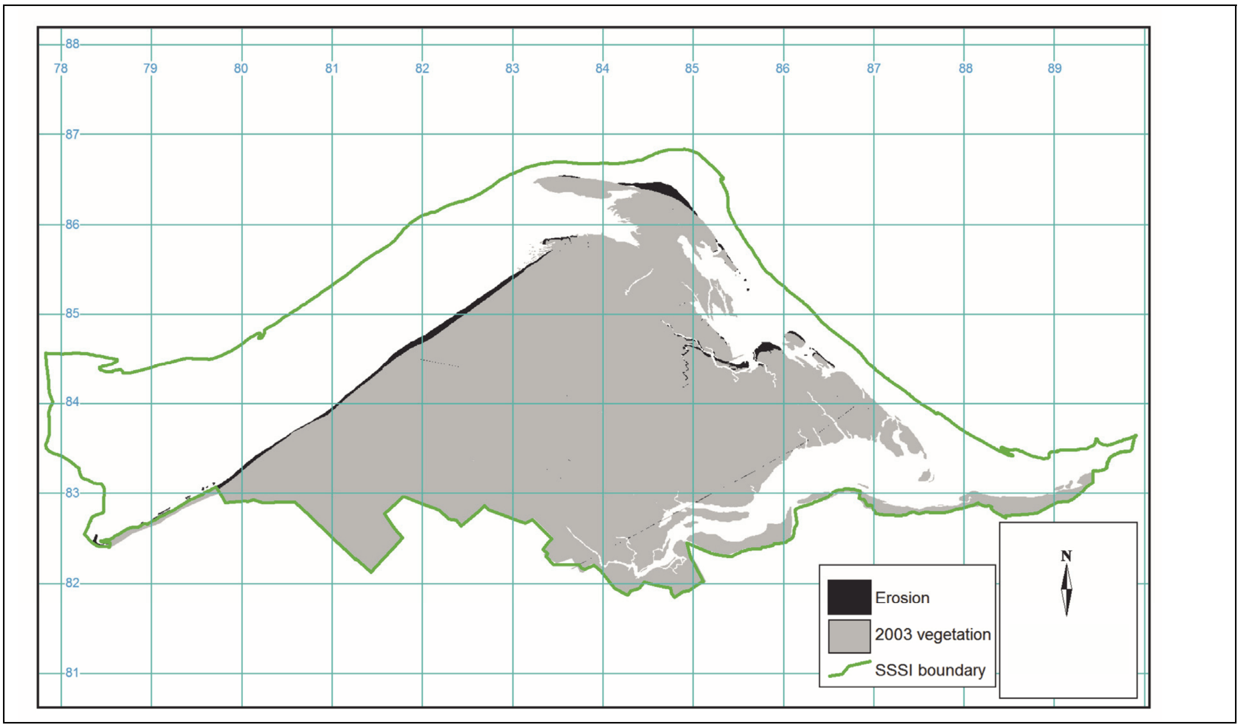


Figure 6. Coastal edge loss locations between 1988 and 2003.
Source: Dargie (2003). SSSI boundary courtesy of SNH (© Crown copyright and database right 2016. Ordnance Survey 100017908)

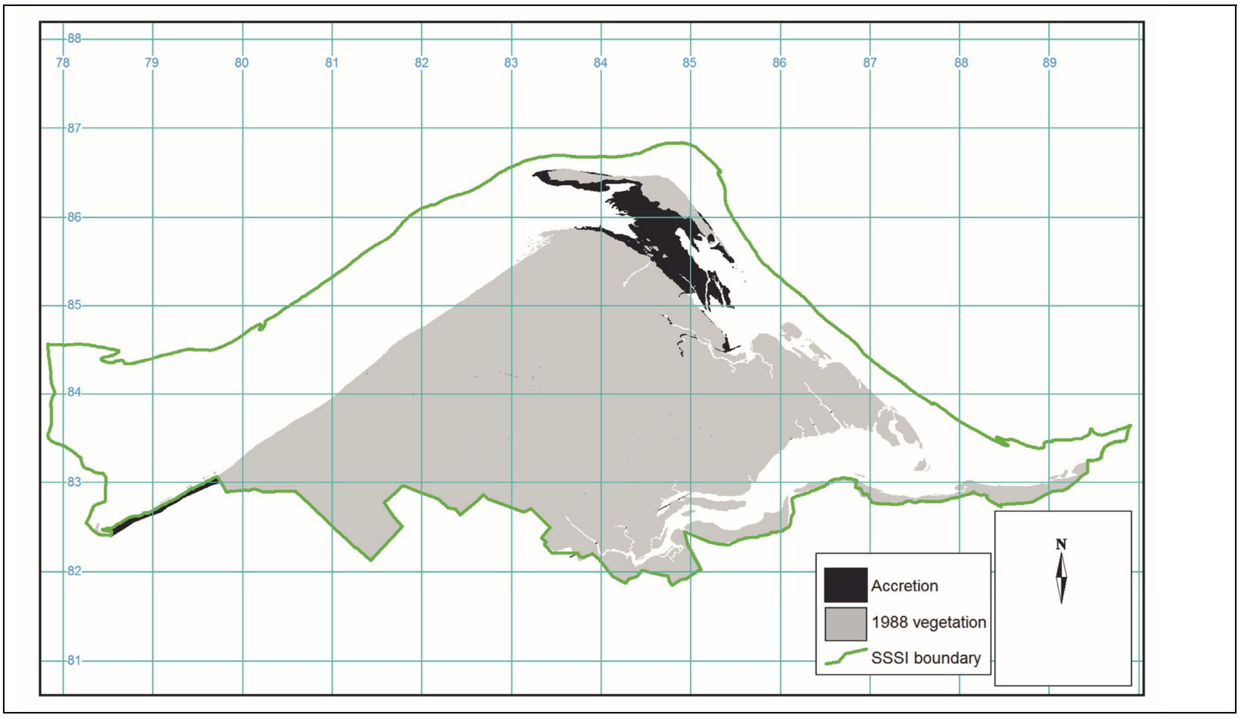


Figure 7. Accretion between 1988 and 2003.
Source: Dargie (2003). SSSI boundary courtesy of SNH (© Crown copyright and database right 2016. Ordnance Survey 100017908)

Table 1. Analysis of changes observed by revisiting the locations of 1988 saltmarsh quadrats

Category	Analysis of 1988 saltmarsh quadrat change	Totals
1	Wetter upper saltmarsh, likely freshwater impact	10
2	Wetter, freshwater effect, dune slack developed on former upper saltmarsh	1
3	Higher relative sea level, NVC change to lower elevation type, level change unlikely	16
4	Higher relative sea level, dune habitat changed to saltmarsh	24
5	Higher relative sea level, possible lowered elevation	6
6	Destroyed by vehicle track	1
7	Lost to creek erosion	4
8	Lost to frontal erosion	3
9	Lower relative sea level, possible change in elevation	5
10	Sand accretion, change in level, now dune habitat	7
11	Tidal access blocked by accretion, may be nutrient-rich groundwater effect too	2
12	Uncertain change, in 1988 much SM13a was a clear pioneer habitat on fresh intertidal sand, likely level change and succession since	16
13	Uncertain change, located in upper marsh primary pan, may reflect worsening drainage - increased waterlogging	4
14	Uncertain, levels affected by pipeline corridor	6
15	Little or no change since 1988, requires quadrat re-survey and numerical interpretation of 1988 and up-to-date differences	112
	Total	217

Table 2. Analysis of changes observed by revisiting 133 locations of 1988 dune quadrats

Category	Analysis of 1988 dune quadrat change	Totals
1	Dune management, change due to rabbits, stock management, mowing	4
2	Dune hydrological change, drier	1
3	Dune hydrological change, wetter	4
4	Dry dune succession as result of reduced sand input	44
5	Dry dune succession to more acidic state	1
6	Reversed succession, close to eroding front, receiving new sand supply from exposed dune face	3
7	Sand accretion over former embryo dune or strand, then dry dune succession as sand supply reduced	8
8	Destroyed, lost to creek erosion	1
9	Destroyed, lost to dune frontal erosion	6
10	Little or no change since 1988, requires quadrat re-survey and numerical interpretation of 1988 and up-to-date differences	61
	Total	133

3.3 Theme III: Changing saltmarsh elevation and conversion of dune to saltmarsh

3.3.1 Vegetation analysis

This section provides an interpretation of results from ordination analysis of Morrich More permanent quadrat records upon saltmarsh habitat. It seeks a strong relationship between elevation and saltmarsh vegetation and then assesses that relationship as evidence of change within the time span covered by quadrat surveys (1987 to 2013) and revisits sea level (2015).

3.3.1.1 Ordination analysis of 1279 Morrich More permanent quadrat records

Ordinations are graphical procedures which seek to place a set of objects (in this case 1279 quadrats) in a low-order space (e.g. two dimensions) using object attributes (in this case percent cover values for 54 species). The procedures set like or similar objects close together and place very unlike or totally dissimilar objects well apart. The quantitative basis for doing this is very varied and often complex. The graphical output requires careful interpretation, e.g. rotation of graphical axes to maximum correlation with one or more likely driving forces (Dargie 1984) and checks to ensure that underlying procedures and biodiversity variation (alpha and beta diversity gradients) have not combined to warp and distort the low-order summary space (Dargie 1986a). Such distortion is known from earlier British saltmarsh analysis, with a single gradient twisted into a complex three-dimensional shape (Adam 1978). Different methods should be applied and carefully compared before selecting a 'best' result based on clarity of species patterns, strength of correlation with independent variables, and/or explained variance. This is the approach recommended by McCune & Grace (2002) and the PC-ORD software package has a wide range of ordination methods and graphical interpretation tools to do this. That recommended approach has been followed here.

The 1279 quadrat x 54 species dataset was processed by various methods, correlating outputs with quadrat elevation, then checking for distortion due to species richness, and making interpretations based on species patterns along unrotated and rotated axes, Detrended Correspondence Analysis (DCA) was considered the best result for use in this report. Non-metric multidimensional scaling was also excellent and that strongly indicated that a two-dimensional interpretation was required (scree plot analysis, see McCune & Grace (2002)). The DCA result was readily interpreted in two dimensions, with a third axis seemingly superfluous (but produced anyway because the DCA component of the package always provides a three-dimensional result).

The DCA two-axis solution (Figure 8) shows a striking triangular spread of samples with a further line of samples extending from the right-hand apex. Axis 1 is an elevation gradient extending from high marsh on the left to the lowest samples on the right. Little rotation (5°) was needed to fit the first axis to LiDAR data with strong correlation (Figure 9): LiDAR elevation (R^2 = 0.817; elevation = 2.6754 – 0.002214 DCA_Axis_1). The varied density of quadrats along Axis 1 reflects altitudinal frequency (Figure 4), with two zones of high density in the centre and low densities (fewer quadrats) at the upper and lower ends of the gradient.

DCA Axis 2 had no strong environmental correlates but species sequences suggested different soil conditions developed mainly in upper marsh environments. These ranged from drier and better drained sectors to ground which was probably waterlogged for long periods. This range of conditions is much more confined (or is weak) in the middle and lower marsh samples, explaining the lack of spread on the second axis for those elevations.

The character of each axis is covered in subsequent sections.

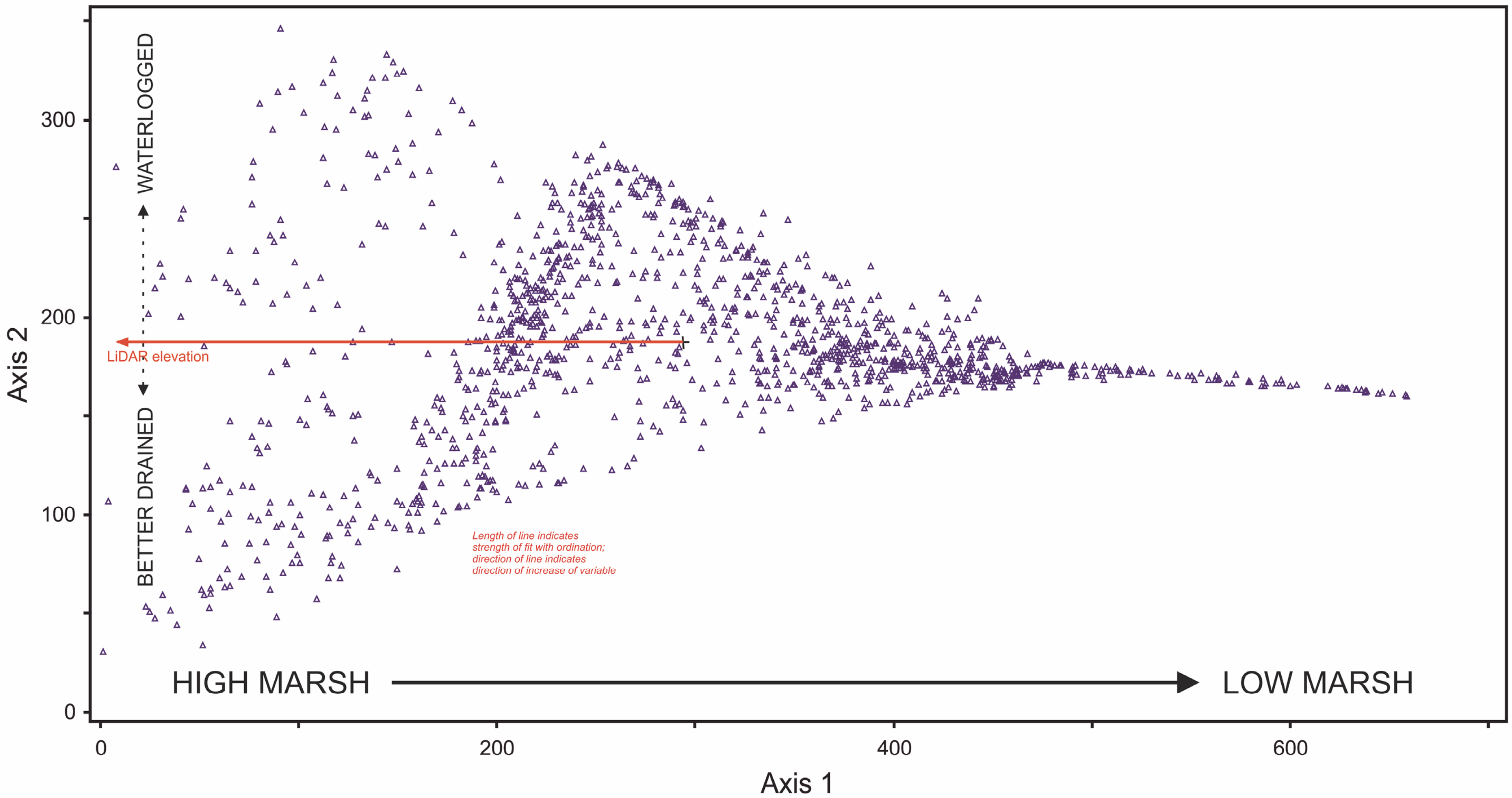


Figure 8. Quadrat locations plotted on two-axis Detrended Correspondence Analysis (DCA) ordination biplot with LiDAR elevation

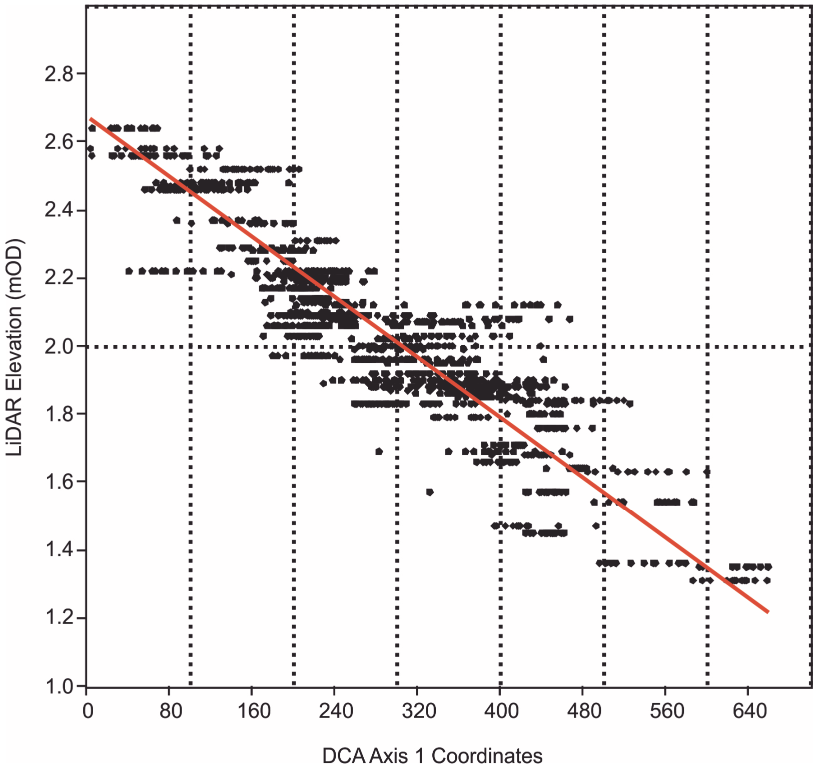


Figure 9. Reduced Major Axis (RMA) regression fit of LiDAR elevation on DCA Axis 1

3.3.1.2 The elevation gradient

Species response curves (percent cover fitted to quadrat coordinates) are generated for each axis of a PC-ORD ordination solution and those representing all common species with maximum cover >10% are shown in Figure 10. An additional axis showing elevation (mOD) is added to Figure 10, based on RMS regression with LiDAR values for quadrats (Figure 9). Each response curve is derived by fitting a moving kernel average over the maximum cover values in the kernel range (i.e. it ignores low scores and absences). Each curve therefore represents the likely optimal plant response, ignoring other limiting factors not associated with elevation.

The species sequence on DCA Axis 1 is remarkably clear and shows the components of different saltmarsh communities and sub-communities (Rodwell 2000) in moving up marsh from the low marsh (right) end of Figure 10: SM8 > SM13e > SM13d > SM16a > SM16b or SM16c > SM16f > SM16e or SM19. There are no sharp breaks marking an immediate community switch on the elevation gradient and this illustrates the continuity of vegetation in environmental space (marsh elevation), in contrast to the occurrence of these NVC types on the ground at Morrich More where they are often discrete (discontinuous) due to the nature of elevation surfaces. This is in accord with many vegetation patterns summarised in contrasting ways (ordination, vegetation mapping) (Austin 2013).

A very similar species sequence describing continuous variation for the site is given in Dargie (1989), based on a seriation technique which isolates species significantly associated with five zones of a gradient (Dargie 1986b). Both analyses show several species which are unusual upon an upper saltmarsh, based on their absence in accounts by Adam (1990) and Rodwell (2000): *Calliergonella cuspidata, Schoenus nigricans, Carex arenaria, Agrostis capillaris, Molinia caerulea* and *Nardus stricta* feature in Figure 10. Several other Figure 10 species can be regarded as typical: *Blysmus rufus, Sagina maritima, Agrostis stolonifera, Trifolium repens, Carex flacca, Rhytidiadelphus squarrosus, Scorzoneroides autumnalis*.

Additional species from seriation in Dargie (1989), some typical rather than unusual, included *Juncus articulatus, Potentilla anserina, Euphrasia officinalis* agg. (probably *E. confusa*), *Carex nigra, Juncus balticus, Peltigera canina* (probably *P. neckeri*), *Eleocharis quinqueflora, Centaurium littorale, Sagina nodosa, Plantago coronopus, Triglochin maritima*.

It might be important that a few high marsh species recorded in permanent quadrats did not feature in Dargie (1989) seriation results: *Schoenus nigricans, Carex arenaria,* and *Molinia caerulea.* These were also absent or rare in the 1987 corridor permanent quadrat records and each of these species seems to have expanded in terms of cover. *S. nigricans* only appeared in three quadrats (46, 47 and 48) from 2006. These species have developed only recently on the upper marsh and this is interpreted here as likely additional evidence of increased freshwater forcing in parts of the southern strandplain.

The species present in high marsh conditions (the left side of Figure 10) have a mix of waterlogging and better drained soil preferences. These contrasts are separated quite clearly on DCA Axis 2 (Figure 11) and are discussed in 3.3.1.3.

3.3.1.3 The second gradient: waterlogging and drainage

Figure 11 shows species response curves for DCA Axis 2. Care is needed in interpreting this axis because response curves in the centre include some lower marsh species which might show little relationship with soil drainage: *Fucus cottonii* and *Salicornia europaea* agg.. The remaining species seem to fall into those occurring in waterlogged areas and those requiring better drainage on the upper marsh, with a further central species set which might indicate intermediate drainage conditions for middle marsh elevations.

The middle marsh set is made up of *Suaeda maritima,* some *Salicornia europaea* agg. and *Spergularia media,* but it also has two much more dominant species which characterise conditions: *Puccinellia maritima* and *Armeria maritima.* These have very similar intermediate preferences in the middle marsh but *A. maritima* extends further on to the upper marsh (where it requires good drainage) and it has a distinct lower shoulder on its Figure 11 response curve.

Higher-coordinate DCA Axis 2 quadrats have waterlogged conditions. This is inferred from constituent species, knowing their generally high (>6) Ellenberg F (moisture) scores (Hill *et al*. 2004, 2007): *Plantago maritima* (F=7), *Juncus gerardii* (7), *Glaux maritima* (7), *Carex flacca* (5), *Triglochin maritima* (7), *Carex extensa* (7), *Molinia caerulea* (8), *Calliergonella cuspidata* (7), *Schoenus nigricans* (8), *Juncus articulatus* (9), *Carex nigra* (8), *Juncus balticus* (8), *Scorzoneroides autumnalis* (6), *Eleocharis quinqueflora* (9) and *Blysmus rufus* (8).

