Natural England Commissioned Report NECR153

Survey and analysis of vegetation and hydrological change in English dune slack habitats

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Foreword

Natural England commission a range of reports from external contractors to provide evidence and advice to assist us in delivering our duties. This work was conducted under a Memorandum of Agreement between Natural England and the Centre for Ecology and Hydrology and British Geological Survey, initiating a programme of linked vegetation and hydrological studies.

Background

Sand dune slacks also known as dune wetlands, are a rare and threatened habitat in England. The habitat is also of European significance and has suffered from limited research to date because of the small sizes, rarity and geographically peripheral location around the coast. The aim of this work is to improve the conservation status of this habitat through increased understanding of dune ecohydrological functioning.

The key elements of this work for all sites with dune wetlands are to:

- Produce an up-to-date inventory and description of dune wetland vegetation in England.
- Provide information on soil conditions linked to vegetation data.

In addition, for a limited number of 'key sites' in England to:

- Improve understanding of soil and geological conditions underpinning the dune sites.
- Enhance long term water table monitoring.
- Undertake fine detail water table monitoring of key dune slacks (annual cycle).
- Produce ground terrain models of key dune slacks.
- Quantify scrub evapotranspiration (Braunton Burrows).
- Develop 'conceptual models' of the hydrological functioning of key dune sites.

Natural England will use the findings in a number of ways, including to information further research, report on the condition and status of this habitat and to provide management and restoration advice to site managers and others.

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Further information
This report can be downloaded from the Natural England website: **www.naturalengland.org.uk**. For information on Natural England publications contact the Natural England Enquiry Service on 0845 600 3078 or e-mail **enquiries@naturalengland.org.uk**.

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Survey and analysis of vegetation and hydrological change in English dune slack habitats

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Flooded slack at Birkdale Hills LNR, August 2012.

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Executive Summary

This Work was conducted under a Memorandum of Agreement (MoA) between Natural England and the Centre for Ecology and Hydrology and British Geological Survey, initiating a programme of linked vegetation and hydrological studies. As stated in the MoA, the overall aim of this collaboration is '*To improve the conservation status of dune wetlands of European importance and the condition of the dune wetland features of sand dune SSSIs identified in Appendix 1, through a major improvement in understanding of dune ecohydrological functioning.*'

Ecohydrological studies of this type incorporate many disciplines and in order to clearly define the proposed work, the following aims for vegetation and hydrology were set out:

- Vegetation
    - To provide an up-to-date inventory of dune wetland habitat in England to support Article 17 reporting and condition assessments for these habitats.
    - To combine soil sampling with vegetation analysis to better understand the reasons for change in these habitats over time.

- Hydrology
    - To provide a conceptual hydrological understanding for each of the study sites.
    - To carry out specific studies of near-surface dune hydrological processes in order to aid site management decision making.

The key steps and findings of the work carried out are:

Vegetation survey and interpretation

1. In consultation with Natural England, nine sites were selected for survey of the dune wetland component in the summer of 2012, aiming to partially repeat the Sand Dune Survey of Great Britain (SDGB) in the late 1980s. The selected sites hold 77% of the English dune wetland resource. These sites were:

Site	County	Grid Reference
Braunton Burrows	Devon	SS455355
Sefton Coast*	Merseyside	SD291127
Sandscale Haws	Cumbria	SD185755
Lindisfarne	Northumberland	NU123433
Ross Links	Northumberland	NU134398
Saltfleetby	Lincolnshire	TF475915
Holme	Norfolk	TF711449
Winterton	Norfolk	TG492207

* In this study, the Sefton Coast sites include Ainsdale LNR, Ainsdale NNR, and Birkdale Hills LNR.

2. At each site, all dune wetlands were mapped, with the exception of the three sites on the Sefton Coast, where the majority of the core area was mapped but not satellite areas. Mapping was done digitally in the field onto tablet PCs, and polygons allocated to NVC sub-community level where possible.

3. At each site, vegetation quadrats from the SDGB survey were relocated and re-surveyed, soil samples taken and associated environmental data recorded. Additional quadrats were surveyed adjacent to dipwells, and in some new wetland features. The relevant data from the SDGB quadrats was entered manually and all data stored in an Access database.

4. For each quadrat in 2012, the following measured and proxy explanatory variables were calculated: soil variables (pH, % loss on ignition), vegetation variables (species richness, vegetation height) and proxy variables based on presence/absence of species in the quadrat (Ellenberg moisture, nutrient, light, pH and salinity scores, and climate scores for precipitation, January and July temperatures). Proxy variables were also calculated for SDGB quadrats.

5. Analysis of change in mapped area showed a net loss of dune slack habitat at all sites except Lindisfarne, with loss at four of the large sites (Braunton, Ainsdale NNR, Ainsdale LNR and Birkdale) ranging from 28 – 52 % of slack area in 1990, above the error threshold for interpreting mapping. In many cases this involved a shift from wet slack to dry slack types and from dry slack types to drier non-wetland habitats. At the smaller sites however, net changes in area were low, and probably within the error inherent in mapping.