Some of these are typical of freshwater waterlogging (*C. cuspidata, S. nigricans, J. articulatus, C. nigra)* and others can tolerate both freshwater and brackish wet ground (*C. flacca, T. maritima, S. autumnalis, E. quinqueflora*). The remainder (*P. maritima. J. gerardii, G. maritima, C. extensa, J. balticus, B. rufus*) are more typically halophytic species, usually occurring in waterlogged saline situations. The species mix for DCA Axis 2 quadrats with high coordinates is therefore a mix of freshwater and brackish elements and can be read as evidence for the presence of freshwater forcing.

Relatively few quadrats contain the indicator species for freshwater influence: samples 45 – 48 and 58 – 60 in Figure 3. These lie very close to the outer edge of dune slacks inland. The wettest conditions are associated with 45 – 48, with 58 – 60 slightly drier and towards the centre of DCA Axis 2, perhaps due to a steeper slope (better drainage) towards Inver Bay. The permanent quadrat set therefore contains further information on the location of freshwater forcing and quadrat composition change over time shows that indicators of freshwater influence (e.g. *Schoenus nigricans, Molinia caerulea, Calliergonella cuspidata*) have only developed strongly since the late 1990s. Also, these samples are in front of the same dune ridge south-east of Blue Pool noted as having adjacent saltmarsh showing recent waterlogging and possible future development of SM19 and/or SM20 (see section 3.1). This is important spatial and ecological corroboration of freshwater forcing in permanent quadrat evidence. It suggests that freshwater forcing is increasing around these seven samples.

Conversely, drier and better drained marsh is inferred for low-coordinate quadrat positions on DCA Axis 2, based on their constituent species and generally low to moderate Ellenberg scores (6 or less): *Festuca rubra* (5), *Carex flacca* (5, a markedly bimodal species at Morrich More, occurring in wet and dry environments upper marsh conditions), *Sagina maritima* (7), *S. apetala* (4), *Bryum algovicum* (6), *Agrostis stolonifera* (6), *Sagina nodosa* (7), *Trifolium repens* (5), *Plantago coronopus* (6), *Poa pratensis* (5), *Agrostis capillaris* (5), *Rhytidiadelphus squarrosus* (5), *Cochlearia officinalis* (6), *Nardus strict*a (7), *Cerastium fontanum* (5). Only a few quadrats make up these conditions (67, 71, 77, 85 and 86 in Figure 3). Samples 67, 71 and 77 seem to lie on steeper sections of marsh quite close to drainage creeks and might not be suitable for waterlogging. Samples 85 and 86 are on very gentle slopes in the Fendom Burn area. They ought to show waterlogging because they are distant from the main drainage channel. However, the marsh here contains deep drains further north which show signs of cleaning (recent excavated spoil) and the marsh nearby also has an older unmaintained drain network close to samples 85 and 86. In these two cases present and past artificial drainage has probably prevented waterlogging development in recent decades.

This drainage gradient in saltmarsh vegetation was not observed in earlier seriation analysis (Dargie 1989). The original DCA and seriation output for 1988 analysis was still available. It was checked and in fact this waterlogged to better drained soil continuum was present as the second DCA axis. It was not considered or discussed in detail in Dargie (1989) because middle and low marsh species confounded interpretation. A gradient with *Blysmus rufus* and *Rhytidiadelphus squarrosus* at each end and *Fucus cottonii* in the centre seemed bizarre in 1989, a time when ordination interpretation software was not available.

Seriation results for 1988 data showed the following significant species composition for waterlogged conditions: *Calliergonella cuspidata, Triglochin maritimum, T. palustris, Blysmus rufus* and *Eleocharis quinqueflora*. Drier, better drained soils were characterised by *Armeria maritima, Festuca rubra, Plantago maritima, P. coronopus, Centaurium littorale, Elytrigia arenaria, Sagina nodosa, Euphrasia confusa, Rhytidiadelphus squarrosus, Cerastium fontanum, Peltigera neckeri, Agrostis capillaris* and *Plantago lanceolata*. These two species sets are therefore comparable with those extracted from permanent quadrats in this 2016 analysis. Great similarity in results for two different quadrat sets confirms the presence and importance of the drainage gradient.

The 1988 dataset lacks two freshwater indicators which are presently widespread today in wet upper saltmarsh in outer Morrich More (*Schoenus nigricans, Molinia caerulea*). Their absence from the drainage-waterlogging gradient in the 1988 data analysis suggests they have expanded considerably since 1988, helping to indicate the principal areas of freshwater forcing.

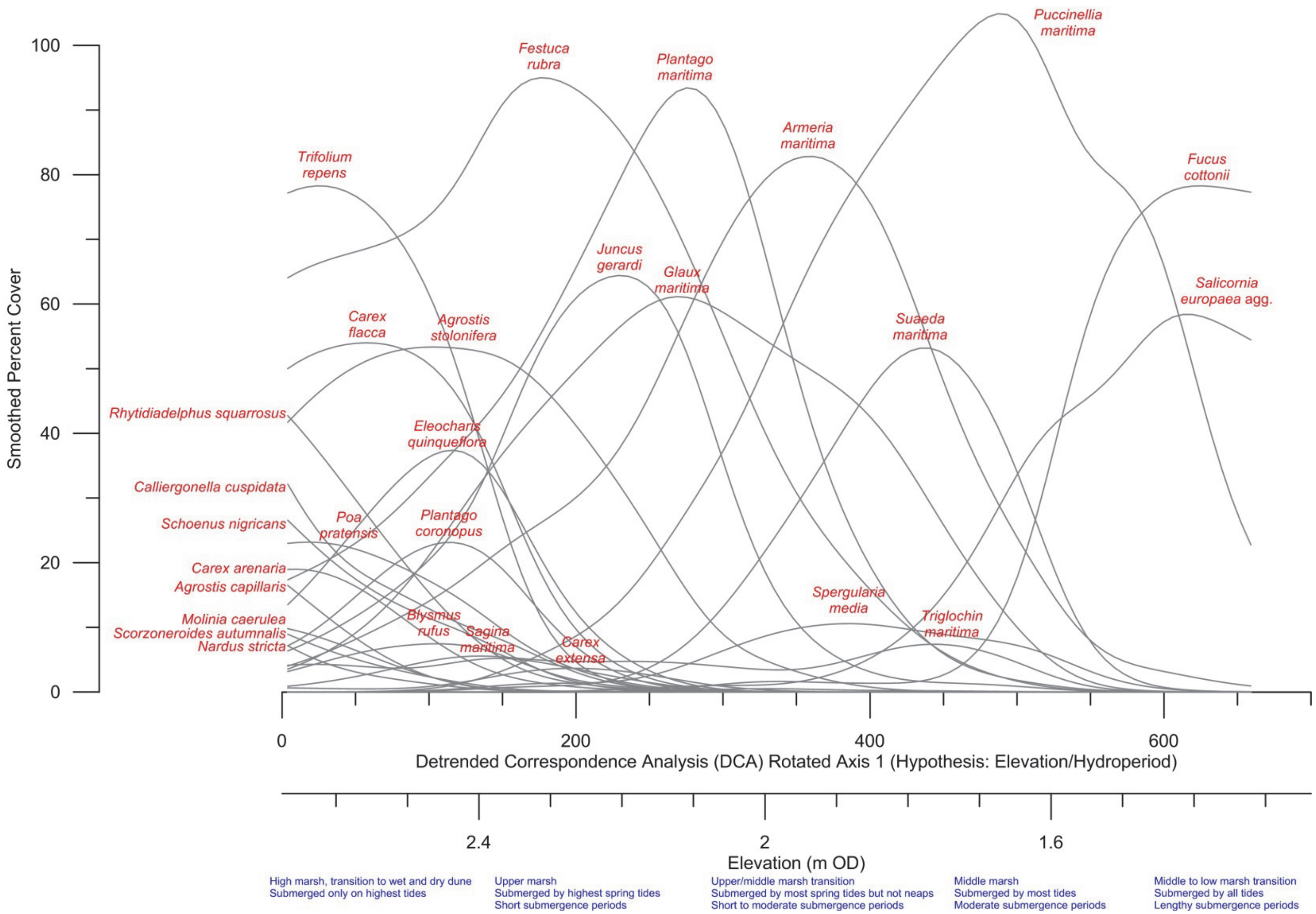


Figure 10. Species response curves and interpretation for DCA Axis 1

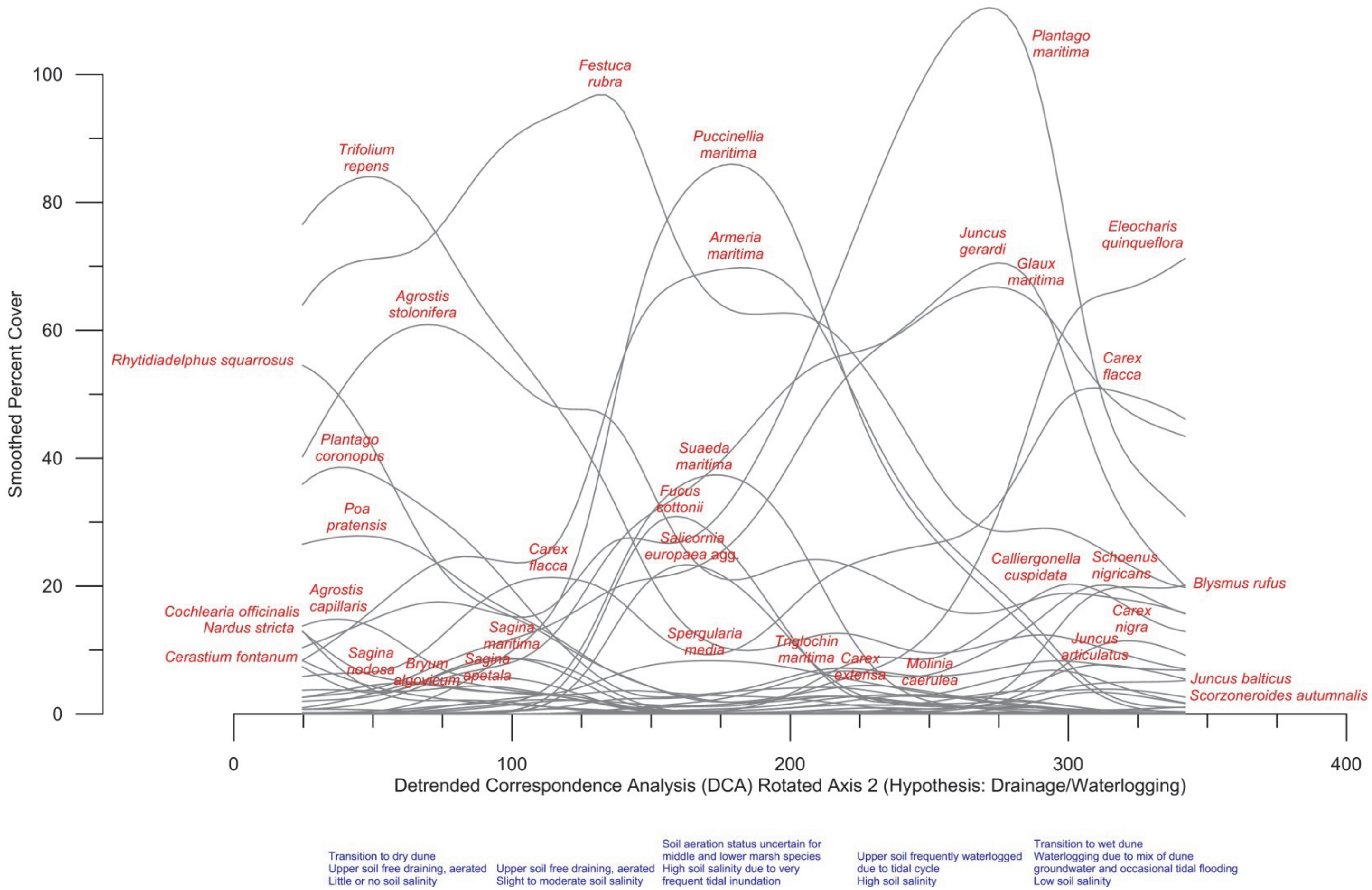


Figure 11. Species response curves and interpretation for DCA Axis 2

3.3.2 1988 Quadrat location re-visits

This section concentrates on results from re-visiting 1988 quadrat locations for saltmarsh samples, plus dunes in the outer strandplain. The results of rapid comparisons with 1988 field recording sheets are summarised in Table 1 (saltmarsh records, 217 quadrat re-visits) and Table 2 (dune records, 133 re-visits). Comment focusses on results which might be evidence of RSLR.

Two categories of saltmarsh change can be interpreted as support for RSLR as a key driver. The locations of these changes are mapped in Figure 12.

Category 3 (16 cases) covers saltmarsh types which have switched between 1988 and 2015 to types found at a lower level on the elevation continuum. Examples include the following 1988 → 2015 switches: SM13a → SM8/SM13e, SM16c → SM16a and SM16f → SM16bc. There are few cases of these switches on the lower marsh and almost all (i.e. except SM13a → SM8/SM13e above) involve interchange in the SM16 upper marsh zone.

Category 4 (24 cases) involves a switch from dune or dune/saltmarsh transition to saltmarsh. Examples include SD12/H11 → SM16f, SD17 → SM16ef/SM20, SD15 → SM16f, SD5 → SM16f and S19 → SM19. There is a near-even split between 1988 wet and dry dune switches to saltmarsh. This evidence is more convincing (as RSLR evidence) than Category 3, based on the degree of change. It also requires less subjective judgement than for Category 3 which frequently relies on assessment of SM16 type which is not easy for some NVC sub-communities. Both Category 3 and Category 4 changes are well spread throughout Morrich More saltmarsh (Figure 12), with the largest concentration at the head of Blue Pool. Together they make up 18% of the 217 re-visited 1988 saltmarsh samples. The concentration of almost half of all cases close to Blue Pool, where there is also evidence of freshwater forcing, suggests an interaction of processes. The proportion (18%) is sufficiently high to suggest that more careful comparison (full quadrat resurvey) would draw in other samples, particularly from those showing little or no obvious change (Category 15).

The results in Table 2 covering 1988 dune quadrats have no signal of change which might relate to RSLR. Four locations (Category 3) show increasing wetness which might be evidence of a rising watertable which in turn could be the result of recent freshwater forcing. However, there is also one case of the reverse (Category 2). The strongest trend in Table 2 represents dry dune succession (mobile to semi-fixed dune) and that is probably driven by reduced sand supply, to amounts sufficient to maintain a high cover of the moss *Syntrichia ruralis*. 2015 re-visits did not include samples within the very extensive dune slack complex in the centre of the SSSI and any conclusion on drivers of change there would need checks on a further 210 1988 quadrats. The results found for dune samples are to be expected, with dune succession shown to be the most important process, likely driven by reduced sand supply. This of course could be indirectly due to RSLR, with changes in the balance of erosion and accretion due to RSLR then affecting sand available for delivery to foredunes.

To summarise, revisited quadrats contain evidence of samples changing to lower saltmarsh types or sand dune changed to saltmarsh, alterations which could be due to RSLR. However, the major change present in dune samples could be indirectly driven by RSLR, reducing sand supply and allowing extensive succession from mobile to semi-fixed dune.

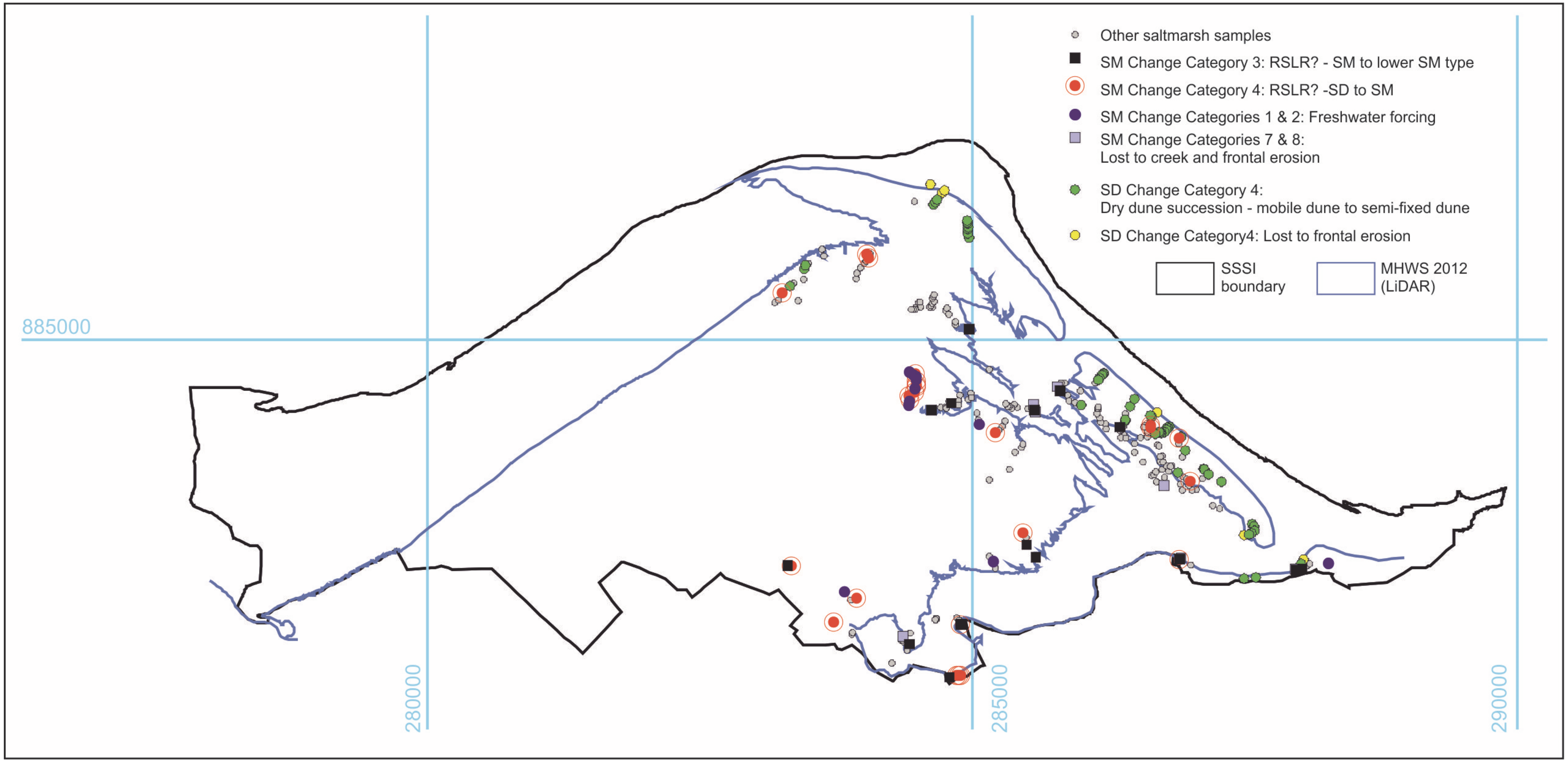


Figure 12. Location of change in 1988 saltmarsh quadrat positions considered to reflect RSLR and freshwater forcing.
Grid lines are spaced at 5 km intervals.
SSSI boundary courtesy of SNH (© Crown copyright and database right 2016. Ordnance Survey 100017908).

3.4 Theme IV: Assessment of road corridor impacts on saltmarsh vegetation

This section assesses the possible effect of road impact upon saltmarsh vegetation change, compared with vegetation change at different marsh levels and different parts of the Morrich More strandplain. Road effects are assessed as potential complications for the interpretation of ordination results and signatures of tidal and other sea-level influence.

The quadrat layout in Figure 3 was planned as part of monitoring by Aberdeen University staff, with samples set out between 12 October and 1 November 1987 and distributed either side of the pipeline road corridor (Dargie 1989). Guidance from the Nature Conservancy Council (NCC) in 1987 required transects to run from the landward limit of tides to the saltmarsh edge above mudflats, as marked on a 1:25000 map supplied by NCC. The pipeline corridor ran along the lower part of this saltmarsh and this led to an asymmetric layout of samples (many more above the corridor than below). The corridor road was a possible partial barrier to tidal ebb and flow because it was raised at least 1 m above the marsh surface, ran the length of the corridor and used a restricted number of culverts to maintain tidal flow. It might have modified tide levels on at least one side of the barrier. These effects in turn might have altered vegetation, obscuring or complicating other vegetation change.

No pipeline launching took place after 2001 and formal monitoring reporting ceased at that time. The corridor was partly restored in 2006. Stone and culverts were removed from creek and mudflat sectors. The raised stone road elsewhere was reduced to marsh (or dune floor) level, but the remaining stone and a weak geotextile were left in place to avoid major disturbance to underlying sediment. No regular systematic monitoring was undertaken after restoration to study the speed of habitat response or creeks to restored near-natural tidal conditions.

An assessment of road impacts requires a series of steps to isolate and identify these effects.

First, the integrity of DCA ordination results needs to be validated, particularly the strength of the elevation gradient on DCA Axis 1. Regression analysis (Figure 9) indicates a significant negative linear relationship with LiDAR elevation but the LiDAR data are gathered from a single overflight (probably in 2012 but exact date unknown). The same quadrat elevation had to be inserted for each date of survey and this is obvious in Figure 9 as 92 horizontal quadrat strings of dots representing 14 survey years (13 surveys in the case of Blue Pool quadrats). Given the strength of regression (R^2 = 0.817) it is possible that DCA Axis 1 coordinates contain better information on elevation change over time, enabling this limitation in LiDAR data to be overcome.

Second, any strong patterns of change either side of the road, contrasting with additional samples in the Blue Pool area (9 quadrats), within a different saltmarsh catchment, need to be related, if possible, to results of other monitoring (AURIS 1992a, b; 1993a, b; 1994a, b; RSK Environment Ltd. 1995, 1996, 1997, 1998, 1999, 2000, 2001, 2002), plus earlier pre-corridor work on tidal forcing of groundwater (Hansom & Leafe 1990; Leafe 1990).

Third, tidal information for the Morrich More area between 1987 and 2013 is required, developed as a set of models covering a range of sea-level change scenarios including road impact, eustatic sea-level rise and isostatic sea-level fall.

Finally, if road effects on vegetation are present and are important, the validity of the Morrich More permanent quadrat data set must be considered as a basis for investigating sea-level - induced habitat change.

This section examines the above matters in the following sequence:

i. Pipeline corridor monitoring is reviewed, covering tidal, groundwater and culvert/creek monitoring studies. This also includes reference to relevant Sheffield University research (Hansom & Leafe 1990; Leafe 1990).

ii. Earlier ordination studies of permanent quadrat data are reviewed.

iii. The suitability of DCA ordination results for this type of investigation is considered by looking in more detail at regression analysis using annual data sets, followed by a plot of DCA quadrat positions in relation to the pipeline launch corridor.

iv. Morrich More tides are modelled to estimate an annual average tide elevation. Results are then modified as seven further tidal model variants, one reflecting likely road modifications north of the pipeline corridor.

v. Subset analysis is used to take account of road position, quadrat elevation (above or equal to/below MHWS, 1.98 mOD) and strandplain position (inner or outer). Graph comparison (smoothing splines) of predicted elevation (DCA Axis 1) is used to compare subsets, as well as comparing subset trends with different tidal models.

vi. A second subset analysis was applied to drainage change over time (DCA Axis 2) using the same approach as for elevation.

vii. The validity of the permanent quadrat data set is assessed in the context of results from i to vi above.

3.4.1 Tidal, groundwater and culvert/creek monitoring

A tidal gauging programme was maintained by consultants acting for the road corridor developer between 1991 and 2001. Two water level recorders were used at a culverted location, sited each side of the road, with records maintained over one week periods in summer and winter by AURIS (each sufficient for one spring to neap cycle), followed by two weeks in autumn or early winter by RSK. Early tidal reporting in AURIS (1993a, b; 1994a, b) includes brief results for December 1990, July 1991 and November 1991, with more detail for May 1992 and November 1992 including graphs and tide gauge charts. The siting of tide gauges changed in 1992 from Fendom Burn to outer Morrich More (Chainage 4495) and that site was maintained in 1993. Locations were switched by RSK back to Fendom Burn in 1994. Detailed tidal information and graphs are given in most RSK monitoring reports from 1994 onwards. Gauge comparisons were used by consultants to assess short-term (hourly) and longer term (spring to neap cycles) patterns in level difference either side of the road.

The following points attempt to summarise a considerable volume of monitoring data and comment (>4000 pages), as well as identifying important gaps in information:

(i) no pre-development baseline studies were undertaken on tides and hence there can be no comparison between conditions during pipeline corridor operation and pre-development natural variation. Some tidal information is available in Leafe (1990) and Hansom & Leafe (1990), derived from a water-level recorder sited on outer Morrich More immediately north of Inver Bay. This is not comprehensive and was mainly gathered for use in saltmarsh groundwater studies.

(ii) Most information comes from Fendom tide gauges and there was no two-pair comparison in 1992/93 when gauging position was changed. It is possible that tidal effects at Fendom and Chainage 4495 differ because the Fendom Burn carries drainage discharge from the interior of Morrich More. There is no information on the effects of interior discharge on tide levels.

(iii) In 1992 (AURIS 1993a) a 2-3 h lag was noted before tide levels were at equilibrium on both sides of the road, during both rising and falling tides. A change in instruments in 1993 (AURIS 1994a) recorded much shorter lags. Short lags are also a feature of RSK monitoring and that initial long lag time is probably an error. This also casts doubt on the overall accuracy of 1992 tide gauging equipment. This large lag time was not considered to be highly significant, since the maximum difference between the two sides was 'only' 10 – 12.5 cm. However, that difference represents about 10% of the tidal range occupied by Morrich More middle and upper saltmarsh and it was likely to drive vegetation change. Records for 1992 and 1993 showed seaward levels higher than landward, with a difference of 4-5 cm common in the short AURIS observation periods.

(iv) RSK tidal records over two autumn weeks per year varied in timing, with start times between 22 September and 15 November. This might have affected the scale of difference between landward and seaward gauges.

(v) Tide level height and duration differences between seaward and landward tide gauges vary considerably between 1993 and 2001. Tide height information is limited for 1992 and 1993 but seaward levels were higher than landward (noting that records are from Chainage 4495). In 1994 (Fendom siting) landward tidal levels were 5 – 6 cm higher than seaward. This pattern was reversed in 1995 (1 – 10 cm higher to seaward) and in 1996 (2 – 3 cm higher to seaward). Thereafter (1997 to 2001) landward tidal levels were higher than seaward and the difference seemed to increase over time: 1997 2 -3 cm; 1998 4–5 cm; 1999 7–8 cm; 2000 9-10 cm; 2001 9–10 cm. The higher water on the landward side showed large spring tide spikes (0.4 – 0.6 m) but only for a very short duration, followed by slow falls in level which maintained the notable landward – seaward height difference for 6 hours or more on a single tide. Over the remainder of a single tidal cycle (for both springs and neaps) the landward marsh has water levels of the order of 0.05 m higher than to seaward for the period 1997 to 2001. Overall, the year to year differences in road-affected tidal levels, as well as variability in the scale of height difference either side of the road, should be considered large enough to affect vegetation.

(vi) There was no reference to rising sea levels in monitoring reports. There was discussion in results for 1996 and 1997 of a possible fall in sea level in Inver Bay as an explanation of results (a change from 1996 seaward higher to 1997 landward higher). The commentary was inconclusive and was not raised in later reporting (because higher landward records occur in all years after 1996).

(vii) University of Sheffield groundwater research established piezometer (dipwell) transects in 1988 and 1989 (Hansom & Leafe 1990; Leafe 1990). Three (A-C) ran NW-SE and a fourth (D) SW-NE was located close to the proposed road corridor and to its north. Changes in groundwater were recorded during daylight hours over several summer and equinoctial tides. These were correlated with tidal records and significant regressions were found for May, June-July and September data sets. There was a weaker result for June-July, probably due to evapotranspiration also affecting water levels. The strongest regression (groundwater level = 0.383 tide level + 1.04, R^2 = 0.87) was in September 1989. These results demonstrate tidal forcing very clearly. Groundwater level lagged behind tide level by about 20 minutes.

(viii) These piezometer transects were re-used between 1991 and 2001 for saltmarsh groundwater monitoring after road construction, adding a fifth transect (E) running south of the corridor and close to it, SW to NE, parallel with transect D. Observations of watertable level were made +/- 1 h high and low water for a spring to neap tide cycle. Two piezometer transects (A and C) are close to vegetation transects T2 and T3 (Figure 3), with the third (B) transect between these. Monitoring reports do not relate vegetation change to piezometer results. Reports recorded groundwater levels and give the elevation of piezometers (top of pipe) but, worryingly, these elevations differed from year to year (they should be constant). This casts doubt on using these results on a year to year basis. There was no assessment in monitoring results of groundwater level differences north and south of the road (Transects D and E). Instead, discussion concentrated only on Transects A – C with 15 piezometers (only two located south of road).

(ix) The 1993 (AURIS 1994a) reporting on hydrology (piezometer readings) considered the road to be affecting saltmarsh groundwater levels for 300 – 400 m into adjacent landward marsh areas, with large changes (lowering of groundwater) in levels north of the road. In addition, it was recorded that, where the road lies more than 20 or 30 metres from the marsh edge or a creek, ponding occurred during virtually all tidal cycles during the year. No later report infers such a large distance of effect for the road but ponding close to the road is frequently mentioned and it might have increased over time. There is no linkage in reports between surface water ponding and the development of higher average tide levels north of the road. There was no mapping of ponding distribution, nor of its duration.

(x) Monitoring comment in 1995 (RSK 1996) suggests that groundwater variation might have equilibrated, following considerable year-to-year change in 1993 and 1994. Discussion emphasised that it was difficult to confirm equilibrium without reference to a pre-development baseline. This conclusion (and caveat) is also made in 1996 and 1997. However, more variability was noted in 1998 and the comment on equilibrium is not made again in subsequent annual reports. There is reference to Hansom & Leafe (1993) in RSK (1997, 1999, 2001) but there was no attempt to use the Sheffield University results as a summary of pre-development natural variability and assessment of equilibrium character.

(xi) Groundwater results for piezometer transects only covered a single spring to neap sequence, using records +/- 1 h of high and low tide measurements during daylight hours (usually recording 14/15 values per season per dipwell). Transect–to–transect and year-to-year variation was considerable. Rainfall records were not collected to aid interpretation, particularly for summer tides when flooding was not extensive and rainfall/evapotranspiration interplay would have been important in controlling the development of high salinity upon the upper marsh. It is impossible to generalise from aggregated results in RSK (2002) and it is probably unsafe to use findings for assessing effects on vegetation over several years. It is likely that monitoring in present times would use water-level loggers to gather the key information, supplemented by water sampling for chemical analysis.

(xii) Overall, monitoring reports provided no concluding account of the effects of the development corridor upon tide and saltmarsh groundwater. There is a major gap in yearly recording, with no reporting between 2001 and 2006 when the corridor was still in place. There has been no monitoring of tide or saltmarsh groundwater since the corridor was restored in 2006.

(xiii) Culvert and creek monitoring was done by detailed topographical surveys of selected sample locations. AURIS work considered that it took 1 to 2 years for creeks, culvert surrounds and creek sediment to adjust to the constructed road.

(xiv) There has been no monitoring of sediment balance for the main marsh surface but there was speculation in some reports that higher tide levels north of the road had durations sufficient to increase sediment deposition. There is almost a complete lack of information on sediment balance for Morrich More and this is perhaps the most serious weakness in its information set.

3.4.2 Vegetation response to pipeline corridor development

Early monitoring reports did establish evidence of vegetation change and there has been one further study of permanent quadrat data (Dargie 2001).

Effects on vegetation were noted in an interpretation of DCA ordination by Professor C. H. Gimingham (University of Aberdeen), covering 1990 and 1992 permanent quadrat records (AURIS 1993a, b). The stated 1990 records were probably from 1991 recording (no quadrat data explicitly dated 1990 are present in monitoring reports held by SNH). Changes in vegetation over time (drying of upper marsh, wetting of middle marsh) were interpreted as perhaps an early effect of the corridor acting as a partial tidal barrier. Ordination was abandoned as an interpretation method after the contract for monitoring was transferred to another consultancy (RSK) in 2004. There was no further assessment in monitoring reports of the early changes initially detected by Gimingham.

RSK analysis of vegetation data was done quadrat by quadrat, comparing one year with the earlier year. Annual conclusions considered natural year-to-year variability was responsible for observed changes. The quadrat set was never examined using multivariate methods. RSK (2002) sets out each quadrat with species Domin scores for each year between 1994 and 2001. Many quadrats show systematic gradual reductions, year by year, in cover for several species, with minimum scores around 1995 and 1996, followed by increases thereafter. Opposite trends are also present. There are increases in *Puccinellia maritima* and *Suaeda maritima* around 1995 and 1996, with declines before and after that period. The significance of these two pattern sets is missed in all monitoring commentary. The two pattern sets occur in quadrats around the road corridor and in those located, as controls, in the Blue Pool area.

A further ordination analysis was applied to permanent quadrat data for the period 1987 to 1999 (Dargie 2001). This used non-metric multidimensional scaling in conjunction with quadrat elevation data collected in 1993 (but which excluded Blue Pool samples). An elevation gradient was established by regression, but it was much weaker ($R^2 = 0.485$) than that for DCA results in this report ($R^2 = 0.817$). Checking against LiDAR data in 2015 suggested that five Fendom quadrats were assigned 1993 altitudes which were probably 0.5 m too low and this will have contributed to the low explanation in Dargie (2001).

Variation on the second axis was considered to represent wetness (a gradient from waterlogging to drier conditions), as with Gimingham's interpretation. Importantly, analysis of the second axis detected a possible impact of the pipeline corridor road. Larger-than-expected numbers of quadrats north of the road were present in quintiles representing the driest and wettest extremes (13 and 17 quadrats respectively). The equivalent numbers for south-of-road samples were 5 in the driest quintile and 3 in the wettest quintile. There is an imbalance in quadrats either side of the road (55 to the north, 28 to the south, see Figure 3). The dry extreme difference (13/5) was only slight but the north-south difference for the wettest quintile (17/3) was considered evidence of a strong difference in wetness either side of the corridor. Many quadrats involved were a great distance from the corridor centreline, suggesting that the road was responsible for waterlogging over distances extending 500 – 600 metres on the northern side of the corridor. This observation agrees with groundwater commentary in AURIS (1994a). However, freshwater forcing as an alternative explanation to a road effect was not considered in Dargie (2001).

Importantly, the 2001 ordination did not show a marked triangular configuration in the two-axis ordination of samples, as in Figure 8 in this study. This suggests that the strong drainage variation in Figure 8 has developed markedly since 1999 (the latest sample year in the 2001 study).

3.4.3 The suitability of DCA ordination for quantifying elevation and drainage change

The estimated elevation of a quadrat in each survey year was calculated from the DCA Axis 1 – LiDAR RMA regression (Figure 9): elevation (mOD) = 2.6754 - 0.002214 DCA Axis 1. The results of further RMA regressions for each year (LiDAR on DCA estimated elevation) are given in Table 3. The stability of high correlation and very low probabilities of random association suggest that a very similar elevation relationship has persisted through time. It is important to note the steepest regression slopes occur in 1994 and 1995, with more gentle relationships before and after this phase.

Attention is drawn here to the slightly weaker results for 1987 which is the result of sampling in October/November 1987. That was the date of quadrat establishment, immediately after planning permission was granted for the pipeline corridor. All other subsequent sampling has been done in July or early August. The 1987 quadrats have, for example, very low cover values and overall frequency for *Suaeda maritima* and *Salicornia europaea* agg., the possible result of frost kill during exposure at low tide or simply senescence and death at the end of the growing season. This is only one obvious observation on 1987 data and there will probably be other seasonal effects. It is advised that 1987 results are handled with caution – they contain similar trends to other years but sampling outside the growing season has produced weaker data for 1987. The data are excluded in later analysis from graphical plots.

Given the high significant correlations for yearly data sets, the average elevation per year (based on DCA Axis 1 coordinates) is likely to be a reasonable estimate of sea-level effect on vegetation averaged over tides. These values and standard errors are given in Table 4.

There is no statistical difference (variance F test, mean Student t test, $p<0.001$) between northern and southern quadrat subsets, either for DCA Axis 1 or DCA Axis 2 values. This agrees with quadrat scatter in the DCA ordination (Figure 13) which shows an excellent continuum of points. North and south group members are thoroughly mingled, as with Blue Pool samples. A very strong road effect would produce a clear separation of north- and south-of-road samples. Instead, Figure 13 suggests that road effects are absent or, if they exist within the vegetation data, they are subtle in character. Overall, DCA quadrat coordinate output can be considered a sound data source for further analysis.

Table 3. Summary statistics on year-set correlations and RMA regressions, x = Estimated quadrat elevation from DCA Axis 1 (mOD), y = quadrat LiDAR elevation 2012 (mOD)

Year	*r*	R^2	*p*	Constant	Slope
1987	0.888	0.788	4.777 E-29	0.3076	0.86306
1991	0.910	0.827	4.264 E-36	0.0398	0.98442
1992	0.914	0.835	5.805 E-37	0.0280	0.98638
1993	0.916	0.839	1.945 E-37	-0.0597	1.02100
1994	0.913	0.834	8.161 E-37	-0.1118	1.05340
1995	0.905	0.819	3.663 E-35	-0.0865	1.04900
1996	0.902	0.813	1.540 E-34	0.0199	1.00770
1997	0.908	0.824	9.179 E-36	-0.0195	1.02130
1998	0.901	0.811	2.354 E-34	-0.0162	1.01770
1999	0.907	0.823	1.223 E-35	-0.0673	1.03580
2000	0.914	0.835	5.422 E-37	-0.0206	1.00410
2001	0.897	0.804	1.250 E-33	-0.0182	0.99919
2006	0.917	0.841	1.170 E-37	-0.0841	1.01790
2013	0.913	0.834	6.781 E-37	-0.0076	0.98858

Table 4. Estimated average quadrat elevation (mOD) for individual survey years based on DCA Axis 1 regression

Year	Average elevation (mOD) estimated using DCA Axis 1 regression	Standard error	n
1987	2.022	0.035	83
1991	2.014	0.031	92
1992	2.022	0.031	92
1993	2.039	0.030	92
1994	2.026	0.029	92
1995	2.010	0.029	92
1996	1.987	0.030	92
1997	1.999	0.030	92
1998	2.003	0.030	92
1999	2.017	0.029	92
2000	2.035	0.030	92
2001	2.042	0.030	92
2006	2.069	0.030	92
2013	2.053	0.031	92

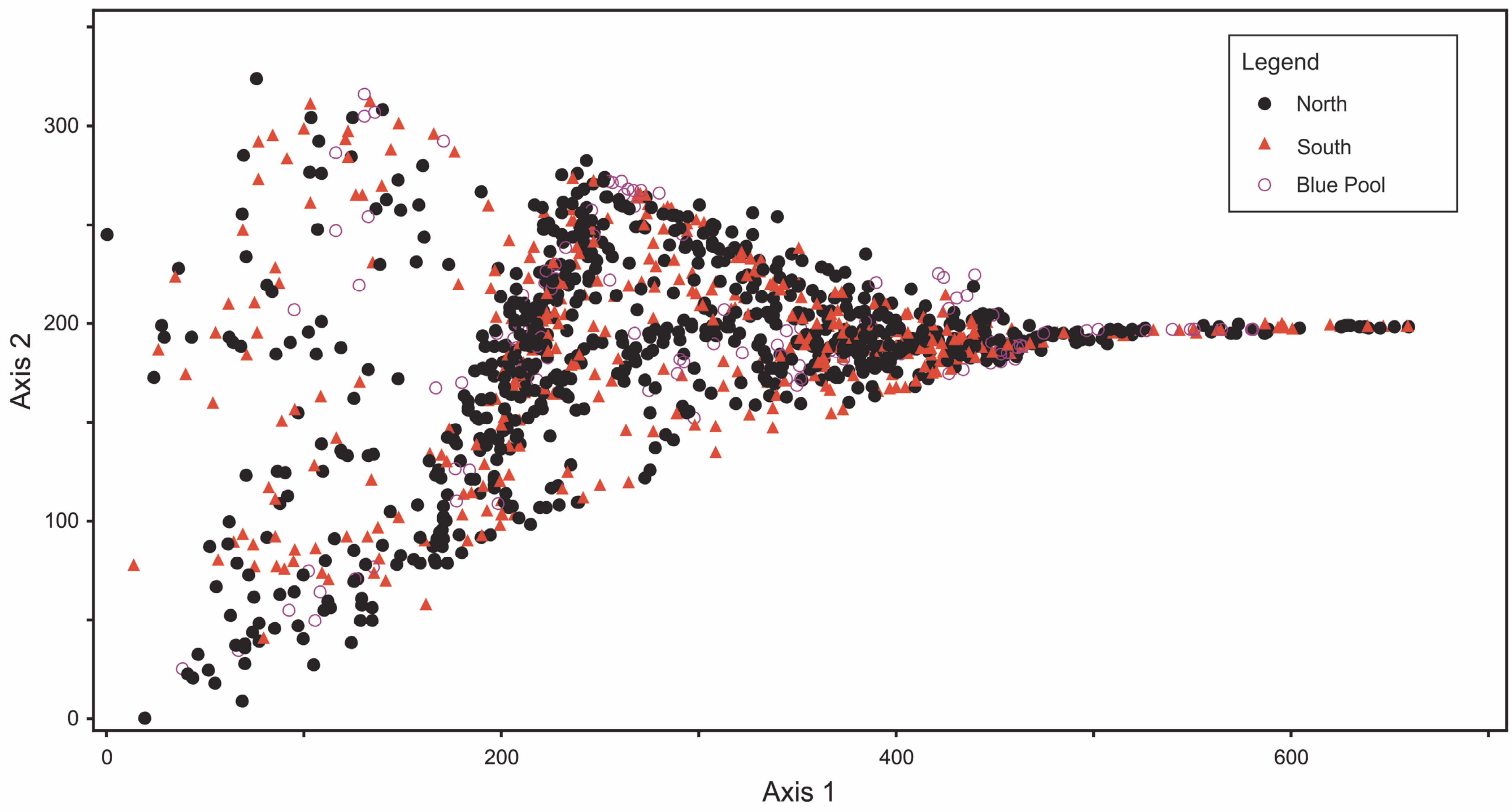


Figure 13. Distribution of North, South and Blue Pool sample subsets upon DCA ordination plot

3.4.4 Tide modelling and adjustment for road effects

Tidal information in previous work is very limited in duration for Morrich More. Modelling is the only available method of gaining information covering the duration of vegetation records, in which a summer average or yearly average can be calculated for each year of vegetation survey, or for the complete period of study (1987 to 2013, a span of 27 years). A yearly average would 'integrate' tidal variation into a single figure, to be related to equivalent averages for vegetation data (e.g. yearly averages of all quadrat scores in DCA ordination).

3.4.4.1 Generating tidal models for Morrich More

Tidal modelling required data from a nearby tide gauge. Data from Wick (approximately 101 km NNE of Morrich More) was initially considered for use as the base for modelling. This is the closest operating tide gauge to Morrich More with a long run of data. However, this site was rejected when detailed inspection revealed that records were very sensitive to the level of terrestrial flow from the River Wick.

Historical tide gauge data (1964 to 1975) from Invergordon (approximately 20 km SSW) was sourced from the British Oceanographic Data Centre (BODC) and the longest run without missing data (as hourly records) was identified. This was almost a year, September 1969 to September 1970. BODC Invergordon records are not openly available because there is uncertainty regarding gauge elevation in relation to local datum changes when the tide gauge was operational. Gauge data were supplied by BODC with this reservation stressed. Despite this uncertainty, it is straightforward to fit these records to Morrich More tides.