6. Analysis of change in quadrats showed a significant decline in the Precipitation score across all sites between 1990 and 2012, but no consistent decline in Ellenberg moisture score. However, moisture scores decreased strongly at two sites: Braunton and Birkdale. Ordination analysis of the quadrats showed a shift from wetter to drier species assemblages at Braunton and the three Sefton coast sites. In combination with the changes in mapped area of wetlands, this suggests a general drying trend across all sites, which is more marked on the Sefton Coast and at Braunton. Further work is required to understand the reasons for this.

7. The quadrat data also showed a significant increase in Ellenberg nutrient scores and a decrease in light scores across all sites. This suggests a shift towards more eutrophic species assemblages with a loss of light demanding species. These trends are consistent with impacts of elevated nitrogen deposition operating at a national scale, but may be compounded by local site factors, such as scrub encroachment at Birkdale.

8. Vegetation changes in quadrats at Lindisfarne, Ross Links, Holme and Winterton are not clearly explained by the explanatory variables described above, and further work is required to understand the reasons for change at these sites.

Hydrological investigation

1. For each site the geological setting, surface topography, surface water features, climatic setting and land cover were assessed and the most important hydrological processes identified.

2. Conceptual groundwater flow models were developed for each site based upon information collected both during the desk study and field investigation.

3. Water level time series data exist for 3 of the sites (Braunton Burrows, Ainsdale Sands and Sandscale Haws). Analyses of data from Braunton Burrows and Ainsdale Sands have been published in previous reports (Robins (2007) and Clarke & Sanitwong (2010) respectively). Where appropriate, information from these reports has been used to inform development of the conceptual models. Interpretation of the data from Sandscale Haws has been difficult as the locations (and therefore accurate elevations of the dipwells) are very approximate.

4. Attempts have been made to identify the hydrological pressures at each site. These include increasing rainfall interception due to growth and development of vegetation, long term climatic trends, management of open water features (ponds, drains etc), abstraction and irrigation on neighbouring land, and seepage from the dunes either inland or towards the sea. Fully quantifying the impacts of these pressures on dune hydrology and subsequent impact on dune vegetation will require more detailed monitoring and analysis. These needs are identified in the site reports.

5. A short review of methods for measuring evapotranspiration discusses the pros and cons of the techniques currently available. Due to likely constraints of heterogeneous land cover and topography, and practical issues of power supply and security, some techniques are not feasible.

6. Near surface recharge processes and moisture regime are investigated in a preliminary test of soil moisture profile logging at Braunton Burrows. Although the meteorological conditions during the monitoring period July to November 2012 were much wetter than expected in an ‘average’ summer and hence the soil moisture levels were higher than normal, there is evidence that under dry conditions some rainfall events may not penetrate further than 20 cm.

Comment on overall interpretation

1. Use of the National Vegetation Classification (NVC) system (Rodwell 2000) as a tool for classifying dune vegetation carries some limitations due to the wide range and co-varying nature of the environmental gradients operating in dune systems, coupled with the relatively small and unrepresentative dataset used to generate the classification for this vegetation type. These limitations should be borne in mind when undertaking or interpreting mapping of dune vegetation.

2. Mapping of vegetation is not a purely objective process, with variability of up to 30% between professional surveyors working on the same area of vegetation (Hearn et al. 2011). This variability, compounded by the poor fit of many dune vegetation types to the NVC, means that caution should be applied when interpreting changes in extent of different vegetation types over time. Particular care should be taken not to over-interpret minor changes in mapped area, given the likely error involved.

3. The findings reveal an extremely worrying picture of large-scale drying out of dune wetlands in England, combined with a strong signal of eutrophication. This is consistent with recent studies showing dune wetlands are sensitive to relatively minor changes in average hydrological conditions, with predictions of major habitat loss under climate change (Curreli et al. 2013). They are also consistent with recent work

showing eutrophication impacts at only slightly elevated groundwater N concentrations (> 2 mg N L^{-1}) (Rhymes et al. 2014).

Further work

1. Further work is recommended to install dipwells, and co-located vegetation quadrats at a number of new sites, and to extend existing eco-hydrological monitoring points at other sites (e.g. Birkdale, Lindisfarne) to capture a wider range of dune wetland types, and to cover the spatial context required to interpret the impact of local drivers of hydrological and vegetation change such as the prograding green beach at Birkdale, or extensive site management programmes.

2. Further work is recommended to collate data on historical site management (e.g. grazing history including stocking densities, winter stock feeding, scrub clearance, water abstraction, alterations or additions to surface drainage or ditches etc.) at each of these sites, and to jointly analyse hydrological, management and vegetation data sets in order to understand the drivers of change in dune wetland vegetation across England.