WTWC (World Tides World Currents) tidal analysis software (Boon 2004) was used for modelling. This was supplied by Professor John D. Boon, Virginia Institute of Marine Science. It required the Matlab 2012 package for operation. The WTWC software calculated tidal harmonic constants from tide gauge records, with a minimum requirement of at least six months of continuous data. The tidal harmonic constants file was then used to predict tides for a specified period (e.g. a year) and interval (e.g. every 10 minutes), for time periods well outside that for the supplied tide gauge records.

The Invergordon data were initially sent to Professor Boon who considered the information sound, extracting a good set of harmonic tidal constants. His analysis was repeated by the author using WTWC software and Matlab 2012. The harmonic constant data file was then used by the author to generate yearly 10-minute interval tidal data for Invergordon for the period 1987 to 2019.

The predicted high tide levels for Invergordon were regressed (reduced major axis regression, RMA) on 197 high tide levels recorded at Fendom (seaward tide gauge) for the time periods that Fendom data were available between 1993 and 2001 in RSK reports. The regression (Figure 14) was highly significant ($p<0.00001$, $R^2 = 0.797$) and was applied to all annual 1987 to 2019 Invergordon data to produce modelled tide data for Inver Bay:

$$\text{Fendom (mOD)} = 0.36179 + 1.0261 \text{ Invergordon}$$

There was little difference in the timing of high tide between observations at Fendom and WTWC predictions at Invergordon, except for some neap tides. Residuals in Figure 14 will probably be strongly influenced by weather, particularly atmospheric pressure, wind direction and wind speed.

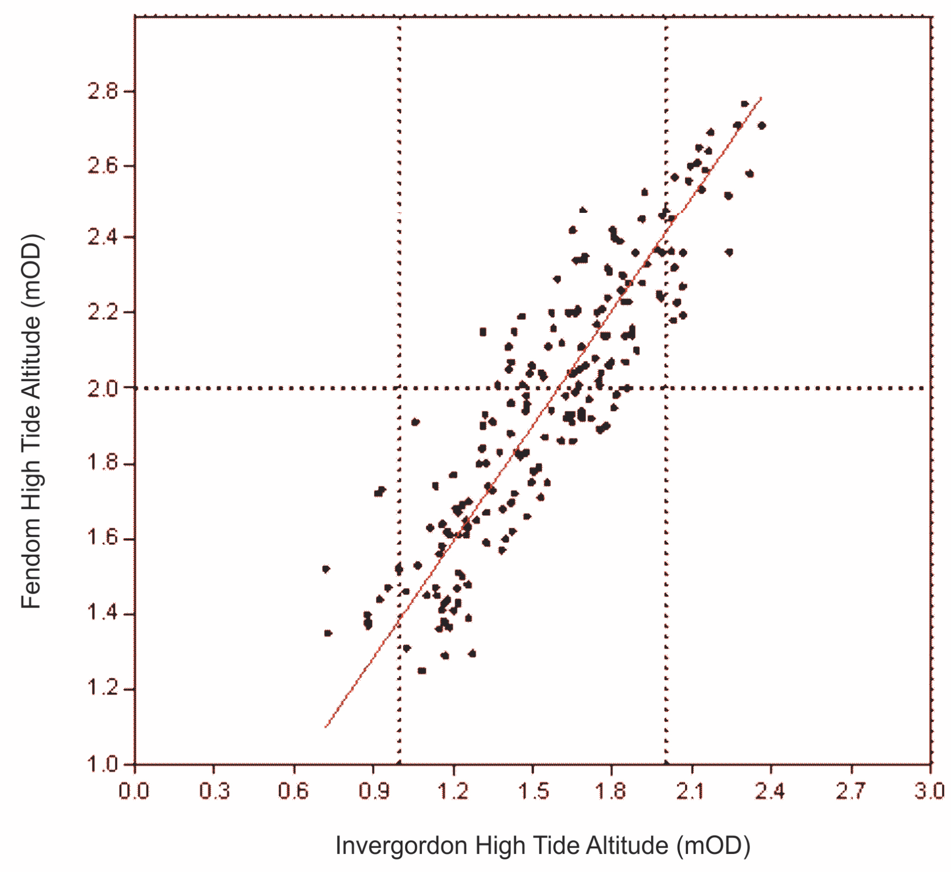


Figure 14. RMA regression of Fendom (Morrich More) high tide (mOD) on predicted high tide for Invergordon (mOD), based on 197 high tides recorded at Fendom between 1993 and 2001.

Eight models of yearly average tide were produced (Table 5), the latter seven (Models 2 – 8) being adjustments made to the first:

i. The first (Model 1) calculated an average annual value using predicted Morrich More tide levels. The average was based on summer tides (16 March to 15 September), applied only to tide levels above 1.30 mOD (the lowest quadrat LiDAR elevation in the permanent quadrat set). Summer tide averages differed only slightly from a full annual average.

ii. The second model (Model 2) adjusted the Model 1 averages to take account of monitored differences (1992 to 2001) in tide elevation north and south of the corridor road. The 2001 adjustment was also applied to the period 2002 to 2006, when the road remained in place but no monitoring was done. It is uncertain if 2006 vegetation data was influenced by restored tidal conditions following removal of culverts and road removal to saltmarsh surface. Exact details of restoration timing are not available (it was certainly complete by August) and this 2006 adjustment might be incorrect. The 2006 value could be closer to the Model 1 value. The adjusted data set applies only to quadrat sets north of the road corridor (i.e. southern quadrat and Blue Pool sample locations are assumed to have been unaffected by the road).

iii. The third model (Model 3) adds 1 mm per year to Model 1 values, to simulate a 1.0 mm eustatic rise in sea level based on 1.4 mm/year estimate for the British Isles over the 20th century (Rennie & Hansom 2011), reduced annually by 0.4 mm to reflect isostatic change (rate of sea-level fall) in this part of the Inner Moray Firth (exact value uncertain).

iv. The fourth model (Model 4) subtracts 0.4 mm per year from first model values, to reflect only isostatic change, assuming the long-term pattern of sea-level change (isostatic rebound exceeding eustatic rise) has persisted in recent decades.

v. The fifth model (Model 3A) was constructed as for Model 3, but used 2 mm as an annual rate of eustatic sea-level rise.

vi. The sixth model (Model 4A) was constructed as for Model 4, but used 0.8 mm per year as an annual rate of isostatic rebound (falling sea level) exceeding eustatic rise.

vii. The seventh model (Hybrid Model 1) assumed Model 4 conditions until 1999 (falling sea level), followed by a switch to Model 3 for 2000, 2001, 2006 and 2013 (rising sea level).

viii. The eighth model (Hybrid Model 2) assumed Hybrid Model 1 conditions up to and including 2001, adding model 3A conditions (accelerated sea-level rise, 2 mm per year) for 2006 and 2013.

The model data in Table 5 are graphed in two ways:

i. First, the full annual average sequence between 1987 and 2013 (Figure 15) uses a sinusoidal fit to variation over time, applied to Models 1 to 4. Six amplitude/phase/period additions are used in the fit for Model 1 (Figure 15a, R^2 = 0.999). The fit for other models is slightly weaker because non-tidal elements have been introduced.

ii. Second, a smoothing spline is used to trace trend through time, applied only to years with vegetation survey (Figure 16 for Models 1 to 4, Figure 17 for Models 5 to 8). The number of sample years, 14, is too small for more sophisticated time series analysis and a spline is needed to provide a trend for years without data. Comparing Figure 16 with Figure 15, the switch to only quadrat survey years obscures much year to year variation in missing intervening years (1988 to 1990, 2002 to 2005, 2007 to 2012).

Despite obscured variation, this use of splines is important because it is also applied below to vegetation data (Figures 18, 19) and allows comparison of tidal models with vegetation (DCA output) on an equivalent visual basis.

3.4.4.2 Average tidal variation between 1987 and 2013

The maximum range for Model 1 average summer tides (Table 5, Figure 15a) is 0.058 m (1995 tidal maximum minus 2005 tidal minimum). This is a considerable difference which, on a yearly average change basis over 10 years, approximates 6 mm/year of sea-level change at Morrich More. This is much larger than 20th century and current annual rates of regional eustatic sea-level rise or isostatic sea-level fall reviewed in Rennie & Hansom (2011). An understanding of the variability in average predicted summer tide height is given below.

The first and most important period identified in the sinusoidal fit for Model 1 (Figure 15a) has a duration of 18.57 years. This represents tidal variation due to the 18.61-year lunar nodal cycle which is the result of the moon’s orbital plane differing from the sun's 23.5° ecliptic. The lunar orbital plane varies by about 5° either side of the ecliptic on a cycle taking 18.61 years to complete (Boon 2004).

The moon's tide-producing astronomical force varies, amongst other factors, with the angle (declination) between the sun's ecliptic and the lunar orbital plane (Haigh *et al*. 2011). The highest and lowest tides (and hence maximum tidal range) produced by the 18.61-year cycle occurs at the minimum declination, termed lunar nodal minimum. July 1978, March 1997 and October 2015 were the three most recent lunar nodal minima. Each produced highest and lowest astronomical tides. A lunar nodal maximum declination (lowest tidal range) occurs with a lag time of 9.305 years after a nodal minimum. March 1969, November 1987 and June 2006 were the most recent lunar nodal maxima. The length of the cycle and its contribution to tidal range result in periods of sustained very high tidal ranges for a year or more around the time of a lunar nodal minimum. The reverse (low tidal ranges) occurs around the time of lunar nodal maximum. The character of lunar tidal forcing also varies with declination (Ray 2007). Large declination (around lunar nodal maximum) maximizes diurnal forces at the expense of semidiurnal, with the reverse at lunar nodal minimum.

The lunar nodal cycle is only one component of Morrich More tidal variation and other important tidal harmonic components produce sharp changes from year to year. Importantly, these obscure the lunar nodal component in Figure 15a. The lunar nodal minimum in 1997 is not a peak year in terms of average predicted summer tide height. Instead, it is markedly lower and sits between three-year long periods of higher averages either side (1994-1996, 1997-2000). There is also a disparity for the 2006 lunar nodal maximum year, which has a higher average height compared to the notably lower minimum in 2005.

Model 2 (Figure 15b) is distinct and shows as expected a prolonged period of tidal ponding north of road between 1997 and 2006 (the year of road restoration). A three-year period of falling ponding levels (1994 to 1996) noted in monitoring reports (section 3.4.1) is also clear. Model 3 (Figure 15c) and Model 4 (Figure 15d) both show moderate but progressive change over time when compared to Model 1. These changes reflect the size of annual adjustments made to Model 1 data (+1 mm per year for Model 3, -0.4 mm per year for Model 4).

The over-simplification imposed by years without vegetation sampling creates large visual differences between each model in its full form (Figure 15) and spline equivalent (Figure 16). However, comparing the model shapes in Figures 15 and 16 shows that the differences in model construction are retained in Figure 16 results. Model 2 (Figure 16b) remains very distinct. The variant shapes of Model 3 (Figure 16c) and Model 4 (Figure 16d) are very clear when related to Model 1 (Figure 16a). The main weakness of all spline graphing is the lack of data for the missing years after 2001, making the right-side of Figure 16 graphs dependent on only 2006 and 2013 values. Spline graphing retains much information, despite this weakness.

All variants developed from Model 1, except for Model 2, contain a similar pattern of 'roller-coaster' rises and falls. Eustatic modification increases average tide height through time until in 2013 it almost equals the 1995/96 tidal maximum (Model 3, Figures 15c and 16c) and strongly exceeds it in Model 3A (Figure 17a). Isostatic modification (Models 4 and 4A) show the reverse in Figures 16d and 17b. Hybrid models (Figures 17c and 17d) show the early isostatic phase followed by strong eustatic adjustment from 2000 onwards.

Table 5. Modelled summer average tide level (mOD) for Morrich More

Shading marks years with data adjusted for possible road barrier effect (data based on road corridor monitoring results)

Year	Model 1	Model 2	Model 3	Model 4	Model 3A	Model 4A	Hybrid Model 1	Hybrid Model 2
1987	1.754	1.754	1.754	1.7540				
1988	1.761	1.761	1.762	1.7606				
1989	1.746	1.746	1.748	1.7452				
1990	1.753	1.753	1.756	1.7518				
1991	1.765	1.715	1.769	1.7634	1.773	1.7618	1.7634	1.7634
1992	1.775	1.725	1.780	1.7730	1.785	1.7710	1.7730	1.7730
1993	1.764	1.724	1.770	1.7616	1.776	1.7592	1.7616	1.7616
1994	1.780	1.820	1.787	1.7772	1.794	1.7744	1.7772	1.7772
1995	1.794	1.784	1.802	1.7908	1.810	1.7876	1.7908	1.7908
1996	1.792	1.762	1.801	1.7884	1.810	1.7848	1.7884	1.7884
1997	1.770	1.870	1.780	1.7660	1.790	1.7620	1.7660	1.7660
1998	1.786	1.831	1.797	1.7816	1.808	1.7772	1.7816	1.7816
1999	1.791	1.866	1.803	1.7862	1.815	1.7814	1.7862	1.7862
2000	1.780	1.875	1.793	1.7748	1.806	1.7696	1.793	1.793
2001	1.753	1.848	1.767	1.7474	1.781	1.7418	1.767	1.767
2002	1.769	1.864	1.784	1.7630				
2003	1.769	1.864	1.785	1.7626				
2004	1.753	1.848	1.770	1.7462				
2005	1.736	1.831	1.754	1.7288				
2006	1.759	1.804	1.778	1.7514	1.797	1.7438	1.778	1.797
2007	1.764	1.764	1.784	1.7560				
2008	1.751	1.751	1.772	1.7426				
2009	1.745	1.745	1.767	1.7362				
2010	1.771	1.771	1.794	1.7618				
2011	1.780	1.780	1.804	1.7704				
2012	1.770	1.770	1.795	1.7600				
2013	1.775	1.775	1.801	1.7646	1.827	1.7542	1.801	1.827

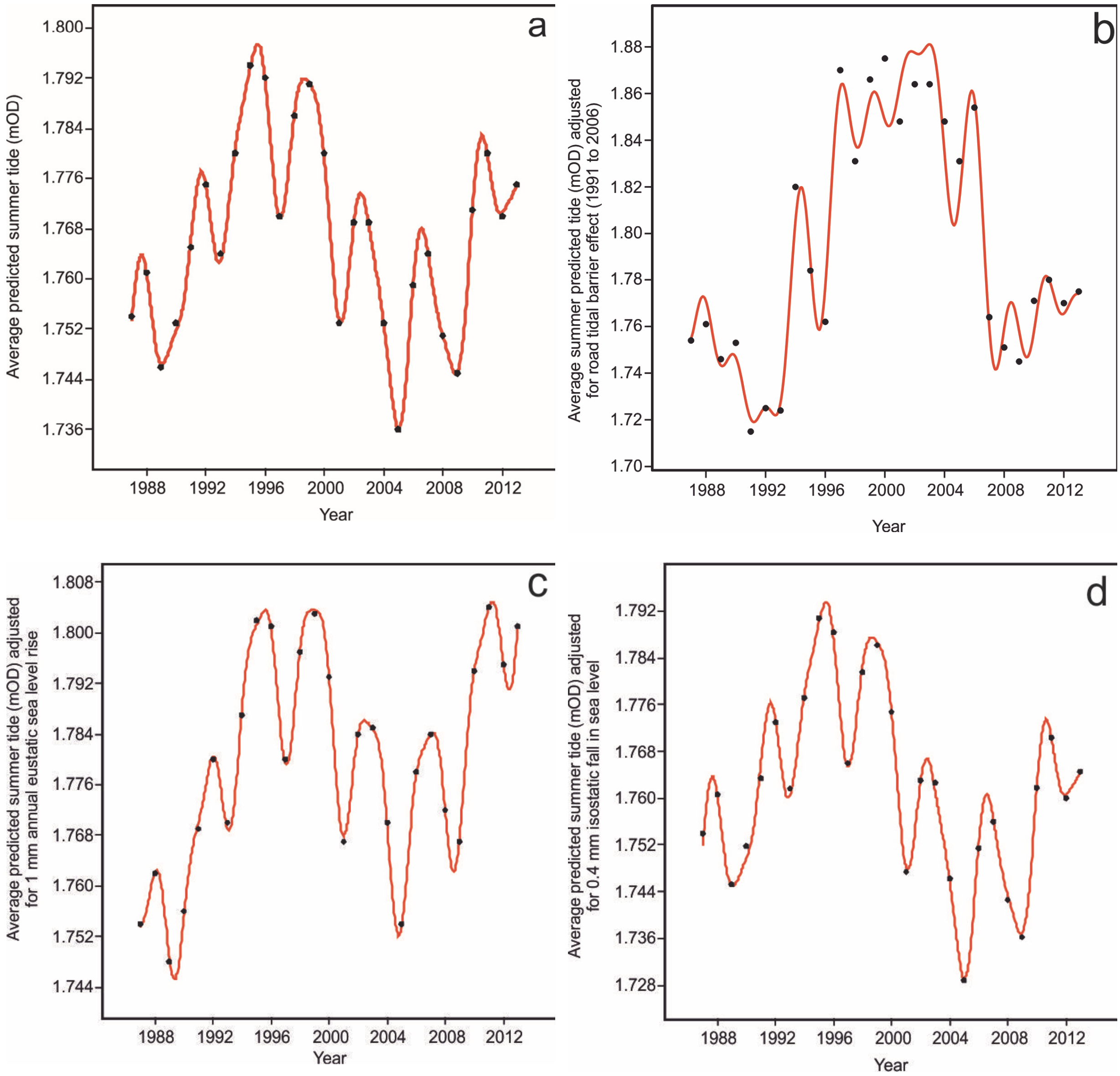


Figure 15. Sinusoidal fit for average predicted summer tides >1.30 mOD 1987 to 2013
a Model 1; b Model 2; c Model 3; d Model 4

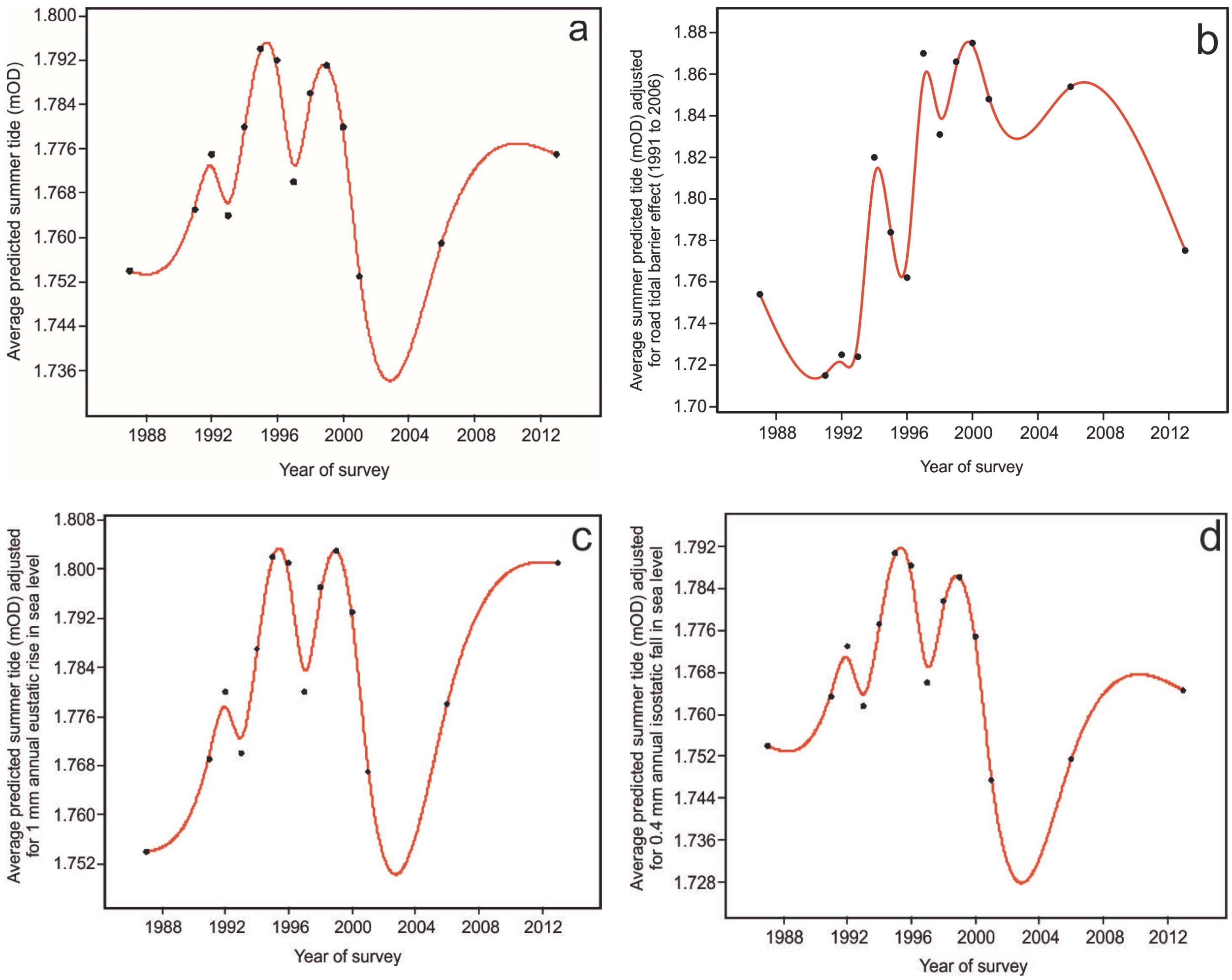
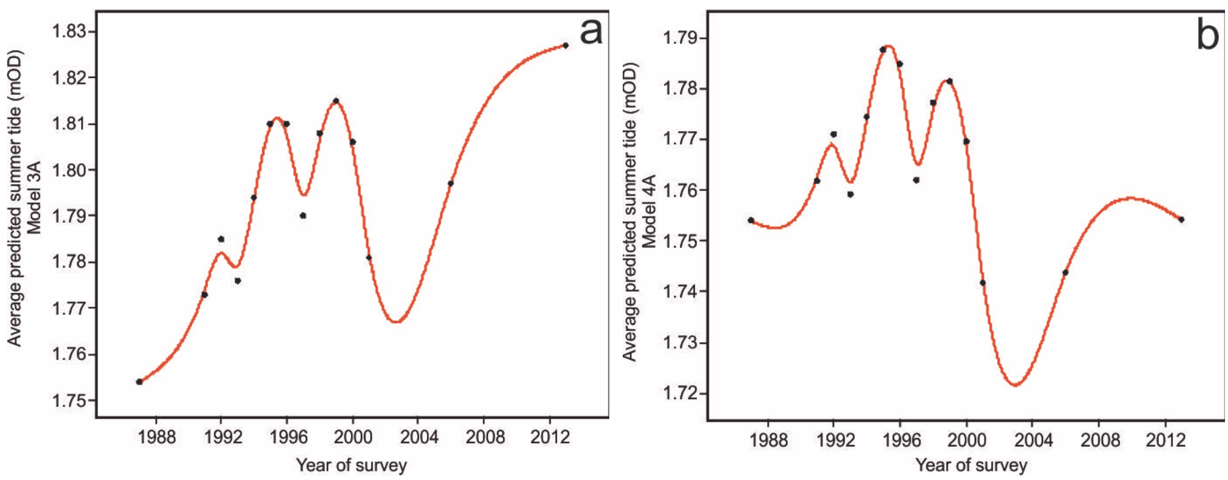


Figure 16. Smoothing spline fitted to modelled average tide levels for 14 survey years a Model 1; b Model 2; c Model 3; d Model 4



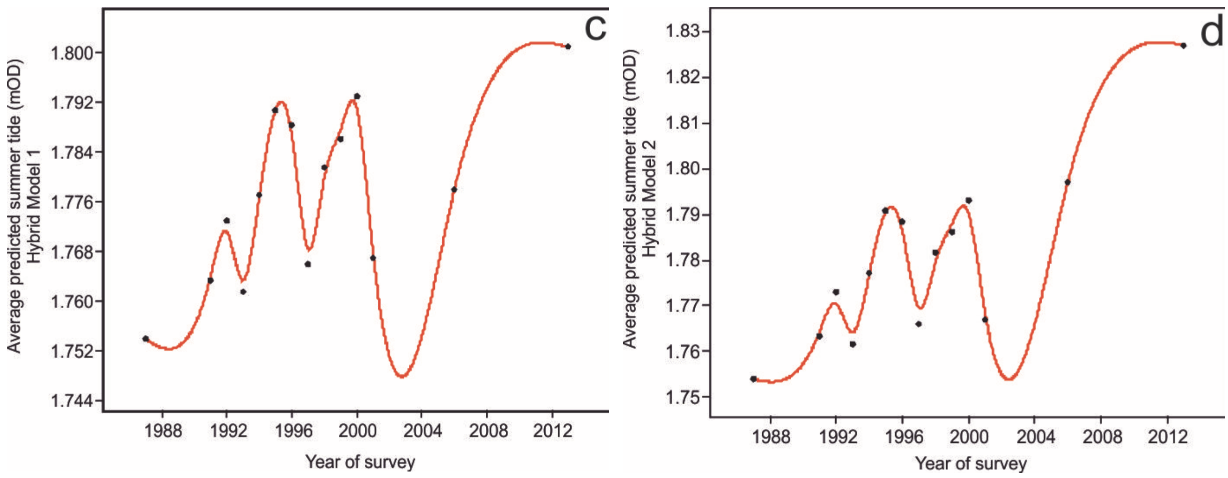


Figure 17. Smoothing spline fitted to modelled average tide levels for 14 survey years a Model 3A; b Model 4A; c Hybrid Model 1; d Hybrid Model 2

The modelling results allow discrimination of different tidal, eustatic, isostatic and road barrier effects within a small family of spline shapes. These shape forms can now be compared to those extractable from vegetation data, as summarised upon DCA Axis 1 and Axis 2. It is assumed here that annual average elevations calculated from DCA ordination are reasonable proxies for an annual sea-level effect on vegetation, expressed through tidal variation. Duration, depth and extent of tidal inundation are well-known, accepted drivers of zonation on saltmarsh (Ranwell 1972; Adam 1990). The species 'balance' recorded as Domin scores should be a good measure of the preceding tides and tidal cycles in a growing season, i.e. it is a proxy of preceding tidal conditions. The same principle should also apply to drainage conditions, especially since Morrich More tides are known to force saltmarsh groundwater levels (Hansom & Leafe 1990; Leafe 1990).

There is now the opportunity to compare the shape of vegetation splines based on DCA-derived annual averages with the shape of the eight spline-forms of the tidal models discussed above (Figures 16 and 17). If there is a close fit between a vegetation spline and one or more tidal models, this will suggest the drivers of sea-level change affecting vegetation between 1987 and 2013.

3.4.5 Subset structuring of the 2015 DCA ordination analysis

Subset analysis is used below to investigate the interaction between possible road effects, marsh elevation and strandplain position within DCA vegetation results. The full quadrat set and subsets are treated as a sample population and sub-populations respectively. There is no reference to the behaviour of individual quadrats over time. The analysis excludes 1987 quadrats due to late sampling and lack of Blue Pool samples.

Subset analysis divides the quadrat population of 92 into three sub-group sets:

i. First, they are split into sets north and south of the road corridor (55 quadrats to the north, 28 to the south). Blue Pool quadrats (9 samples recorded between 1991 and 2013) are included as a further subset. They are in a different saltmarsh catchment to the main set either side of the development corridor. The separation into northern and southern subsets allows comparison seeking evidence of a road effect in vegetation response over time.

ii. Second, the 92-quadrat population is divided by 2012 LiDAR altitude (≤1.98 mOD 43 samples at or below MHWS; >1.98 mOD, 49 samples above MHWS). This enables tide influence to be compared between lower and upper marsh over time.

iii. Third, the 92-quadrat population is divided by position on the Morrich More strandplain. Outer samples (total 58) are those lying north-east of all dune slacks (Blue Pool, quadrats 1 to 51). Inner strandplain samples cover quadrats 53 to 85 in Figure 3 (total 34 quadrats) and lie south-east and south-west of dune slacks. This division seeks evidence of different vegetation response to change over time between the outer strandplain and inner parts of Inver Bay (including Fendom).

This subdivision structure was used after disregarding an earlier analysis using a more complicated division (Blue Pool, three Inver Bay zones north-of-road and three Inver Bay zones south-of-road). This was discarded because of severe imbalances between quadrat numbers in sub-sets. Very small sample sets produced averages with very large standard errors (or no average at all) and these sets were considered unsafe for tracking change in vegetation through time.

To illustrate this problem of sample imbalance, the above subset divisions (BP Blue Pool, N North, S South, L Lower, U Upper, I Inner, O Outer) can be reconstructed as 10 possible groups. Their quadrat totals for any year of sampling between 1991 and 2013 would be: BPUO 2, BPLO 7, NUI 13, NLI 1, NUO 20, NLO 21, SUI 12, SLI 8, SUO 2, SLO 6. More than half of these totals are <10 and two (BPUO, SUO) are too small to be at all reliable. The subset divisions provide adequate totals, except for Blue Pool (9 quadrats). This subset is handled with care.

The initial layout in 1987 was not done at random. This makes formal statistical testing very difficult, if not impossible. Instead, analysis here is descriptive. It uses smoothing spline graph comparison to compare subsets, as well as comparing subset and different tidal model graphs.

Average yearly values for DCA Axis 1 elevation and DCA Axis 2 coordinates were calculated for the all-quadrat set and seven subsets (BP, N, S, L, U, I, O). Elevation values are given in Table 6. DCA Axis 2 values (drainage/wetness) are given in Table 7. These averages were used to construct smoothing splines. DCA elevation splines are presented in Figure 18. DCA Axis 2 splines are presented in Figure 19.

Table 6. Annual elevation averages for 92 permanent quadrat set and subsets

Predicted elevation averages (mOD) based on DCA Axis 1 coordinates								
Year	All Quadrats	Blue Pool	North of Road	South of Road	Upper Marsh	Lower Marsh	Inner Strandplain	Outer Strandplain
1991	2.014	1.742	2.074	1.983	2.217	1.782	2.142	1.939
1992	2.022	1.757	2.094	1.964	2.224	1.791	2.135	1.955
1993	2.039	1.775	2.111	1.984	2.232	1.819	2.142	1.979
1994	2.026	1.772	2.099	1.965	2.210	1.816	2.105	1.979
1995	2.010	1.768	2.086	1.940	2.201	1.794	2.103	1.956
1996	1.987	1.747	2.051	1.938	2.188	1.758	2.101	1.920
1997	1.999	1.777	2.062	1.946	2.195	1.776	2.118	1.930
1998	2.003	1.758	2.074	1.943	2.190	1.789	2.111	1.940
1999	2.017	1.765	2.087	1.963	2.205	1.803	2.123	1.955
2000	2.035	1.774	2.113	1.965	2.229	1.813	2.141	1.972
2001	2.042	1.756	2.121	1.979	2.235	1.822	2.152	1.978
2006	2.069	1.834	2.147	1.991	2.262	1.850	2.157	2.018
2013	2.053	1.798	2.125	1.995	2.250	1.830	2.151	1.996
Maximum	2.069	1.834	2.147	1.995	2.262	1.850	2.157	2.018
Minimum	1.987	1.742	2.051	1.938	2.188	1.758	2.101	1.920
Range	0.082	0.092	0.096	0.057	0.074	0.092	0.057	0.097
Quadrats	92	9	55	28	49	43	34	58

Table 7. Annual drainage/wetness averages for 92 permanent quadrat set and subsets

	Drainage/wetness averages (DCA Axis 2 coordinates)							
Year	All Quadrats	Blue Pool	North of Road	South of Road	Upper Marsh	Lower Marsh	Inner Strandplain	Outer Strandplain
1991	185.0	178.1	191.8	173.8	179.2	191.5	172.1	192.5
1992	183.1	174.0	188.1	176.2	180.4	186.2	171.6	189.8
1993	187.7	175.0	198.1	171.4	186.1	189.4	176.7	194.1
1994	187.3	173.9	195.3	176.0	188.7	185.8	179.4	192.0
1995	192.5	171.5	201.3	182.1	198.6	185.6	189.8	194.2
1996	188.6	178.2	196.3	176.7	190.6	186.2	183.8	191.3
1997	188.9	169.9	197.5	178.1	190.2	187.3	180.5	193.8
1998	186.6	172.2	193.4	177.6	189.8	182.8	178.6	191.2
1999	189.3	174.4	197.8	177.3	191.0	187.3	179.3	195.1
2000	190.4	177.6	200.4	174.8	191.7	188.9	175.0	199.4
2001	183.2	175.2	189.8	172.9	181.0	185.8	167.0	192.8
2006	179.5	170.7	186.1	169.5	175.7	183.9	166.8	187.0
2013	192.9	174.4	204.2	176.6	199.3	185.6	179.9	200.5
Maximum	192.9	178.2	204.2	182.1	199.3	191.5	189.8	200.5
Minimum	179.5	169.9	186.1	169.5	175.7	182.8	166.8	187.0
Range	13.4	8.2	18.2	12.6	23.7	8.7	23.0	13.5
Quadrats	92	9	55	28	49	43	34	58

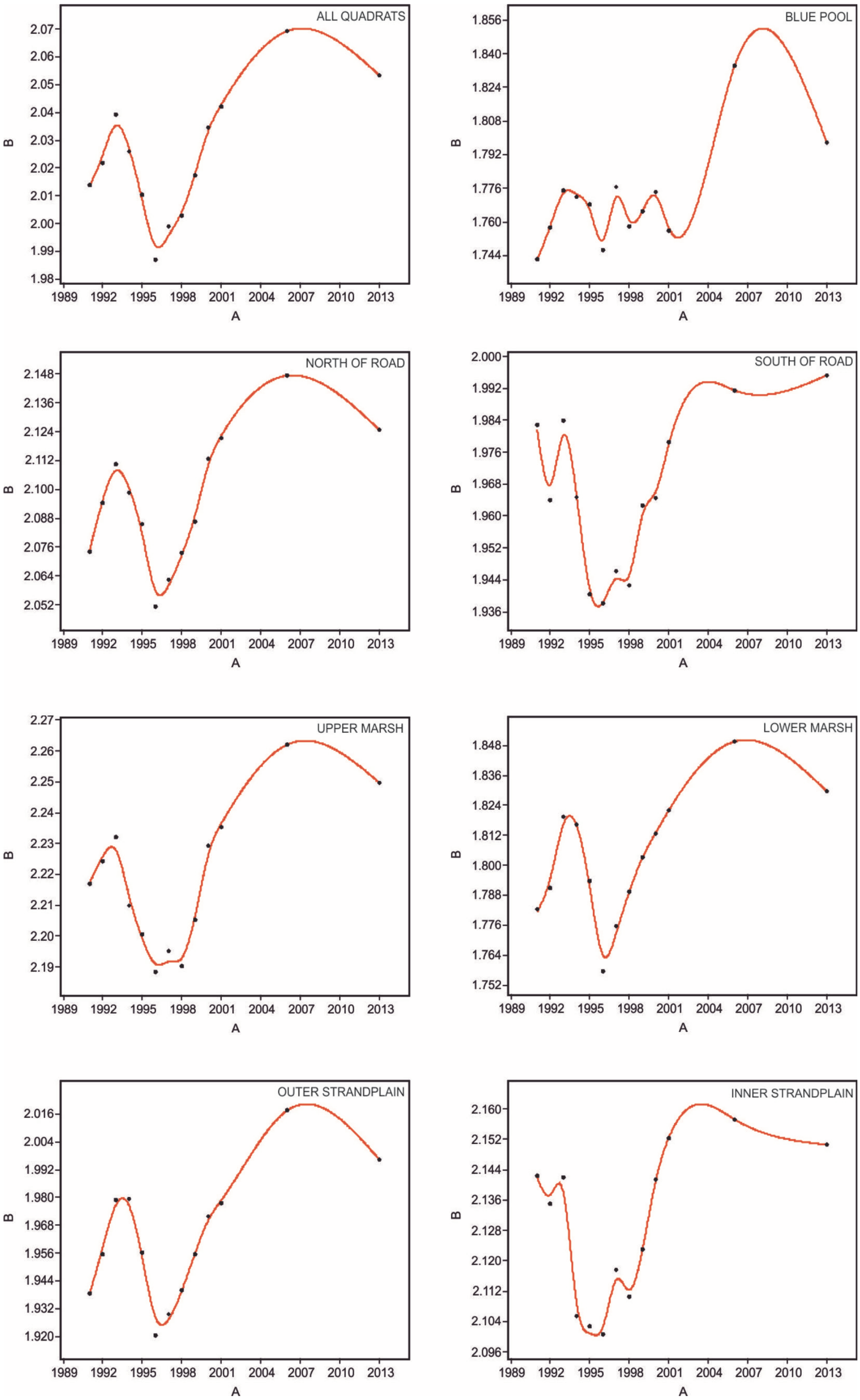


Figure 18. DCA Axis 1 predicted elevation: Smoothing splines applied to all quadrats and seven quadrat subsets
A Year of vegetation survey
B Predicted elevation (mOD)

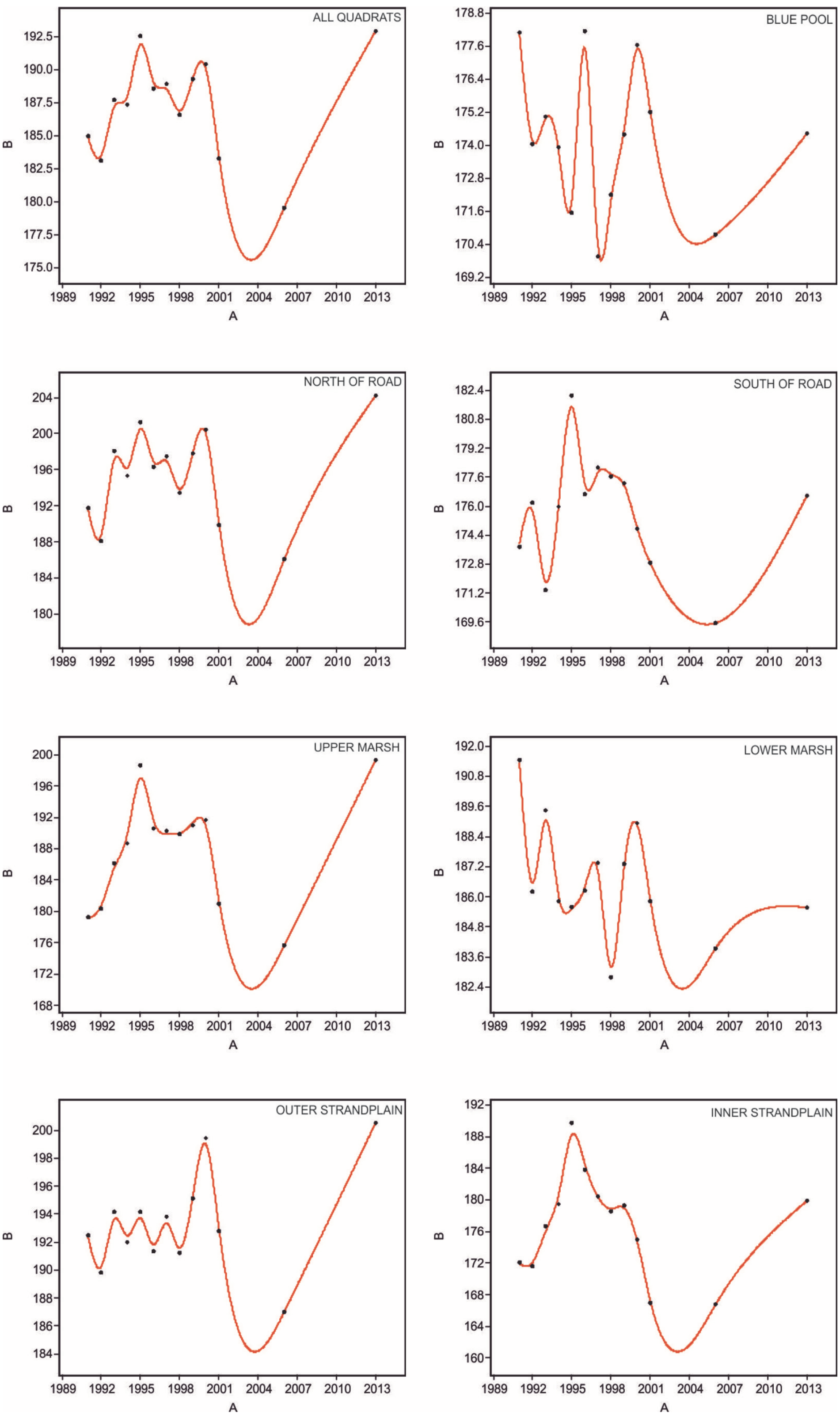


Figure 19. DCA Axis 2 saltmarsh wetness: Smoothing splines applied to all quadrats and seven quadrat subsets
A Year of vegetation survey
B Average DCA Axis 2 value (low values drier, higher scores wetter)

3.4.6 Elevation change over time in vegetation

The immediate impression comparing smoothing splines in Figure 18 is of overall similar form for all results except for Blue Pool. The remaining six subsets represent different ‘slices’ of the all-quadrat result. The lack of major differences within these six subsets points to common processes operating on the elevation gradient in Morrich More saltmarsh between 1991 and 2013. These processes, at the outset, do not seem to have been strongly altered by a road barrier effect, saltmarsh altitude or strandplain position. First impressions need to be set aside. Subtle but important differences are present within major spline shape components (section 3.4.6.1) and within the six subsets (section 3.4.6.2). The differences allow an outline model to be developed which explains the elevation change signals within DCA Axis 1 results. A road barrier effect is an important component of the model.

3.4.6.1 Common features in smoothing splines

This section discusses the strongest features appearing in the shapes of all smoothing splines except Blue Pool. The focus here is concentrated on the All-Quadrat result in Figure 18 which is considered representative of the similar spline shape is four of seven subsets (North of Road, Upper Marsh, Lower Marsh, Outer Strandplain). The All-Quadrat spline suggests an unbalanced sinusoidal relationship through time which contains phases of emergence (rising elevation) and submergence (falling elevation). Emergence is the dominant theme throughout the 23-year period of data availability, with shorter periods of submergence.

The maximum range (0.082 m, Table 6) in the All-Quadrat result occurs between 1996 and 2006, a 10-year interval. The timing of the maximum and minimum elevations is close to half that of the 18.61 lunar nodal tidal cycle and suggests that DCA Axis 1 contains a strong lunar nodal signal which overrides other tidal variation (e.g. considerable variation between 1996 and 2001 in Tidal Model 1, Figure 16). The lowest elevation (highest sea level, maximum average duration of saltmarsh tidal inundation) occurred in 1995/1996, in advance of a lunar nodal minimum (March 1997). There are vegetation data available for the June 2006 nodal minimum, but not for the period 2002 to 2004. However, the 1996 – 2006 10-year interval, plus the monotonic sequence (falling sea level) between 1996 and 2001, are strong indications that the 18.61 lunar nodal cycle is involved as a driving force affecting Morrich More saltmarsh. If this is correct, it is the first time this effect has been isolated in a UK and perhaps European saltmarsh vegetation study (see section 4.1.3).

At first sight the lunar nodal cycle is an unlikely important driver of coastal processes and habitat change because it only affects tidal range by up to 4% of nominal tidal range. This is the case assumed by Rennie & Hansom (2011) in considering its effects on estimation of RSLR.