3. Further primary research is recommended to characterise hydrological regimes for less-studied dune wetlands, focusing on transitions to wetter and to more eutrophic communities; to establish guideline thresholds and loads for nutrients in groundwater; and to study the interactions between eutrophication and changing hydrological regimes.

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1 Introduction and Background

Dune wetlands are a rare and threatened habitat in England. This habitat is of European significance and to reflect their nature conservation importance, two Habitats Directive Annex 1 habitats cover all dune wetlands, Dunes with Salix repens (H2170) and Humid dune slacks (H2190). The current conservation status assessment for these habitats in the UK, concludes that H2170 is 'unfavourable, bad and stable' and H2190 is ‘unfavourable, bad and declining’ (JNCC, 2013).

Sand dune slacks ('dune wetlands') have suffered from limited research to date because of their small size, rarity and geographically peripheral location around the coast. The only comprehensive survey of England's sand dune vegetation (including their wetlands) occurred in the late 1980s and 1990 (Radley, 1994). This survey is subsequently referred to as SDGB throughout this report. Natural England is required to provide management and restoration advice for this habitat in addition to reporting on the condition and status of this feature, making use of the best available evidence and scientific understanding of the biological, hydrological and physical processes.

The link between abundance and diversity of dune wetland species and site conditions has been the subject of various UK studies dating back to the 1950s (e.g. Ranwell (1959), Willis (1963)). More recent studies have investigated the impact of nutrient levels on dune species (e.g. Jones 2004). As part of a suite of reports on wetland habitats, generic guidelines for the key vegetation communities of dune slacks have been developed by Environment Agency, Natural England and Countryside Council for Wales. Two documents (Davy *et al*., 2006, Davy *et al*., 2010) highlight the main principles to take account of in condition assessment, impact assessment and restoration projects and help to conceptualise how dune wetlands work. They include recommendations for further studies to refine these guidelines and improve their operational application at the site level.

Some management has been undertaken on some sites, using best available evidence and understanding at the time to ensure suitable conditions for dune species, but this has also prompted a need to improve understanding of the underlying factors driving change - both at a site level and more generally for the resource as a whole. An understanding of hydrological functioning in dunes and the response of vegetation is fundamental for effective action to assess and improve the condition of dune wetlands. In order to address the current gaps in the knowledge, a collaborative agreement was set up between the Centre for Ecology and Hydrology (CEH) and Natural England (NE) in March 2012. The work covered in this agreement (henceforth referred to as MOA) provides key information on the extent, quality and hydrological processes of dune slacks, to help refine conceptual hydrological models and provide data to help understand the potential impacts of climate change on these water-dependent habitats.

The key work elements identified in this agreement were:

For all sites with dune wetlands:

- An up to date full inventory and description of dune wetland vegetation in the UK, concentrating initially on England
- Information on soil conditions linked to vegetation data.

For a limited number of 'key sites' in England:

- Improved understanding of soil and geological conditions underpinning the dune sites.
- Enhanced long term water table monitoring.
- Fine detail water table monitoring of key dune slacks (annual cycle).
- Ground terrain models of key dune slacks.
- Quantification of scrub evapotranspiration (Braunton Burrows).
- Development of 'conceptual models' of the hydrological functioning of key dune sites.

It is anticipated that this project will make a major contribution towards effective management of dune wetlands and will be a significant coastal contribution to Natural England's 2011/12 Key Performance Measure 1 '*We increase the area of SSSI in favourable condition whilst maintaining 95% area in favourable or recovering condition, and Performance Measure (LB5) Contribute to an integrated surveillance and monitoring strategy so that interventions to deliver biodiversity and landscape objectives can be properly informed and outcomes monitored*.'

Outcome 1: A healthy well functioning natural environment

Outcome 2: Maintain and improve the condition of protected sites

Outcome 3: Maintain, improve and create priority habitats

2 Aims and Objectives

2.1 *Overall aim*

To improve the conservation status of dune wetlands of European importance and the condition of the dune wetland features of sand dune SSSIs identified in Appendix 1 through a major improvement in understanding of dune ecohydrological functioning. This will be achieved by a combination of whole resource habitat surveys, establishment of additional long term water table monitoring, and targeted more intensive studies at 'key sites'. The full list of tasks which form the basis of the contract are shown below.

2.2 *Vegetation related aims and objectives*

- To provide an up to date inventory of dune wetland habitat in England, with mapped polygons assigned to NVC sub-community where possible, that can be used for Article 17 reporting in 2019, and for updating condition assessments of dune wetland SSSI features.
- To combine soil sampling with vegetation quadrat data collection in order to inform interpretation of vegetation patterns, and add considerably to the relatively small data set used originally for compilation of the NVC dune wetland classification. Analysis of these datasets is not included in the current study but is recommended as a future activity.