Measured tidal range data are not available for Morrich More, which relies here upon modelled tide data. However, the published range for Invergordon (approximately 20 km SSW of Morrich More) is 4.7 m (UKHO 2015; Highest Astronomical Tide HAT 4.90 m minus Lowest Astronomical Tide LAT 0.20 m). Four percent of nominal tidal range for Invergordon is 0.188 m. Modelled average tidal data for Morrich More (Model 1, Table 5), based on Invergordon tide gauge data, shows a range of 0.058 m between 1995 (close to nodal minimum) and 2005 (close to nodal maximum). However, this was based only on tide levels ≥1.3 mOD (the LiDAR altitude of the lowest permanent quadrat). It is not a correct measure of the lunar nodal component of Morrich More tides because the sampled altitudinal range for permanent quadrats omits the lowest saltmarsh habitats on mud and sandflats (e.g. SM8 *Salicornia europaea* vegetation). The lunar nodal range is therefore at least 0.058 m.

An elevation range of 0.082 m is estimated from vegetation for All-Quadrats between 1996 and 2006 (Table 6). This is large compared to 0.058 m from tidal Model 1. If the modelled tidal data are accurate (calculating average sea level above a quadrat base of 1.3 mOD), this suggests that elevation change in vegetation might be affected by factors additional to the lunar nodal cycle. For example, the vegetation signal for elevation change could also be being driven by sediment deposition, long durations of ponded saline water on the saltmarsh surface between immersions at high spring tides, plus surface erosion.

If the vegetation signal for elevation includes such other factors, in addition to a combination of marsh altitude, the lunar nodal cycle and other tidal variation, their interaction might explain the switches between emergence and submergence after 1993 and following 2006. These dates might mark tipping points in which rate of sea-level rise starts to exceed rate of accretion. The switch to emergence after 1996 marks the reverse, rate of accretion exceeding sea-level rise. The submergence signal after 1993 and 2006 might include a response to saline water ponding, itself likely to increase following higher average sea level as the lunar nodal minima approached (1995/96, 2014/15). High average sea level at nodal minimum should result in increased erosion around the coastal edge and within saltmarsh creeks, followed by increasing sediment delivery to the main saltmarsh surface. Sediment deposition might be responsible for the rise in elevation after 1996, the most striking feature of the all-quadrat spline. These explanations are speculative because there is no information on sediment accretion rates, saline water ponding or surface erosion for Morrich More saltmarsh.

Overall, the dominant asymmetrical sinusoidal feature of seven smoothing splines represents a very strong vegetation signal. It is hypothesised here that this signal is an elevation trend in vegetation which is driven by the lunar nodal cycle (controlling sea level) and an interaction between the rate of sea-level rise and other factors, including the rate of sediment accretion. Tipping points in 1993, 1996, and between 2006 and 2013 mark equal rates of sea-level rise and sediment accretion. They are followed by a switch from emergence to submergence (1993, 2006 to 2013) or the reverse (1996), depending which is larger (rising sea level/saline water ponding/surface erosion versus rate of accretion).

If this hypothesis is correct, emergence immediately after tidal maximum in 1996 is explained by a rapid increase in sediment accretion, with sediment deposition rates much exceeding those before 1996. The factors controlling the asymmetry in the smoothing splines are likely to involve sea-level driven erosion elsewhere upon the strandplain, producing sediment transport on a scale much larger than before the 1993 tipping point. The switch to asymmetry after 1996 involved rates of accretion exceeding rate of sea-level change until some stage after 2006 (close to the 2006 nodal maximum), with rate of sea-level rise exceeding sediment deposition up to 2013 (increasing as the next nodal minimum, October 2015, is approached). The gentle fall in elevation between 2006 and 2013 suggests that sediment amounts in the system were still high, mitigating the effects of increasing sea level.

3.4.6.2 Explaining subset variation in smoothing splines

This section considers the very different smoothing spline for Blue Pool, as well as subset variants of the dominant shape in the All-Quadrat result.

The Blue Pool analysis shows three oscillations up to 2001, perhaps diminishing in height (amplitude) over time. There is then a pronounced rise in elevation to 2006 and a steep fall to 2013. As stressed above, these results are based on trends in only nine quadrats and caution is needed in interpreting Blue Pool results. Falling elevation between 1993 and 1996 is in advance of the 1997 lunar nodal minimum but 1997 is at a higher elevation. The broad pattern suggests three oscillations around a general emergence trend between 1991 and

2001 which might have been partly forced by isostatic rebound. There is then the sudden switch to strong emergence up to 2006, followed by a strong decline to its 2013 position. With only two sampling dates after 2001, the spline approximates the nodal maximum (minimum tidal elevation) in 2006 as the peak. The large increase in elevation between 2001 and 2006 is later and more abrupt than all other subsets. Expressed as elevation change per year, 2000 to 2001 (Table 6) was a fall of 0.018 m, followed by a rise of 0.016 m per year between 2001 and 2006. The change between 2000 and 2002 would be equivalent to a vegetation-signalled rise of 0.034 m, a large figure suggesting a major input of sediment around this period.

This period is contemporaneous with the accretion and new saltmarsh formation recorded by Dargie (2003), about 1.5 km to the north, upon Whiteness Sands inside Innis Mhor. It is reasonable to suggest that this major phase of sediment deposition extended, at the same time, further south into the Blue Pool area but there is no evidence to confirm this. Major coastal edge erosion and modification around Innis Mhor, together with less severe edge loss further south, probably supplied the sediment accounting for an elevation rise between 2001 and 2006, as well as more recent times.

There are three, perhaps four, spline shape variants which do not appear in the dominant spline shape for All-Quadrats, North of Road, Lower Marsh and Outer Strandplain. There is a small but clear oscillation between 1991 and 1993 in the South-of-Road and Inner Strandplain results. These subsets suggest either that 1992 had higher tides or that there was a tidal/sediment effect occurring shortly after pipeline road construction in 1990. The second variant occurs after the 1996 tidal maximum, as a two-year phase of little elevation change (Upper Marsh), or as a ‘ripple’ with a minor elevation peak in 1997 (South of Road, stronger for Inner Strandplain). The 1997 peak suggests a fall in sea level between 1996 and 1998. The Blue Pool 1997 oscillation is a similar feature. The third variant is a marked slowing (Inner Strandplain) or reversal of elevation fall (South of Road) between 2006 and 2013. A fourth possible variant is a slight ripple between 1999 and 2000, found only in the South of Road spline. This suggests a small fall in elevation due to local sediment accretion variation, since it absent or very slight in other subset splines.

A more detailed consideration of these variants, the Blue Pool result and the dominant asymmetrical pattern in all results is given in relation to tidal models below.

One further feature of subset elevation change needs emphasis here. There is considerable variation in the range of elevations derived from vegetation for the period 1991 to 2013 (Table 6). The maximum range is found for the Outer Strandplain, 0.097 m between 1996 (close to nodal minimum in 1997) and maximum in 2006. However, the more interesting results come from South of Road (0.057 m) and Inner Strandplain (0.057 m). These two results are almost the same as the range between tidal maximum (1995) and minimum (2005) calculated from modelled tidal data (0.058 m, 1.794 minus 1.736, Table 5). These differences suggest that samples south of the road corridor and within the inner parts of Inver Bay have a vegetation elevation response which, at extremes, almost exactly equals the lunar nodal range. These subsets seem almost unaffected by large increases in sediment deposition post-1996 (i.e. falling average sea levels between 1996 and 2006 account for all or most elevation change).

These variable results for elevation range allow the outline elevation model above to be expanded, to take account of a major road effect. Much higher values for the non-tidal component of elevation are associated with Blue Pool, North of Road, Upper Marsh and Outer Strandplain. Excluding Blue Pool, most quadrats in these subsets lie north of the road corridor. It is hypothesised that maximum rates of sediment delivery to saltmarsh here came via Blue Pool on spring tides. The sea levels for spring tides (and sea surges) exceeded the altitude separating Blue Pool from the outer part of Inver Bay saltmarsh, delivering sediment in suspension to ground containing quadrats 1-9, 15-33, 37-50 (Figure 3). Furthermore, it is proposed that water was ponded behind the corridor road for sufficient duration to allow enhanced settlement out of the water column.

The vegetation elevation residual (DCA elevation change – (Tidal Model 1 elevation change x -1)) is calculated in Table 8 and is used here to support this road-effect expansion of the elevation model. Positive values in Table 8 represent a rise in elevation due to sediment accretion. Negative values are assumed to represent ponded saline water covering quadrats between immersions at high spring tides for successive spring tide phases. This would produce a vegetation response equal to a rise in sea level. Negative values might also represent surface erosion, although this is thought to be rare. There is good consistency between subsets for individual change periods, some relatively quiescent (91/92), others very dynamic (96/97), with five periods (excluding 06/13) showing evidence of prolonged ponding.

Elevation residuals in Table 8 suggest that the Blue Pool subset between 1991/1992 and 2000/2001 showed an average annual rise of 0.003 m, but with major variations. Maximum accretion occurred in 1996/1997, very close to lunar nodal minimum (March 1997). This suggests that eroded sediment from foredune loss was redistributed via the Blue Pool sediment cell. Other subsets with a low average quadrat altitude (South of Road, Inner Strandplain) are less dynamic (0.001 and 0.002 m/year respectively) for the same period. In contrast to these, subsets affected by a road barrier tidal effect (North of Road, Outer Strandplain) have elevation residuals (0.006 and 0.005 m/year respectively) which show much higher accretion rates, the result of enhanced settlement north-of-barrier and a higher suspended sediment concentration compared to Blue Pool, the likely source of sediment delivery. Lower Marsh has a similar high rate of accretion (0.005 m/year) and many of its quadrats are found north-of-road on the outer strandplain (21 out of 43 quadrats).

Conditions south of the road corridor also need consideration in relation to this evolving model explaining vegetation elevation signature. The Inner Strandplain and South of Road subsets show a much lower residual within elevation change. This suggests sediment is being recycled within Inver Bay which might be acting as a semi-closed sediment cell, in contrast to Blue Pool which is a much more open system, receiving and dispersing sediment. There is one contrast between the two which might indicate processes happening within Inver Bay. The third spline shape variant, change after 2006, shows a rise in elevation to 2013 for South of Road and a fall in elevation for Inner Strandplain. Modelled sea-level change between these years amounted to a rise of 0.016 m (Model 1, Table 5). The net change (residual) for South of Road is 0.003 m/year accretion, compared to 0.002 m/year Inner Strandplain (1.5 mm/year). This suggests that there is up-estuary decline in net sediment capture since road restoration. The higher accretion in the outer estuary probably marks re-establishment of a Blue Pool sediment pathway to Inver Bay following road corridor restoration.

There is one additional important line of evidence supporting the role of Blue Pool supplying sediment to the interior of the outer strandplain, from where it is swept south for deposition or transfer into Inver Bay. The vegetation map of Dargie (1989) shows a continuous extent of saltmarsh out to Patterson Island, occupying all the outer strandplain south of Blue Pool and inside frontal dunes. Whiteness Sands further north, inside Innis Mhor, had almost no saltmarsh in 1988. The Blue Pool sediment route towards Inver Bay has probably been operational for many decades.

Table 8. Residual change (m/year) in vegetation elevation signature after accounting for tidal change (Tidal Model 1)
Positive values represent sediment accretion
Negative values (shaded) represent effects of ponded standing saline water between spring tide flooding or surface lowering by erosion
* Average annual rate of change

Change Period	All Quadrats	Blue Pool	North of Road	South of Road	Upper Marsh	Lower Marsh	Inner Strandplain	Outer Strandplain
1991/1992	-0.002	0.005	0.010	-0.029	-0.003	-0.001	-0.017	0.007
1992/1993	0.028	0.029	0.027	0.031	0.019	0.039	0.018	0.035
1993/1994	-0.029	-0.019	-0.028	-0.035	-0.038	-0.019	-0.053	-0.016
1994/1995	-0.030	-0.018	-0.027	-0.038	-0.023	-0.037	-0.017	-0.037
1995/1996	-0.021	-0.020	-0.032	0.000	-0.010	-0.034	0.000	-0.034
1996/1997	0.034	0.052	0.033	0.030	0.029	0.040	0.039	0.031
1997/1998	-0.012	-0.035	-0.005	-0.020	-0.021	-0.002	-0.023	-0.006
1998/1999	0.009	0.002	0.008	0.015	0.010	0.009	0.008	0.011
1999/2000	0.028	0.020	0.037	0.013	0.035	0.020	0.029	0.027
2000/2001	0.035	0.009	0.036	0.041	0.033	0.036	0.038	0.033
2001/2006*	0.007	0.017	0.006	0.004	0.007	0.007	0.002	0.009
2006/2013*	0.000	-0.003	-0.001	0.003	0.001	-0.001	0.001	-0.001
Change 1991/1992 to 2000/2001	0.004	0.003	0.006	0.001	0.003	0.005	0.002	0.005
Change 2001/2006 to 2006/2013*	0.003	0.005	0.002	0.003	0.003	0.002	0.002	0.003

3.4.6.3 Comparison with tidal models

The dominant spline shape component for most subsets shows only a weak relationship with any individual tidal model. The multiple 'roller-coaster' peaks and troughs of tidal splines (Figures 16 and 17) obviously do not mirror (in inverted form) the single plunge to 1996 tidal maximum found in all subsets except Blue Pool (Figure 18).

The fit with Tide Model 2, incorporating barrier effects recorded in 1991 to 2001 monitoring, is as weak as other models in this respect. The outline model developed above explains why. The barrier effect is expressed less through an effect on elevation and more through sediment deposition. Accretion was not monitored other than in work associated with surface change around selected culverts. Sediment deposition on the main saltmarsh surface has never been recorded. The outline model shows that sediment deposition north-of-road and on the outer strandplain depends on suspended sediment from the Blue Pool area. There is probably only a modest input from Inver Bay waters and culvert scour.

The implication of a poor fit with tidal variation is that vegetation elevation is a response variable largely controlled by the lunar nodal cycle, as amended by local sediment budget and saline water ponding between sequences of high spring tides. The road tidal barrier effect introduced to this model magnifies the sediment component to produce the strong asymmetry in four subsets which dominate the full sample set. This dominance imposes that asymmetry on the All-Quadrat spline. The main shape of the South of Road and Inner Strandplain subsets have much less asymmetry and shows much stronger forcing by the lunar nodal cycle. Even here post-2006 shape seems determined by sediment, some of which could be via Blue Pool, helping to create the inferred Inver Bay gradient of sedimentation decrease up-estuary.

The subsets for Blue Pool, South of Road and Inner Strandplain each show some moderate inverse tidal influence for parts of their spline shape:

i. Blue Pool elevation change shows the inverse expected relationship with sea level (Tide Model 1) between 1993 and 1998 and again 1999 to 2000. The 1997 lunar nodal minimum occurs within the most continuous period. Changes for 1991 to 1993 and 2000 to 2001 are anomalous and might have involved substantial accretion or erosion. The sudden switch to a steep rise between 2001 and 2006 must represent a major sediment input, completely obscuring any further tidal effect.

ii. The 1991 to 1993 oscillation in the South of Road and Inner Strandplain subsets is an inverse fit to sea-level change in Tidal Model 1, with highest average tide in 1992 coinciding with lowest elevation in the vegetation signature for this period. The vegetation signature is markedly stronger for South of Road and might represent a lower sediment effect in this subset, compared with Inner Strandplain. If that is the case, the sediment decline up-estuary inferred for 2006 – 2013 might have been the reverse (increasing up-estuary) in 1991 – 1993, when the road corridor was acting as a barrier. That pattern would fit a major change in sediment delivery via the Blue Pool area since 2001, with impacts south of the pipeline corridor since 2006.

iii. The 'ripple' observed for 1997 – 1998 in the South of Road and Inner Strandplain splines, involving a small elevation rise in 1997 and fall to 1998, coincides with a notable fall in average tide in 1997 (Tide Model 1, Figure 16).

iv. The very slight 'ripple' between 1999 and 2000 (higher elevation in 2000 but with a much-reduced rate of elevation change) coincides with a fall in average tide between 1999 and 2000 (Tide Model 1, Figure 16).

It is therefore significant that small elevation changes associated with year-to-year tidal variation, separate from the lunar nodal cycle, are found only in subsets unaffected by the presumed road barrier effect on sediment deposition. This includes some Blue Pool variation up to and including 2001.

3.4.6.4 Evidence for RSLR

Tidal models 3, 3A plus Hybrid Models 1 and 2 (Figures 16 and 17) demonstrate that eustatic sea-level rise should result in average tide levels in 2013 which are close to:

i. the high average tides of 1995/1996 and 1998/99 (Model 3); or

ii. exceed the 1995/96 and 1998/99 average tide levels (Models 3A, Hybrid Model 1, Hybrid Model 2.

The vegetation elevation signal, if it was purely driven by sea level, would show an inverse relationship, including a strong fall between 2006 and 2013. That applies only to the Blue Pool result in Figure 18 smoothing splines, with weak falls for the remainder except for South of Road which shows a slight rise. This, at best, is weak evidence of RSLR within the smoothing splines of different subsets or the All Quadrat result.

All tidal models in this study are primitives in the sense that they do not incorporate a sediment response. Interpretation of DCA Axis 1 elevation splines can only account for spline differences by including a sediment/saline water ponding residual factor, plus an interaction with the pipeline corridor road as a tidal barrier, as set out in the section 3.4.6.2 model. That enhances sedimentation north-of-road, but mainly on the outer strandplain.

There is a critical information gap in the outline model developed above: an explanation for the major increase in elevation observed in most subsets after 1996 (close to lunar nodal minimum) and after 2001 for Blue Pool. The major accretion recorded between 1988 and 2003 for saltmarsh further north (Whiteness Sands), plus more recent sediment derived from coastal edge erosion, have been cited as the sources of an increased sediment pulse. However, the driver of that pulse is not identified. The strong and near-continuous vegetation elevation response for most subsets was kick-started after 1996 (close to lunar nodal minimum).

RSLR might be responsible for an increased sediment supply to Morrich More saltmarsh but it is more likely to be the result of erosion during and following high average tides between 1998 and 2000 (Model 1, Figures 15 and 16). The very new saltmarsh described by Dargie (2003) inside Innis Mhor was formed of deep soft unconsolidated sand which was very slow and tiring to traverse in capturing edge boundaries. That sand was being slowly trampled by sheep seeking the fresh swards of new *Puccinellia maritima*, the dominant pioneer species even on the highest sectors. There was little *Festuca rubra* at that time, or species such as *Glaux maritima* and *Armeria maritima*. The soft sand was obviously derived from edge erosion along the north-western edge of Morrich More. However, it was not generated as a gradual process from the edge mapped in 1988 vegetation survey. A major pulse in erosion (possibly exacerbated by RSLR) might have followed the high average tide levels between 1998 and 2000 but substantial sand compaction by sheep grazing would have occurred before 2003 observations, providing a firmer surface in 2003. Instead, the erosion pulse is more likely to have come in 2002 and early 2003, a period of quite high average tides (Model 1, Figure 15), also possibly exacerbated by RSLR.

In summary, it is not possible to extract a clear RSLR signal in elevation results. It could be present, acting in addition to tidal variation. Further work is needed to test objectively for its presence and strength.

3.4.6.5 Summary of elevation change results

Overall, visual comparison of subset and tidal model splines shows that there is only a minor influence exerted by tidal variation outside the lunar nodal cycle. The major drivers of subset spline shape are the lunar nodal cycle acting in concert with different sediment deposition and saline ponding patterns. Those patterns vary in time and space, according to subset analysis. A major difference in sedimentation occurs either side of the pipeline road corridor between 1991 and 2006 (the date of road restoration) and it is hypothesised that, between 1990 and 2006, outer strandplain sediment coming from the Blue Pool area was deposited north of the corridor road during impoundment following high spring tides and perhaps storm surges. Sediment deposition north of the road barrier, only on the outer strandplain, produced a major increase in the vegetation elevation signal. This introduced major asymmetry into the elevation signal. The outline model presented above explains almost all major and minor components of smoothing spline shapes.

The model does not account for a large sediment pulse coming from the Blue Pool area at some stage after 2001. RSLR might be involved, helping explain a major pulse of erosion along the north-west shoreline of Morrich More in 2002 and early 2003, resulting in the formation of very extensive young saltmarsh. The high average tides in 2002 and 2003 are not captured in vegetation elevation splines due to no vegetation sampling. RSLR enhancement of tide levels might explain the rapid erosion and coastal edge change around the outer edge of Innis Mhor over the past fifteen years, with more minor edge erosion further south around Patterson Island. Sediment derived from that recent erosion probably continues to feed into the central outer strandplain via Blue Pool.

3.4.7 Wetness change over time in vegetation

Smoothing spline curves for drainage/wetness using DCA Axis 2 coordinates are illustrated in Figure 19. The splines are calculated using Table 7 averages for All-Quadrats and the seven subsets already used in elevation analysis.

3.4.7.1 Variation in wetness spline form

Figure 19 has much more diversity in general spline form than elevation equivalents (Figure 18) and the shapes up to 2001 are very different to elevation trends. There are strong contrasts between subset pairings (North/South of Road, Upper/Lower Marsh, Outer/Inner Strandplain). The contrasts imply, up until 2001, that road position, marsh elevation and strandplain position are involved, directly or indirectly, in understanding wetness variation over time.

Common features are more easily identified after 2001. There is seemingly a major change, a dip (drying) to around 2003, followed by a steep rise via 2006 to 2013 (a strong increase in wetting). This switch in pattern is equivalent in timing to the strong change observed for Blue Pool elevation and this timing is probably important. It occurs well after the substantial vegetation elevation changes (Figure 18) in other subsets which began shortly before the lunar nodal minimum of 1997. Only the Lower Marsh subset deviates from this late switch pattern in Figure 19. It shows only a weak increase in wetting between 2006 and 2013. Care is needed in interpreting the late switch in all subsets because smoothing splines use only two points (2006 and 2013) after 2001. The trends depicted must have obscured considerable wetness change within the ten years not sampled between 2001 and 2013. The steep fall to 2003 in most splines is probably a spline error in estimating the timing of the lunar nodal maximum which occurred in 2006.