2.3 *Hydrology related aims and objectives*

- Using existing published geological and hydrological data, develop a conceptual hydrogeological understanding for each study site identifying the important drivers and pressures at each.
- To investigate the near-surface moisture regime and summarise the current understanding of distinction between the root zone moisture regime and water table regime.
- To review the currently available methods for measuring evapotranspiration and identify the methods most suitable for application in sand dune habitats.

Table 1. Tasks which form the basis of the work undertaken under this contract.

Outcomes	Outputs	Reporting
Task 1. Integrated hydrology, topography and dune slack vegetation study along transect across Braunton Burrows key site to elucidate fine scale relationship between vegetation communities and water table.	Dipwell, vegetation and topographic data all entered into a GIS and digital terrain model. Analysis of correspondence between NVC sub-communities and hydrological regime. Recommendations for repeat/refinement of study on other key sites.	Section 2 of Stratford *et al.*, 2012, *An Assessment of the Ecohydrological Conditions at Braunton Burrows.* Report to Natural England.
Task 2. Deep core drilling of dry dune hills at Braunton Burrows key site to elucidate soil moisture and water table characteristics under dry dune vegetation, in order to refine conceptual hydrological models for dune systems.	Results of deep core drilling, along with analysis of this data and estimates of percolation rates through 'dry' sand, with commentary on strengths/weaknesses of techniques used.	Section 3 of Stratford *et al.*, 2012, *An Assessment of the Ecohydrological Conditions at Braunton Burrows.* Report to Natural England.
Task 3. Hydrochemical analysis of groundwater at Braunton Burrows and Sefton Coast key sites to clarify age of the groundwater. Combined/compared with deep core drilling results, rates of groundwater recharge from rainfall can be much more closely estimated.	Results of chemical analysis of water samples, along with analysis of this data and estimates for age of groundwater based on this analysis, with commentary on strengths/weaknesses of techniques used.	Section 4 of Stratford *et al.*, 2012, *An Assessment of the Ecohydrological Conditions at Braunton Burrows.* Report to Natural England.
Task 4. Review of existing unpublished hydrological and vegetation data for all dunes sites in order to refine list of sites for full dune wetland vegetation surveys in 2012.	Summary, by site, of data found with reasoned hierarchy of sites recommended for full survey in summer 2013.	Appendix 2 of this report.
Task 5. Summarise existing published geological and hydrological data for all dune sites with wetland.	Short hydro-geological description of each dune site with wetlands.	See individual site reports, listed in Section 8 of this report.
Task 6. Vegetation survey of hierarchy of dune wetland sites identified in desk study in order to provide up to date information on current extent and quality of resource, with analysis of change since last comprehensive survey in late 1980s.	Vegetation data entered into a GIS, with report providing overview of resource and also individual site reports.	Section 5 of this report.
Task 7. Soil samples linked to vegetation survey of hierarchy of dune wetland sites identified in desk study, in order to provide additional information to help explain association of vegetation communities and water regime.	Analysis of soil samples (pH, moisture, organic matter), archiving of samples, and data included in vegetation reports.	Section 4.4 of this report and individual site reports, listed in Section 8.
Task 8. Exploration of potential for root zone moisture regime to influence understanding of links between vegetation community and groundwater regime.	Short report summarising current understanding of distinction between root zone moisture regime and water table regime, with recommendations for any field study at a key site to explore any additional data requirements.	Section 7.1 of this report.

Task 9. Field experiment designed for a key site to quantify evapotranspiration rates from a range of dune vegetation in order to refine conceptual hydrological models for dune systems.	Report reviewing current techniques for measuring evapotranspiration and their applicability to dunes, with recommendations for dune trial.	Section 7.2 of this report.

3 Methodology

3.1 *Vegetation Survey*

3.1.1 **Site selection**

A subset of priority sites (listed below) were selected from those surveyed in the SDGB survey of the late 1980s/early1990s (Radley 1994) in discussion with Natural England staff. Selection was based on the extent of the wetland component at each site, their interest from an eco-hydrological perspective, any existing data, and the practicalities of having to select only a component of the total dune wetland due to the resources available. The full list of English dunes with the extent of wetland resource at each site is provided in Appendix 1. Appendix 2 provides more detail on the selection criteria used to determine the final list of sites to survey.