The All-Quadrat spline is an amalgam of the diverse individual subsets but it is biased towards North of Road because that sector holds by far the largest number of quadrats. Comment here concentrates on the subset splines but it is noted that the All-Quadrat result in Figure 19 shows year-to-year changes in wetness which, at first sight, might be following tidal variation. These changes show a roller-coaster effect of two peaks (1995, shortly before lunar nodal minimum, 2000) and three troughs (1992, 1998, 2003 – close to 2006 lunar nodal maximum). However, the fit with average predicted tide (Model 1, Figure 16) is poor. Assuming higher average tides result in increased wetness (B axis, Figure 19), 1992 should be a minor peak, 1997 should be a trough and 1999 should be a peak, instead of 2000. Only 1995 is correct as the overall tidal maximum and the highest peak in four subset splines.

The link between vegetation splines and tide (Model 1 in Figure 16) is summarised in Table 8, using symbols to indicate the direction of wetness change between one year and the next (rising or falling, little difference). The best positive fit with tidal change is South of Road (eight of 12 changes) but even here there is disagreement for a three-year period immediately after 1995/96 and 2001/2006. These disparities are important and are discussed further below.

Table 8. Change over time for average tide, all-quadrat and subset splines (DCA Axis 2 wetness coordinate data). Data source: Figure 16, Figure 19
▲ Increase ▼ Fall ≈ Little difference

Spline	91/92	92/93	93/94	94/95	95/96	96/97	97/98	98/99	99/00	00/01	01/06	06/13
Tide Model 1	▲	▼	▲	▲	▼	▼	▲	▲	▼	▼	▲	▲
All-Quadrats	▼	▲	≈	▲	▼	≈	▼	▲	▲	▼	▼	▲
Blue Pool	▼	▲	▼	▼	▲	▼	▲	▲	▲	▼	▼	▲
North of Road	▼	▲	▼	▲	▼	▲	▼	▲	▲	▼	▼	▲
South of Road	▲	▼	▲	▲	▼	▲	▼	▼	▼	▼	▼	▲
Upper Marsh	▲	▲	▲	▲	▼	≈	≈	▲	≈	▼	▼	▲
Lower Marsh	▼	▲	▼	≈	▲	▲	▼	▲	▲	▼	▼	▲
Outer Strandplain	▼	▲	▼	▲	▼	▲	▼	▲	▲	▼	▼	▲
Inner Strandplain	≈	▲	▲	▲	▼	▼	▼	≈	▼	▼	≈	▲

The general shape of most wetness splines suggests a strong lunar nodal cycle signal upon DCA Axis 2, with high wetness over several years around the 1997 lunar minimum (highest average tides) and a strong decline to lunar maximum (lowest average tides) in 2006. If the lunar nodal cycle is the dominant control of saltmarsh wetness in most splines, its main effects on vegetation are likely to be expressed via groundwater forcing. Leafe (1990) calculated the scale of tidal forcing using regression, with the strongest result in September 1989 (groundwater level = 0.383 tide level + 1.04, R^2 = 0.87). This relationship perhaps varies with stage in the lunar nodal cycle. Groundwater forcing varies the thickness of the upper aerated zone of saltmarsh soil and that layer is probably the main physiological driver of species composition change over time. The importance of summer aeration in British saltmarsh as a physiological factor affecting zonation was demonstrated by Armstrong *et al.* (1985). Wetter average conditions will favour species more tolerant of waterlogging. Phases of higher average tides, mainly driven by the nodal cycle, will produce a wetter sward and, conversely, lower tides will result in drier vegetation, if surface elevation does not change. If sediment deposition is happening too, that could result in long-term drying. The aerated zone will increase in thickness as the surface of the marsh is raised by sediment accretion. Phases of accretion may account for anomalous strong drying 1996-1997 for Blue Pool and 1997-1998 for Lower Marsh, plus the flattened Lower Marsh trend 2006-2013, following road barrier removal. These two subsets have the lowest average altitudes (Table 6). Sediment accretion therefore seems stronger for lower marsh elevations.

3.4.7.2 The effect of the pipeline corridor road as a tidal barrier between 1991 and 2006

There are strong differences between North of Road – South of Road and Outer – Inner Strandplain splines. These contrasts strongly suggest a road effect is present in several DCA Axis 2 splines. The remarkable four small oscillations in wetness for Outer Strandplain might relate to this. This unique vegetation signal applies to a subset which includes most samples considered to be affected by ponding in sections 3.4.6.2 and 3.4.6.3. That interpretation included sediment coming via Blue Pool, with accretion concentrated north of the road after high spring tides between 1991 and 2006.

If that is correct, increasing sediment deposition between 1991 and 1998 for Outer Strandplain samples seems to have maintained a rough balance with wetness, sufficient to completely obscure the effects of the 1997 lunar nodal minimum. There is a slight decline in wetness for this period, suggesting accretion slightly exceeding the average amount of groundwater forcing. The kick upwards in wetness after 1998 to 1999 coincides with a notably-high average tide level, but 2000 saw a moderate fall in average tide. There is an anomaly between 1998 and 2000 when the balance between sediment deposition and tidal impact on wetness seems lost. It implies a reduction in Blue Pool sediment deposition, whilst at the same time ponding continued north of a road barrier. The increase in wetness for this period (North of Road, Outer Strandplain) is probably an expression of ponding north of a road tidal barrier, with little sediment deposition.

Both Lower Marsh and Blue Pool show a small range in wetness over time (8.7 and 8.2 DCA Axis 2 units respectively, Table 7). This contrasts with the All-Quadrat average (13.4) and very high values for Inner Strandplain (23.0) and Upper Marsh (23.7). The Upper Marsh range is understandable, coming out clearly in DCA Axis 2 interpretation (section 3.3.1.3). The high variation over time for Inner Strandplain was not expected. This is the oldest saltmarsh within permanent quadrat sampling. The high range suggests that marsh development over time includes adjustment for wetness throughout much of the marsh elevation range. A limited range in wetness (Blue Pool, Lower Marsh) is probably a feature of young, outer saltmarsh.

The splines for Inner Strandplain and Upper Marsh differ late in the time sequence. Upper Marsh has its highest wetness in 2013 but the Inner Strandplain peak occurs in 1995. This difference is strong evidence of a very recent increase in wetness for Upper Marsh locations (23.7 DCA Axis 2 units) between 2006 and 2013. A proportion of Upper Marsh samples include quadrats showing freshwater forcing (section 3.3.1.3) and these might be responsible for much of this strong recent signal.

3.4.7.3 Evidence for RSLR in vegetation wetness splines

Evidence for RSLR as an additional recent driver of saltmarsh wetness seems absent. A strong increase in wetness occurs between 2006 and 2013 on the outer strandplain, north of the road corridor. In terms of timing, this is contemporaneous with a steep fall in Blue Pool elevation (Figure 18). However, the wetness response is confounded by a road ponding – sedimentation effect and a strong increase in fresh groundwater forcing. Wetness signals for South of Road and Lower Marsh are much more muted. Since South of Road seems most sensitive to tidal variation, it should show a strong response to RSLR. It does not.

3.4.7.4 Summary of wetness change results

Overall, the importance of the DCA Axis 2 spline analysis is seven-fold:

(i) It has identified the lunar nodal cycle as the main driver of saltmarsh ‘wetness’. This is likely to be an important modifier of the tide – groundwater relationship found by Hansom & Leafe (1990) and Leafe (1990).

(ii) DCA Axis 2 is a good proxy. It probably represents groundwater level and its inverse control of the thickness of an aerated zone in the upper soil of saltmarsh. Long-term variation in aeration thickness is likely to be driven by the nodal cycle.

(iii) Analysis suggests that wetness is also affected by freshwater forcing, affecting only samples north of the road and located upon the outer strandplain. A very strong freshwater forcing signal has operated only recently, possibly only between 2006 and 2013.

(iv) The strongest wetness correlation with tide level data is south-of-road. Samples there have notably lower elevations and this demonstrates that drainage is equally important in middle and lower marsh locations in the quadrat set. This was not clear in the DCA Axis 2 interpretation (section 3.3.1.3).

(v) There is good evidence of a major road impact within results, affecting only the north-of-road quadrat component of the Outer Strandplain subset. Sediment deposition (with material coming mainly from the Blue Pool area) and ponding are probably driving a unique series of oscillations and a later steep rise in wetness between 1991 and 2000.

(vi) Evidence for RSLR is absent due to no signal in South of Road and Lower Marsh results, compounded by no clear signal elsewhere due to the strength of a road effect and recent fresh groundwater forcing.

(vii) The separation of data into subsets is effective in improving understanding of Morrich More saltmarsh and its control by varying patterns and drivers of groundwater hydrology over time (the lunar nodal cycle, a road tidal barrier and marsh elevation).

3.4.8 The importance of Morrich More permanent quadrat data

This is probably the only UK saltmarsh vegetation data set with a long series of observations spread over 27 years. These quadrat records show an extraordinary wealth of detail once the likely underlying driving factors are built into interpretation. Earlier use of data was by Gimingham in AURIS (1993a) and Dargie (2001). Their results identified the same trends discussed here but did not pick up the detail of change shown in these 2016 results. The improvement in interpretation in this report is largely due to the availability of LiDAR data as a source of reasonably accurate altitude for each quadrat. Matched with modelled tidal data, the elevation and wetness gradients identified by DCA ordination can be screened via subsets to reveal different combinations of drivers. Smoothing splines have proved a very effective way of interpreting change over time in vegetation elevation and wetness signals. Spline interpretation has helped identify a localised road tidal barrier effect, very strong evidence for the importance of the lunar nodal cycle, and a quite complex hypothesised interaction between tidal variation forced by lunar nodal variation, sediment redistribution via inputs from the Blue Pool area, standing saline water effects, marsh elevation and position on the Morrich More strandplain.

There are limitations in this permanent quadrat data set. One is geographical. Samples are mainly located north of Inver Bay, with only a few locations in the Blue Pool area. There are no permanent quadrats in the most northern saltmarsh upon Whiteness Sands (where saltmarsh only became established after 1988), nor south of Fendom Burn where the best middle and lower saltmarsh habitats of the SSSI are found. The quadrat set is probably not fully representative of the range of variation at Morrich More, including a lack of samples from the lowest saltmarsh levels. It has spatial bias (an imbalance of sample numbers between subsets), has one year (1987) with likely season of sampling differences, and lacks data for the periods 1988-1990, 2002-2005, 2007-2012 and post-2013. The samples are also arranged either side of a road corridor which this study considers to have formed a partial tidal barrier, obscuring or complicating other controls of saltmarsh hydrology. Vegetation sampling in 2006 was probably done close to the time that the road corridor was restored and it is not certain how representative that survey set is of non-barrier conditions.

Despite these limitations this data set has yielded a plausible model of vegetation change over time which includes several drivers and accounts for almost all spatial and temporal variation in subsets. Anomalies are few. Unfortunately, the model is not sufficiently sensitive to confirm a RSLR effect, if it is present in results.

4. DISCUSSION

Discussion here examines the key results and other findings of this project, re-structuring them around two topics:

i. Has this study improved our knowledge and understanding of coastal drivers of Morrich More saltmarsh habitat change?

ii. What further work might be needed to confirm and improve key findings?

The evidence for and role of sea-level driven ecological change is covered within each topic.

4.1 The drivers of saltmarsh habitat change

4.1.1 Identifying drivers of change using monitoring

Identification of habitat change in this report has used a mix of methods and varied earlier information sets which contain gaps, particularly little long-term formal monitoring of habitat apart from the permanent quadrat dataset. In part this is the result of restricted access to a military site. The most significant finding in this project, the role of the 18.61-year lunar nodal cycle, arose from use of monitoring data for a development site within the military area. Monitoring had to be undertaken to fulfil planning condition requirements. Without road construction, there would have been no yearly vegetation recording between 1991 and 2006. Quadrat recording in that period has allowed the nodal cycle to be identified.

It is important to stress that the lunar nodal cycle presents a problem for investigating all UK saltmarsh habitat for evidence of change. Short-term sampling intervals (e.g. quinquennial site condition monitoring reporting for nature conservation purposes) might identify habitat loss by erosion as deterioration, when in fact it might be part of a long-term natural nodal cycle in which sediment is redistributed and new saltmarsh is formed elsewhere. It also complicates understanding of the effects of eustatic sea-level rise. On an annual average basis eustatic rise around the UK is estimated at 1.4 mm/year (Woodworth *et al*. 2009, quoted in Rennie & Hansom 2011). This is smaller than the average annual change (up and down) of tide level due to the lunar nodal cycle. This can be estimated as *c*. 6 – 7 mm/year for Morrich More using tidal Model 1 (Table 5). This has a difference of 0.058 m between 1995 (close to 1997 nodal minimum) and 2004 (close to 2006 nodal maximum) (58 mm over 9-10 years, half a nodal cycle). Eustatic sea-level rise is therefore harder to detect. If it is present within vegetation data, there are at present no procedures capable of isolating each component using vegetation analysis.

This problem of timing is particularly important for change assessed only on two visits (1988 and 2015 for this project). Early detailed survey and research (Dargie 1989, Hansom & Leafe 1990, Leafe 1990) was undertaken quite close to a lunar nodal maximum (1987) and 2015 work was done in a nodal minimum year. Excluding permanent quadrats, variation due to an intervening nodal minimum (1997) is unknown and the degree of change found cannot be considered as a linear rate between 1987 and 2015. All statements on change must be qualified with respect to the lunar nodal cycle. That applies, for example, to the loss of saltmarsh habitat on the south side of Inver Bay, particularly low marsh on sand and mudflats. Is that a result of RSLR driving estuarine turnover, moving habitats up-estuary and upslope? Or is it typical change, part of the adjustments which occur within a lunar nodal cycle? It is fortunate that the permanent quadrat dataset has been available to identify change over time more accurately, to corroborate the findings from other analyses.

4.1.2 Interpreting habitat change as evidence of environmental drivers

Several questions arise when considering the nature and location of habitat change:

i. How much habitat change has been found? This project has identified various types of change but these have not been quantified in terms of their areal extent or their speed of change. Such information is important and if available might change the understanding achieved in this project.

ii. If Morrich More is an exemplar site for investigating coastal change, what are the best habitat signals to use in confirming a recent change in process response, from emergent to submergent conditions (Rennie & Hansom 2011)?

iii. Are there habitat signals which allow change to be separated into that caused by eustatic submergence and that due to the lunar nodal cycle?

The origin of this project, a follow-up to site observations suggesting saltmarsh is invading Morrich More acid dune heath (DEFRA 2012), is an example of the difficulties present in interpreting habitat signals. Figure 20 is the same image as used in DEFRA (2012). The saltmarsh species example used, *Armeria maritima*, is correctly identified but acid dune as the habitat is not. The *Cladonia* present in Figure 20 is *C. rangiformis*, a calcicolous species which is typical of machair and sand dunes with a modest shell sand content (Gilbert 2000). It is rare or absent upon acid dunes. A 1988 quadrat sample of similar composition had a pH value of 7.2 (i.e. slightly calcareous) and soil conductivity of 359 µS (suggesting a slight saline influence). The large grass in Figure 20 is *Elytrigia juncea*, a strand and embryo dune species. It identifies the habitat as an old foredune/strand now surrounded by saltmarsh and stabilised by lichen and *Festuca rubra*.

Figure 20. Dune with Cladonia invaded by Armeria maritima.
Source: DEFRA (2012), Fig. 4.10; image Stewart Angus/SNH

The signal identified in DEFRA (2012) is correct and there is the 1988 evidence to confirm that older cases have switched to saltmarsh. But is that switch permanent, a result of RSLR? Or could this switch in habitat occur as part of the lunar nodal cycle, oscillating between old strand and saltmarsh every 9-10 years? It would require observation over at least one full lunar nodal cycle to be reasonably certain.

The same problem exists for evidence accumulated here for fresh groundwater forcing. A few species allow locations of brackish swamp to be identified, along with upper saltmarsh which might be moving towards such swamp. But has this developed only in the period close to lunar nodal minimum, which might be the period of strongest groundwater forcing and highest vegetation wetness? Or is it the result of RSLR? Or both, acting together? Or neither, with brackish swamp instead representing a phase in a succession from saltmarsh to dune slack which has been occurring over 7000 years under conditions of emergence? The only way to be more certain is to monitor samples for at least one full lunar nodal cycle.

There is no small set of easily-identified species which will provide one answer to these questions. A large species set is best and that, as permanent quadrats, has been analysed in detail. The results from permanent quadrats, with 14 sample years between 1987 and 2013, suggests that most change over time is largely driven by the lunar nodal cycle. There is a strong hint of large recent changes (major increases in saltmarsh elevation since 1997) which might also involve RSLR, but even these can be partly related to high tides for all but one year between 1998 and 2003, causing dune erosion which then provided sediment for an even larger area of new saltmarsh.

Further research on the very long-term importance of the lunar nodal cycle would be important at Morrich More, investigating older sediments for evidence of the cycle (‘rhythmites’) in the same manner that has found it in much older geological deposits (Kvale 2012). There should be a much-repeated lunar nodal signal within the sediments of Morrich More, if it is as important as vegetation evidence suggests.

4.1.3 A model of Morrich More habitat and process change

The main results of this project have been assembled into a descriptive geographical model of Morrich More habitat and process change (Figure 21). This is used here in comparison with earlier studies of the site to consider if improvements have been made in understanding the geomorphological and ecological processes involved in habitat change, particularly the main drivers of change.

Figure 21 maps the approximate extent of likely zones affected by change, as identified from point-based vegetation evidence in section 3. The sectors mapped are extrapolations based on that point-based evidence and some have not been verified in detail. Freshwater forcing requires checking in the field. The nature and extent of road-induced tidal ponding cannot be checked following road restoration in 2006. The remaining change sectors are broadly correct, based on field and remote sensing imagery.

The mapping suggests that the outer Morrich More strandplain has been subject to contrasting habitat change, with varying certainty on the environmental drivers involved:

i Most saltmarsh vegetation probably shows medium-term change in species composition and quantities which is driven by the 18.61-year lunar nodal tidal cycle. Forcing is applied via elevational and groundwater-controlled soil drainage effects. These occur on a loop between the maximum and minimum phases of the lunar cycle (lower to higher average sea levels controlled by tide elevations).

ii Coastal edge retreat occurs along most of the north-western coastal edge and the outer tidal islands but varies in its severity. It is uncertain if it is cyclical in nature or now marks a retreat phase driven by RSLR. There are also smaller areas of dune accretion at the foredune extremities (western Innis Mhor, mouth of Inver Bay), marking the redistribution of eroded sediment. These areas are comparatively small and might indicate a large reduction in recent sediment supply to the beach zone. This is also suggested by a very extensive switch from mobile dune to semi-fixed dune habitat on the intertidal islands since 1988.

iii Change driven by extreme events (e.g. the December 2012 storm surge, creating and modifying overwash fans) is particularly important in modifying Innis Mhor and saltmarsh in its shelter. The difference in size of fans between Innis Mhor and Patterson Island reflects much greater exposure in the north and relative shelter in the south during storm conditions. This agrees with observations on differences in the rate of coastal edge retreat for the two tidal islands.

iv Freshwater forcing occurs along a near-continuous 6 km front, located very close to the north-eastern and south-eastern sides of very extensive dune slack. Its appearance here is probably recent (the last 15 years). This might mark long-term site succession to young dune slack but its recent nature as a very clear zone could also be due to an increase in site rainfall (an untested driver, no site-based data supplied).

v Together with the large area potentially affected by road-induced tidal ponding between 1990 and 2006, these drivers of saltmarsh and dune habitat change affect all the Morrich More saltmarsh system, the western coastal edge and the outer foredune.