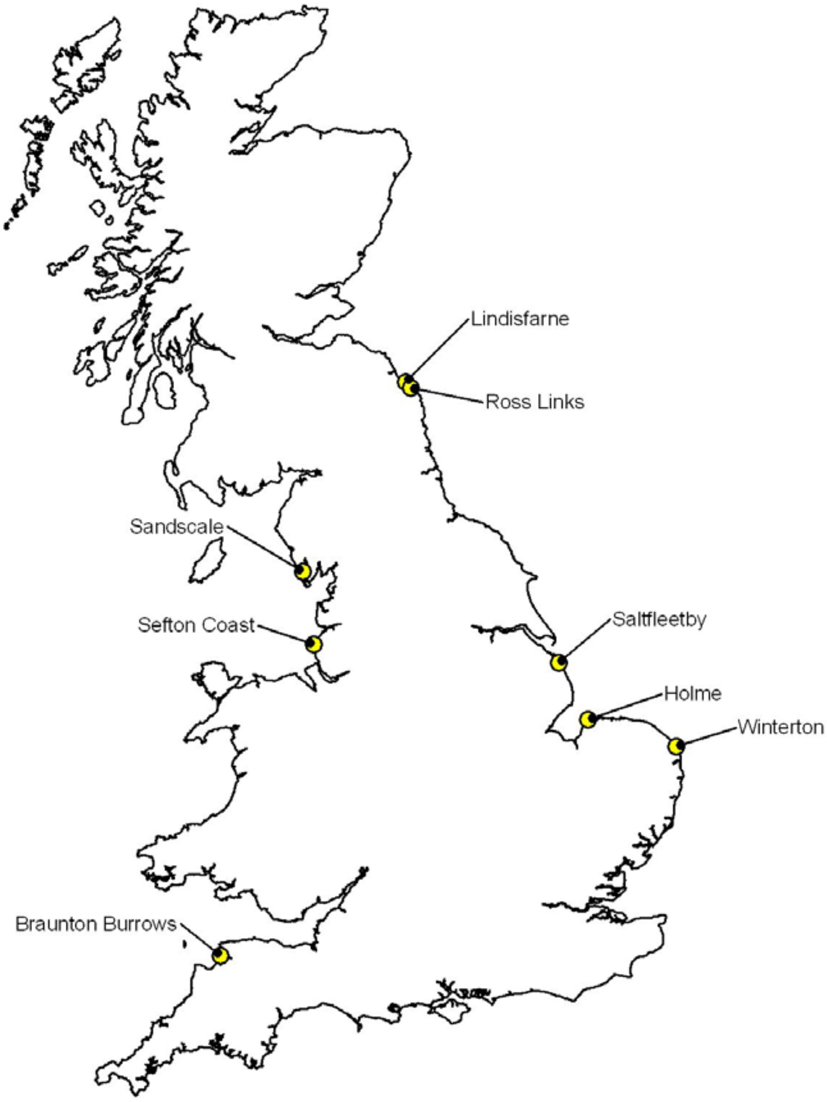

Figure 1. Map of England, Wales and Scotland, with the locations of the sites surveyed shown.

The sites surveyed are listed below (Table 1). In larger sites, where complete coverage was deemed impractical with the time resources available, a section of the dune system was prioritised for survey and mapping in 2012 after consultation with Natural England. Afforested areas (primarily at Ainsdale Sand Dunes NNR), for example, were not deemed a priority.

Table 2. Summary details of all sites surveyed in this study.

Site	County	Grid Reference	Area (ha)	Designations
Braunton Burrows	Devon	SS455355	1347	SAC
Sefton Coast	Merseyside	SD291127		
Ainsdale Sand Dunes			351	NNR, SSSI SAC
Ainsdale and outlying dunes			105	LNR, SSSI SAC
Birkdale Hills			198	LNR, SSSI SAC
Sandscale Haws	Cumbria	SD185755	282	SSSI, SAC
Lindisfarne	Northumberland	NU123433		NNR, SSSI, SAC
Ross Links	Northumberland	NU134398	327	SSSI, SAC
Saltfleetby	Lincolnshire	TF475915		NNR, SAC
Holme Dunes	Norfolk	TF711449	281	NNR, SAC
Winterton & Horsey Dunes	Norfolk	TG492207	109	NNR, SSSI, SAC.

3.1.2 **Preparation (site data collation)**

The CEH/BGS team received a box of reports to consult and copy on the 30th January 2012. A complete list of these reports, the site(s) covered by each report and also a summary indication of the contents in their order within the report/folder can be found in Appendix 2. Unless stated otherwise, the reports were conducted on behalf of Natural England and/or JNCC (or predecessors). Some other material was loose within folders – such cases are listed but clearly identified. Dates refer to the year of survey rather than the related report where these differ. Apart from the “slack quadrat” totals, note that many of these early reports use NVC names and numbers from the draft NVC and were superseded by the eventual publication of the final classification in 2000 (Rodwell, 2000). The community numbers in Appendix 2 refer to those listed in the reports and need translation to the final published NVC. All of these documents have been electronically scanned and are available in .pdf format.

Further information on existing quadrats and hydrological data, and locations of any dipwells was collated by CEH and used to inform optimum location of quadrats at each site during the survey.

3.1.3 **Preparation (field survey)**

Site reports produced as part of the *Sand dune vegetation survey of Great Britain: part 1-England*, (SDGB) (Radley 1994) including NVC survey maps with quadrat locations and target notes, and any other known previous survey data were provided by Natural England. Site reports were scanned, wetland polygons from earlier mapping were digitised and quadrat data (where available) were subsequently manually entered onto computer by the project team. Aerial photographs (taken from 2006-2010) were obtained from Geostore as part of a CEH licence.

GPS-linked portable electronic tablet PCs running Windows XP, and with Microsoft Office 2007 installed were sourced for use in the field survey. ESRI ArcPad 10.0 GIS software was installed for use during the survey, including an editable shapefile with a specially designed data entry form to capture habitat information associated with mapped polygons (see Table 3 in section 3.1.5.3). Digitised survey maps were geo-referenced in ESRI ArcMap 10.0 using key reference points such as grid intersections. Issues regarding inaccuracies in SDGB survey maps became apparent during geo-referencing; these can be attributed largely to distortion occurring during the ortho-rectification of the original aerial photos used as base maps in the 1990 survey (Radley, 1994). The direction of error where it occurred was not consistent across the whole area likely due to differences in distortion of individual tiled aerial photos, and accuracy varied between sites. The most severe distortion was at Sandscale, with disparity of 20 m or more, in addition to likely inaccuracies in actual habitat mapping at this site – discussed in more detail in the site report). In general accuracy of image ortho-rectification was within ten meters.

For sites selected to be surveyed, SDGB quadrats falling within dune slack/wetland habitats were identified from the site reports, and located on hard copies of maps along with all areas of habitat previously identified as dune slack/wetland. Other datasets of interest were identified, including quadrats previously recorded by CEH, location of any piezometers and hydrological data. Grid references of potential additional quadrats to re-survey based on these data were collated for surveyors.

An abbreviated NVC key was constructed by the project team prior to the survey referring only to those communities associated with dune slacks (Appendix 3). As well as the classic dune slack communities (SD13-17), some wetland communities of mires, swamps, and salt-marsh were included, as were certain dry mesotrophic grassland and dune communities likely to arise as transitions or mosaics. NVC community descriptions relevant to dune slacks (Rodwell, 1991a, b, 1992, 1998 & 2000) were digitised, and spreadsheet copies of the NVC floristic tables (JNCC, 2013) obtained and loaded onto tablet PCs.

The computer program TABLEFIT (Hill, 1996) calculates the degree of agreement between new vegetation samples and the floristic tables in British Plant Communities (Rodwell, 1991a, 1991b, 1992, 1998 & 2000), using various measures of goodness-of-fit. This was installed onto the tablet PCs as a further aid to assigning NVC communities.

A database was constructed in Microsoft Access to capture site- and quadrat-specific data (Table 4), and a uniquely named version loaded to each of the survey tablet PCs. A full list of resources and equipment provided to surveyors is given in Appendix 4.

3.1.4 **Training**

Office-based training in the use of mapping and quadrat data-entry software was carried out at CEH Wallingford over two half-day sessions. The experienced botanical surveyors also received three days of intensive training in the field two weeks prior to the start of the survey, at one of the sites to be surveyed (Ainsdale Dunes, Sefton Coast). Training covered vascular and bryophyte plant identification, assignment of vegetation to dune slack and wetland NVC habitats, and field methodology for habitat mapping, recording of quadrats using the electronic tablet system, and soil sampling. Vascular and bryophyte plant identification focussed on those dune-slack specialist species that surveyors were less familiar with; the majority of bryophytes commonly found in dune-slacks were found during training and specimens taken for reference. Training was carried out by experts in each of these fields, including surveyors from the SDGB Survey to aid consistency in NVC methodology. All surveyors were trained in both mapping and vegetation quadrat methodologies.

3.1.5 **Field survey methodology**

When possible, a rendezvous with site staff was arranged for the first day of surveying, enabling significant features and access routes to be pointed out. The teams of surveyors carrying out the mapping and those recording the vegetation quadrats worked together on each site initially until they were familiar with the range of communities present. Once the range of vegetation types at a site had been identified, surveyors worked separately to cover the site more efficiently. Relevant site metadata was completed once the site had been covered and quadrats recorded.

3.1.5.1 Mapping in the field

The use of GPS-linked portable electronic tablet PCs in the field equipped with Arcpad GIS software enabled a variety of layers to be loaded simultaneously and selected or made semi-transparent as required. GIS layers included aerial photos covering the extent of the dunes, scanned and geo-referenced copies of the original survey maps, the editable layers for mapping and, where available, additional survey information for dune slacks recorded since the SDGB survey.