These components of change can be reviewed in the context of earlier understanding of Morrich More habitat development and coastal geomorphology, plus high-latitude saltmarsh ecology:

i. The role of the 18.61-year lunar nodal cycle as a key driver of vegetation of medium to long term cyclical change in Morrich More vegetation was not recognised before this study. This factor does not feature in earlier ecological monitoring reports for the site or in environmental reports produced for statutory agencies, including work on coastal geomorphology. Evidence was available, particularly trends within permanent quadrats and frequent flooding impacts on breeding birds around the pipeline corridor, within and around the 1997 nodal minimum. However, it was not recognized in any monitoring report commentary. Literature searches suggest that British plant ecology has not identified this factor as a systematic and important driver of cyclical change in UK saltmarshes. Elsewhere, historical ecology research for the Bay of Fundy (Canada) (Bleakney 1972) considered the nodal cycle but suggested that extreme events (very high and very low tides in winter and summer) were acyclic in frequency and unpredictable in terms of impact upon mainly bird biota. This conclusion contrasts with cyclical sedimentological evidence (a switch from Poaceae to Cyperaceae pollen around nodal minimum) from high marsh samples taken from Long Island, USA (Clark 1986). However, this evidence is not found for that site post-1930 due to accelerated sea-level rise affecting a microtidal estuary with a spring tide range of 0.18 m (Clark 1986). European saltmarsh studies have almost no reference to the nodal cycle as a driver of vegetation change, cyclical or otherwise. A recent long-term study of surface elevation change on the German coast (Suchrow *et al*. 2012) takes no account of the lunar nodal factor, despite using a large set of potential environmental drivers in regression tree analysis. Analysis of LiDAR and river flow data for the Eden estuary in Fife suggests changes in estuarine cross-sectional form associated with the lunar nodal cycle (Cocholek 2013). Beeftink (1985) presents perhaps the only previous study showing some influence of the nodal cycle on European saltmarsh vegetation. His paper includes vegetation and mollusc data for four permanent quadrats (yearly records, 1962 to 1969 or 1970) located on

Springersgors Marsh (adjacent to Grevelingen, Netherlands – now non-tidal within the Dutch Delta scheme). Contrasting vegetation covers are shown either side of 1967 (close to a lunar nodal maximum year in 1969, but not stated as such by the author). The years 1966 to 1970 showed above average tide levels, presumably due to weather effects in a period when the lunar cycle should have produced lower averages, particularly for 1969. *Aster tripolium* and *Atriplex portulacoides* increased cover in the period 1967 to 1969 and were considered to shift position on the marsh following changes in average tide level which Beeftink (1985) attributes mainly to year-to-year differences in wind speed (i.e. atmospheric pressure). Cover reductions for that period were found in one or two of the highest quadrats for *Elytrigia atherica, Festuca rubra, Seriphidium maritimum* and *Glaux maritima*. These species were considered "sensitive to tidal immersions of seawater", which is taken here to mean sensitive to a higher average tide in the growing season, explaining their reductions in cover between 1967 and 1969. Increases in *Suaeda maritima* (except for the lowest quadrat) and *Salicornia europaea* were attributed to better seed dispersal by tides. Lower covers for these species might therefore be expected around the nodal maximum if tides were not strongly influenced by air pressure and wind. Beeftink (1985) concludes that "years with much wind action on the flood level, especially by lowering the high-water level, and perhaps also the 18.6-yr cycle of the turning of the moon's orbit plane, may stimulate succession". Beeftink's data fit his observed tide data well but the tide data are not representative of lunar nodal maximum tide level and he does not specify 1969 as a lunar nodal maximum. His conclusion is therefore only correct regarding pressure and wind variation around average annual tides. The results for Morrich More are based on a large permanent quadrat set and a longer time sequence than Beeftink (1985). They are much more convincing in showing the influence of the 18.61-year nodal cycle. This study should be accepted as the first European study confirming its role as a key driver of species cover change on a saltmarsh, imposing both an elevation effect and a separate influence on saltmarsh wetness.

ii. Coastal edge retreat is clearly a recent phenomenon for Morrich More. Geomorphological baseline (Hansom & Leafe 1991) and monitoring work (Hansom & Black 1996) used levelled beach transects on Innis Mhor and Patterson Island to assess change, together with air photo interpretation for sorties in 1944, 1967, 1970, 1987 and 1993 (Hansom & Black 1996). Strong edge retreat was not detected in a comparison of beach transects. Air photo analysis showed the formation of continuous saltmarsh between the mainland and Patterson Island between 1970 and 1987, plus a more dynamic coastal edge for Innis Mhor where extension of the western bar sheltered the north-western corner of mainland Morrich More, enabling strong saltmarsh formation. The overall picture was continued accretion in this period. Results in Dargie (2003) show that extensive saltmarsh had formed between the mainland and Innis Mohr in the period 1988 to 2003. Further consideration in this report suggests that the saltmarsh was formed at the very end of this period, with sediment derived from a burst of erosion along the north-western coastal edge following several near-sequential years of high average tides in 1998, 1999, 2000, 2002 and 2003 (Figure 15a). This was largely unrelated to the lunar nodal cycle. Strong accretion inside Innis Mhor was accompanied by considerable dune erosion on its northern side, with more minor losses at the northern end of Patterson Island (Figure 6). These findings suggest the period between 1998 and 2003 was a mix of saltmarsh accretion and localised dune frontal edge retreat for outer Morrich More, both being mainly confined to the north of the outer strandplain. There is a lack of data for the period 2003 to 2013, apart from 2006 Google Earth satellite imagery which shows no dramatic change from 2003 conditions. The December 2012 sea surge caused major edge retreat, breaching the western limb of Innis Mhor and creating two large overwash fans on this sector of the Morrich More. The most northern fan, inside the breach, is still active and either side has saltmarsh vegetation developed on dune microtopography which is modified by tidal action at high water spring tides and wind action during most low tide periods. Patterson Island was less affected by the sea surge, with a fan adjacent to Blue Pool, slight edge retreat and multiple small breaches in sectors which had coalesced into one foredune in the period 1988 to 2003. These breaches have mainly healed along a line south-west of the 2012 dune edge. The period since 2003 can therefore be characterised as one of foredune edge retreat, strong around Innis Mhor (including a breach), less so for Patterson Island, with slight saltmarsh loss. Modest accretion has occurred too, most notably at the western end of Innis Mhor and the southern mouth of Inver Bay. However, retreat has been the dominant theme since 2003, with most such change occurring in one extreme sea surge event. These report findings confirm the impression of coastal geomorphologists familiar with the site (J. D. Hansom & A. Rennie, pers. comm.) that there has been a switch from accretion to erosion for outer Morrich More, particularly in the Innis Mhor area.

iii. The findings on freshwater forcing confirm the impressions of Scottish Natural Heritage staff gained during field visits (S. Angus & A. Rennie, pers. comm.). Extrapolations of extent further suggest that it is occurring as a near-continuous front along two sides of dune slack extent (the groundwater source) but not in the Fendom area. Its absence at Fendom is attributed in this report to the presence of deep artificial drains for many decades. Permanent quadrat results in this report suggest it has developed strongly since an earlier analysis of data for 1987 to 1999 (Dargie, 2001). A study of grazing impacts on dune vegetation inside and outside stock and rabbit exclosures also recorded evidence of a strong rise in water table in dune slack and lower areas of dry dune grassland between 1998 and 2007 (Dargie 2007b). The significance of freshwater forcing is more complicated and involves uncertainties. Its presence is unsurprising, since this will have been a process operating over several thousand years, converting the upper edge of saltmarsh to dune slack habitat. However, the speed of the process is unknown. This report has found evidence that a vegetation signal of forcing has developed quickly since around 2000. It might have accelerated following a predicted increase in regional rainfall, especially in winter (Barnett *et al*. 2006). That increase is a conclusion applied to all northern Scotland and needs examination at site level. The Meteorological Office maintains a comprehensive automatic weather station at Tain Air Weapons Range and data from this station could be examined to check for increased rainfall. It is also possible that lunar nodal forcing or RSLR could also contribute to freshwater forcing but this study has found no evidence for these further complications.

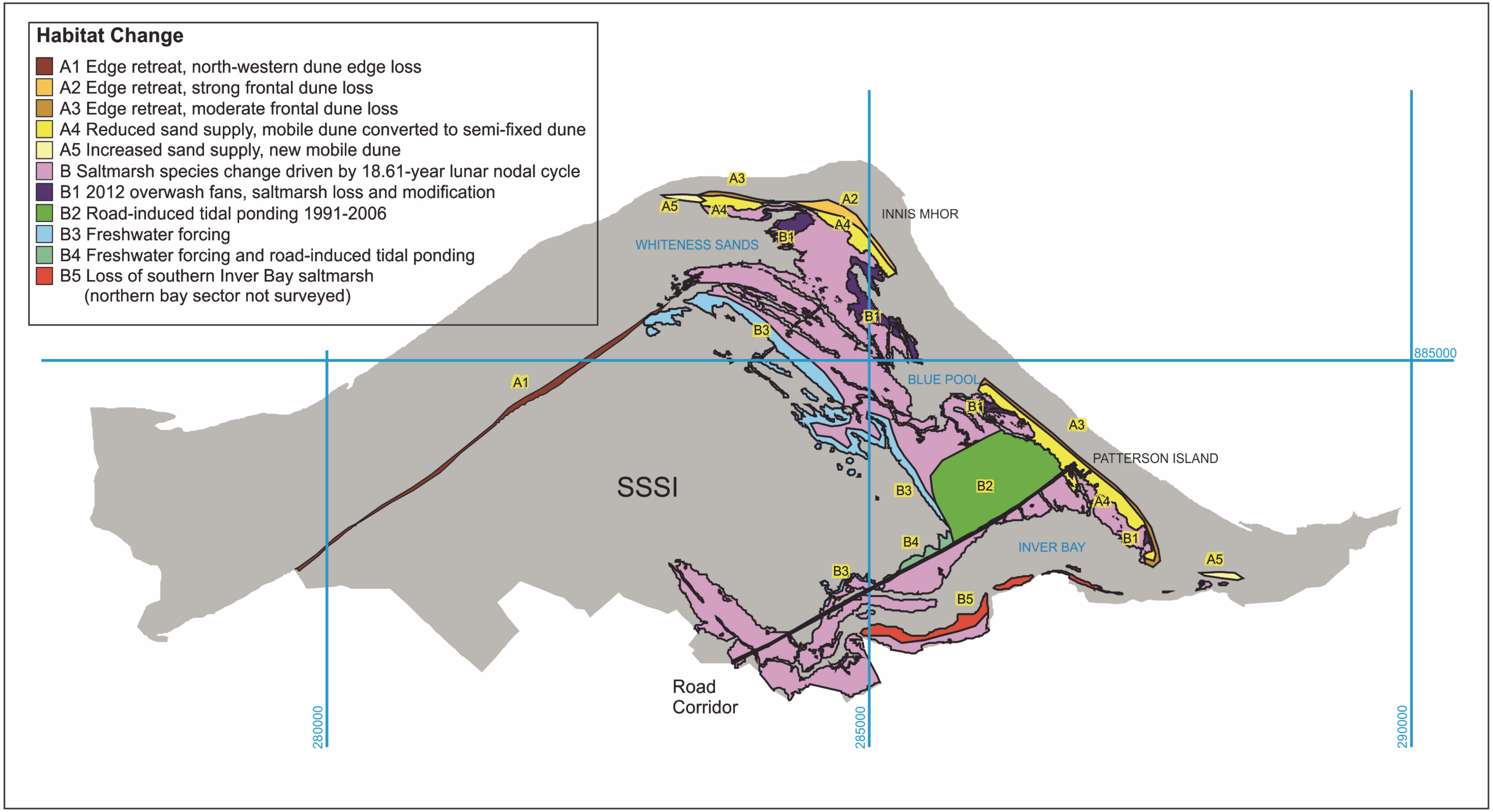


Figure 21. Outline model of recent Morrich More coastal edge and saltmarsh change

Grid lines are spaced at 5 km intervals.

SSSI boundary courtesy of SNH (© Crown copyright and database right 2016. Ordnance Survey 100017908).

4.1.4 Morrich More drivers of saltmarsh habitat change in context

The considerable change uncovered in this study has been assembled principally from quadrat-based surveys, plus some use of vegetation maps. Change has been inferred by observing differences over time and relating them to their spatial position. The time intervals for differences range from one to 29 years.

Two-stage revisitation surveys have become an important source of information in assessing habitat change which might be being driven by climate change, e.g. upland vegetation (Ross *et al*. 2012) and Scottish sand dunes (Pakeman *et al*. 2015). UK results vary. Upland vegetation data based on full vegetation records (i.e. including bryophytes and lichens in addition to vascular plants) shows considerable change, some of it referable to an increase in temperature (Ross *et al*. 2012). Little evidence of temperature-driven change was found for a large sample of Scottish dunes (Pakeman *et al*. 2015), using vegetation records lacking bryophytes and macrolichens, as well as different analytical methods. The approach in the latter study seems to exclude potentially thermophilous species (e.g. *Ononis repens*) and its nominate NVC type (SD7c *Ammophila arenaria – Festuca rubra* semi-fixed dune, *Ononis repens* sub-community, Rodwell 2000). Lack of information on temperature-sensitive vascular plants and cryptogams excludes at least two other important NVC types: SD19 *Tortula (Syntrichia) ruralis* with a southern distribution in Scotland and CG13 *Dryas octopetala – Carex flacca* heath which is rare and confined, for dune conditions, to north-west Sutherland. An examination of such elements might reveal a temperature-driven component of change and further work is needed before dune habitat can be considered fully resilient to temperature change in forthcoming decades.

The principal difficulty with two-stage revisitation is lack of information on the amount of change that occurred between the sampling timings. This is unlikely to be a serious problem for upland habitats and perhaps sand dune habitat away from the coastal edge. Saltmarsh habitat is however driven by considerable short-term forcing (tidal variation) which also contains a longer-term component, the 18.61-year lunar nodal cycle. There is one study of long-term change for Scottish saltmarsh (Taubert & Murphy 2012), including a re-survey of west coast sites undertaken by Gillham (1957). Site choice, different years of survey and different time periods only allow a very general conclusion to be made about saltmarsh resilience, plus an observation that *Salicornia* was now absent from several sites which showed only modest change for higher saltmarsh levels. Variation linked to the lunar nodal cycle is not considered in that analysis and that is probably the case for all UK studies of saltmarsh vegetation until this Morrich More study. Multiple sampling dates are essential to establish its role and in this respect saltmarsh vegetation should not be assessed for change using a two-stage comparison.

Vegetation scientists have neglected the lunar nodal cycle in UK research in part because their work has generally been done in isolation, ignoring work on the geomorphology of saltmarsh and the potential for combined study. Indeed, at least one review of saltmarsh zonation and succession hints that vegetation study alone is sufficient because it is so complex: "to disabuse the geomorphologist of the view that saltmarsh vegetation is merely the icing on a cake fashioned by physical process" (Gray 1992).

A combined approach for future work at Morrich More is likely to yield important advances if a further stage of modelling is undertaken, using field-based measurements to place this site in a UK and European context. The lunar nodal cycle was included in long-term (100 year) modelling by French (2006) for two saltmarsh tidal ranges (macrotidal 4.5 m and microtidal 1.5 m), together with a range of suspended sediment concentrations and sediment retention efficiencies. The nodal cycle was shown to be the key driver of declining hydroperiod and elevation increment for the macrotidal case. Sea-level rise was not included in the model. There was only muted response for the microtidal case, but clear large cyclical change for the macrotidal analysis. Morrich More has an average annual range of 4.86 m, close to the 4.5 m macrotidal example used by French (2006).

The patterns emerging from this study for Morrich More need to be compared with a more sophisticated model than that developed in this work, particularly in the context of the lunar nodal cycle. The effects of RSLR interaction with the nodal cycle can be included in such modelling. Year to year nodal variation exceeds RSLR, so RSLR will amplify its role as driver. This approach is perhaps essential if RSLR estimates and RSLR acceleration are to be estimated for much of the Scottish coast which usually has short tide gauge durations (<60 years) (Houston & Dean 2011), or no gauge data (the case of Morrich More). Work in the Netherlands (Baart *et al.* 2012) has shown that failure to consider the nodal cycle resulted in overestimation of Dutch sea-level rise, and, like Houston & Dean (2011), allows a better estimate of sea-level rise acceleration if included in calculations.

The need for modelling, and model testing, is probably urgent. Rennie & Hansom (2011), also supported by a study in Argyll (Teasdale *et al*. 2011), suggest that available evidence is sufficient to show recent relative sea-level rise is now outpacing estimated rates of isostatic rebound (glacio-isostatic adjustment) across the coast of the Scottish uplift dome. Sea-level rise leads to landward sediment transport, particularly on a barrier island coast (Rosati *et al*. 2013). This has required adaptation in the United States of the long-used Bruun Rule to account for a rise in saltmarsh elevation as sea level rises. However, it might also be necessary to adjust the Bruun Rule to account for the lunar nodal cycle too.

There are other changes occurring too at Morrich More which fit other saltmarsh observations. High marsh accretion reflects either sea-level or hydrological change, but low marsh accretion is more influenced by change in sediment supply, in studies covering the west Cotentin coast of France (Haslett *et al.* 2003) and Bay of Fundy (Chmura *et al*. 2001). These studies do not refer to lunar nodal tidal effects on sedimentation but those impacts are documented in the Netherlands (Oost *et al*. 1993). Full study of the lower marsh at Morrich More is not complete but observations of the south side of Inver Bay showed that the most eastern 1988 occurrences of NVC SM1, SM2 and SM8 vegetation had disappeared, replaced by sand and mud flats without vascular plants. Further west, there was major loss of these habitats along their lower edge in 1988 mapping. This might be an early stage of estuarine rollover in which within-estuary habitats are eroded close to the mouth and re-establish closer to the head. This might be a long-term process in Inver Bay which could differ strongly from the outer strandplain. However, could this degree of change be cyclical instead, driven just by the lunar nodal cycle? Careful modelling should be able to clarify this important conflict of interpretations.

Likewise, watertable monitoring and modelling incorporating the dune – saltmarsh transition with freshwater forcing would clarify the role in forcing, if any, of the lunar nodal cycle. Having observed freshwater forcing at Morrich More, its occurrence is easily stated as the result of increased rainfall in recent decades, as evidenced in DEFRA (2012). However, the increased rainfall trend is derived from one of the steepest rainfall gradients in Britain and the varied nature of the trend needs site-specific analysis. Analysis of Meteorological Office data from its Morrich More automatic station is needed, cross-correlated with the long data sequence available from Kinloss. If freshwater forcing is being driven by a combination of the lunar nodal cycle and RSLR it might represent an unusual form of coastal squeeze which could represent a long-term threat to saltmarsh in much of the site, when compared to other constraints on saltmarsh inland retreat (Torio & Chmura 2013).

4.2 Recommendations

The following recommendations are made to follow-up study findings and fill in information gaps:

i. A dynamic model of saltmarsh elevation change over the next 100 years should be developed, perhaps starting with the model of French (2006). This should incorporate variants with a RSLR component of sea-level change, investigating its interaction with lunar nodal cycle. A sediment component is essential and values will need to be based on site-specific details for suspended sediment.

ii. A second LiDAR survey is recommended to allow construction of a digital terrain model for comparison with 2012 data. This will allow the effect of the 2012 storm surge to be evaluated on the outer strandplain, together with more gradual changes in elevation elsewhere. The accuracy of LiDAR for this purpose also needs consideration because standard error measures (+/- 0.06 m for 2012 data) may not be accurate enough for checking dynamic model predictions. Very detailed topographic transects with millimetre precision might also be required to check model results. The precise altitude of permanent quadrats should also be calculated. This might enable further improvement to the DCA analysis achieved in this study.

iii. A study of rainfall and evapotranspiration modelling based on Meteorological Office site-specific data (Morrich More, Kinloss) should be undertaken and related to a study monitoring watertable variation along a transect from dune slacks through to saltmarsh, preferably in the Blue Pool area. This will enable predictions to be made of likely climate-driven change in the fresh groundwater table and its longer-term impact on upper saltmarsh.

iv. Continued monitoring of vegetation change is recommended. If possible, permanent quadrat recording should be maintained, especially since it has yielded major findings. However, there would be benefits from adding new permanent quadrats to the current set. This could be designed to cover the full altitudinal and locational range of Morrich More saltmarsh, stratified using LiDAR-derived contours. If this scheme is adopted, monitoring every three years is recommended, plus recording nodal maximum and minimum years if missed in a three-year sampling cycle (i.e. 4 samples per 10 years). An initial study into the minimum number of samples required to estimate elevation and wetness signatures in vegetation data is also needed. This would be applied to the seven quadrat subsets used in this study (Figures 18 and 19).

v. Installation of a tide gauge or a more general automatic water level recorder is recommended, perhaps fixed to the inside of the end wall of Portmahomack harbour, if this can be done without interfering with boat moorings. This location only dries out at the very lowest spring tides and is very close to Morrich More. Results can be used to assess the importance of meteorological effects in altering tidal model predictions, as well as providing data inputs for dynamic modelling.

vi. It will be difficult to detect any present or future RSLR signal in vegetation at Morrich More because of the size of the stronger lunar nodal effect. An alternative approach is recommended which might clarify that signal immediately, as well as allowing tracking through time. Saltmarsh within the inner and outer sectors of the Moray Firth could be sampled at several sites representing different positions on the glacio-isostatic emergence dome of Scotland. At-a-site data should cover the altitudinal range using random quadrats, obtaining an accurate measure of altitude per quadrat, perhaps obtained using RTK (Real-time Kinetic) DGPS (Differential GPS). Ordination analysis should be used to extract the elevation signal for all samples.

5. CONCLUSIONS

The following conclusions summarise findings on habitat change at Morrich More.

i. There is strong evidence from 2015 revisits to 1988 quadrat locations of a rise in sea level affecting saltmarsh vegetation, as well as converting the lowermost parts of dunes to saltmarsh habitat. The major foredune change between 1988 and 2015 (conversion from mobile to semi-fixed status) is probably indirectly driven by sea-level rise too, by a change in beach sediment budget which has reduced sand supply to non-eroded parts of the foredune zone.

ii. There is strong evidence of fresh groundwater forcing affecting the inner upper edge of saltmarsh where it is close to the remarkable dune slack complex of Morrich More. Well-developed brackish swamp is best developed in the north of the outer strandplain. Earlier drier forms are appearing inland of the Blue Pool area and these are also part of a very clear wetness gradient identified in a separate set of saltmarsh permanent quadrats. Brackish swamp also occurs in saltmarsh fringing the centre of Inver Bay. It is not developed strongly in Fendom area saltmarsh where it ought to occur due to dune slack proximity. This area of marsh is artificially drained by deep ditches, preventing swamp development.

iii. Tidal modelling suggests that the 18.61-year lunar nodal cycle is responsible for most recent sea-level change at Morrich More. Models adjusted to include eustatic sea-level rise and isostatic fall modify the lunar nodal cycle signal slightly, but it remains the strongest component of sea-level change.

iv. The lunar nodal cycle signal has been detected as a major response of vegetation within permanent quadrat data. It is a clear signal over time within strong elevation and wetness gradients which structure Morrich More saltmarsh. Tidal modelling suggests a magnitude of 0.058 m (approximating nodal minimum minus nodal maximum), with other factors such as sediment balance and standing saline water between high water spring tides complicating the vegetation signal. This is the first time that a lunar nodal signal has been identified in UK and European saltmarsh vegetation science. Its strength suggests that this factor is much more important in saltmarsh development and change than its contribution to tidal range would indicate.

v. 2015 was a lunar nodal minimum year and 2015 observations will have been affected by higher average sea levels. Much of the 2015 evidence for a rising sea level in 1988 quadrat revisits is probably due to the lunar nodal effect.

vi. Vegetation trends (elevation and wetness) compared with tidal models suggest that an additional eustatic sea-level rise component is uncertain in vegetation signals. It might be present but it is small compared to the lunar nodal cycle and cannot be separated at present using vegetation data.

vii. Vegetation analysis has also detected a strong and locally extensive effect from a road. This was constructed as part of a pipeline flowbundle launching corridor which was operational between 1990 and 2006 and is still present after partial restoration. The road acted as a partial tidal barrier in the operational period, interrupting tidal currents and sediment delivery across the outer strandplain between Blue Pool and Inver Bay, inside Patterson Island.

viii. A descriptive geographical model of Morrich More saltmarsh and foredune habitat change is developed which includes various lines of evidence established by this study. The model infers that all parts of the saltmarsh and foredune zone are experiencing change.

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