As the project focused very specifically on dune wetlands, there was no scope to map the more widely distributed (dry) dune communities. For each prioritised area surveyed, every slack or wetland mapped in the original survey was revisited as far as possible, aided by printed copies of the SDGB survey maps with wetland habitats highlighted. Additional slacks were then located by covering as much of the intervening ground on foot as possible, and using georeferenced aerial photos as guidance. To aid the surveyors in distinguishing boundaries between dune wetlands and dry dune communities, it was helpful to identify certain indicator species that could be used to help delineate the edge of dune slacks. The basic premise that dune slacks are influenced by the water table meant that in many cases the extent of species strongly associated with damp habitats provided a useful guide. The relative significance of species differed slightly with each site, but usually included *Hydrocotyle vulgaris* (Marsh pennywort), *Carex nigra* (Common sedge), *Agrostis stolonifera* (Creeping bent), *Eleocharis* sp. (Spike-rush) and *Epipactis palustris* (Marsh helleborine) as well as a range of bryophytes. *Calliergonella cuspidata* was particularly useful where it occurred (particularly in NVC communities SD14-15 and SD17) due to its abundance and mat-forming habit. Conversely, certain species strongly associated with dry habitats such as *Ammophila arenaria* (Marram grass) and *Chamerion angustifolium* (Rosebay willowherb) usually helped identify areas outside the extent of the slack.

Once a dune slack was located and delineated, surveyors identified apparently homogenous stands of vegetation, following NVC guidance (Rodwell, 2006). The boundaries of each stand were walked and digitised using the GPS-tracking functionality in Arcpad. Occasionally the GPS accuracy could drop to as low as 20m, at which point the aerial photos were helpful in confirming the location. Associated with each polygon drawn, the information listed in Table 3 was captured.

Table 3. Digital mapping data collection form filled in for each polygon digitised.

Field	*Data entry method*
ID	Unique polygon ID generated by Arcpad
NVC community	Selected from list OR free text
NVC sub-community	Selected from list OR free text
Notes	Free text field for target notes relevant to each polygon; surveyors included dominant species and previous slack ID where relevant
NVC community 2 (mosaic)	Selected from list OR free text
Proportion NVC community 1	Where a mosaic of two habitats occurs the proportion of each was specified
Proportion NVC community 2	

Due to the time constraints of the survey, it was not possible to follow the standard NVC guidance to record at least 5 quadrats in each stand of vegetation (Rodwell, 2006). A variety of resources were used to identify communities, including surveyors' personal experience, NVC habitat keys & descriptions, NVC floristic tables and the use of TABLEFIT software *in situ*. TABLEFIT can perform a useful function with reduced species lists with or without cover data (as well as single or multiple full quadrats), so mappers were able to make use of this for guidance throughout the survey, where the scale of the project otherwise precluded the recording of full quadrats. Close contact throughout the survey of the mappers with those surveyors who were recording quadrats provided an extra level of quality assurance in the mapping exercise.

All wetland communities within the interior of the dune system were mapped at the NVC sub-community level where possible with a minimum mappable unit of 10 x 10m. Although dry dune and other habitats were not mapped, transitions between wet and dry communities were. Former slacks that were dry in 2012 and no longer contained slack vegetation were identified by target notes, but their boundaries were not mapped.

3.1.5.2 Location of vegetation quadrats

Using the GIS resources described above in the mapping methodology, SDGB quadrats for which data were available were re-located. Some expert judgement by the surveyors was required to re-locate the original quadrat position, particularly where error or distortion in the SDGB survey map was evident. Additional quadrats were recorded adjacent to grid referenced hydrological monitoring locations (dip wells). Occasionally it was not possible to locate the exact position of dip wells in which case the quadrat was positioned as close as possible. Where dipwells were fenced, and either could not be located or the fenced area was impenetrable due to scrub, quadrats were placed outside the fence touching its SW corner. Where dip wells were not visible at all quadrats were located according to the grid reference. Where possible, additional new quadrats were recorded in less common habitats and young natural slacks formed since the SDGB survey.

3.1.5.3 Vegetation quadrat recording methodology

Once quadrat positions were located, a 2x2m quadrat oriented north-south was surveyed. The location of the centre of the quadrat was recorded using a Garmin Etrex GPS, to around ±5 m accuracy. Within the quadrats all vascular plants and bryophytes were identified and percentage cover recorded. Where cover of a species was <1%, a value of 0.1% was recorded where a single individual was present, and 0.5% where more than one individual was present, to enable conversion to Domin values (+ and 1 respectively). Cover values between 1 and 10 were recorded to the nearest 1%, and above that to the nearest 5%. Where species identification was not possible in the field (primarily bryophytes), samples were collected and later verified by a specialist.

Additional parameters such as bare ground, aspect, slope, as well as data regarding management in evidence such as grazing, dunging, urine patches, evidence of scrub clearance, etc. were recorded (Table 4). Vegetation height was measured by placing a metre ruler at 5 random locations within the quadrat, and estimating the sward height to which 80 % of the vegetation reached, within a 20 cm radius of the ruler. A unique ID number was assigned to each quadrat within the database, and where relevant the associated quadrat number from the SDGB survey was noted within the recording form. Two photographs were taken at each quadrat facing North; one looking down on the sward, and the other including the surrounding habitat for context. Unique quadrat ID and a four letter site code were included within photographs. Quadrats were allocated to a NVC community following the methodology described for mapping above, though if required TABLEFIT analysis could be delayed until later on with reference to the full species list.

Table 4. Data collected associated with each quadrat.

Category	*Sub-category*	*Data entry method*
ID	Unique quadrat ID generated by ArcPad	n/a
1990 ID	Quadrat number assigned in SDGB survey	Free text
Characteristics	GPS location	Free text
	Angle of slope (degrees)	
	Aspect (compass degrees)	
	Vegetation height (cm; 5 measurements)	
Management	Grazed?; Rabbit; Sheep; Cattle; Horse; Other animal (specify); Mown; Scrub-cut; Trampled by people; Evidence of fires; Other disturbance (specify)	Choice (yes/no/don't know) & free text to specify 'other'
Additional info.	Flooded at time of survey; Soil sample taken	Choice (yes/no)
	Depth(cm); Photographic record; Soil features	Free text
NVC community	NVC community description	Free text
Vegetation data	Name and % cover for each species	Drop down choice for name and free text for %cover

3.1.5.4 Soil sampling

A soil sample was taken from the SW corner of each quadrat recorded. A plastic corer of 5 cm diameter and 15 cm depth, labelled with quadrat ID and date was hammered into the ground and removed using pliers, and the tube and soil sample within were placed in a plastic bag and sealed. Samples were kept in portable cool boxes with ice packs before being returned to CEH Bangor, where they were stored in cold rooms at 5˚C prior to analysis.

3.1.5.5 Species nomenclature

Plant species nomenclature follows that of Stace (2010) for vascular plants and Smith (2004) for bryophytes. Biological Records Centre (BRC) species codes are associated with all vegetation data within the database.

3.1.5.6 Data handling and storage

Data was backed up at the end of each survey day onto an external hard drive, with quadrat data in the form of Access database files named with Tablet ID and date, and GIS shapefiles containing mapped data were named with surveyor initials, site and date.

3.1.5.7 Laboratory methods – soil analysis & archiving

Soil samples were processed in the laboratory at CEH Bangor as follows: Thickness of the organic horizon (cm), the presence of any buried soil layers, and fresh weight (g) were measured for each sample. Samples were prepared by removing large roots and other debris before thoroughly mixing and sub-sampling for pH (measured in a solution of deionised water at ratio 1:25 w.b.v.), electrical conductivity (in the same solution, EC measured with a Dow Corning conductivity meter), and moisture and organic matter content (percentage loss on ignition %LOI). For moisture content, samples were dried at 105 °C for 72 hours and reweighed. For organic matter content (%LOI) samples were then combusted in a muffle furnace at 375 °C for eight hours, a temperature sufficient to burn off organic carbon but not to dissociate too much carbon dioxide from shell carbonates (Ball 1964). Soil samples were then air dried, sieved to 2 mm, labelled and archived by CEH for future analysis if required.

3.1.6 **Data analysis**

3.1.6.1 Digitising SDGB wetland polygons

Digitised maps of the SDGB survey were only available for the Sefton Coast. For all other sites, polygons of wetland areas had to be digitised based on scanned hard copy maps, georeferenced to the best possible accuracy in ArcGIS v10, given underlying distortion. While some SDGB survey maps were based on aerial photographs which had been accurately orthorectified, others had not been. The SDGB maps for Sandscale were particularly distorted and this made some mapping in the field difficult when attempting to revisit previously mapped wetland areas.

3.1.6.2 Identifying polygons for change comparison.

In the field, surveyors attempted to map all slack areas designated as slack in the SDGB survey and any additional areas of slack seen while in the field, usually new slack or scrapes resulting from deliberate site management. As noted in section 3.1.1 and covered in detail for individual site reports (section 8), in practice on the larger sites, some areas of SDGB wetland were not mapped. This was predominantly an issue on the Sefton Coast, where the majority of slack area within the 3 main sites of Ainsdale NNR, Ainsdale LNR and Birkdale Hills LNR were surveyed, but smaller satellite areas and sites were not visited.

3.1.6.3 Categorising vegetation types for change analysis

Due to the wide diversity of wetland types encountered, and the number of intermediate or transitional communities mapped, it was necessary to simplify the categories of vegetation included in the change analysis. This was made more complicated by the fact that some sites used the 'preliminary' NVC classification when mapped in the SDGB survey, for which there is no direct translation to the new NVC. There is a simple correspondence table (see Appendix 5) which, for slacks, only differentiates between acidic and calcareous slack types, and does not adequately cover early successional slack communities such as SD13 and SD14. More detailed cross-matching had been done previously at some individual sites e.g. The Sefton Coast sites, but this was based on re-analysing individual quadrat records and target notes, and therefore does not provide consistent matchings, because allocations differ depending on the species composition. Furthermore, the cross-matching would only be relevant for the Sefton Coast and would have limited applicability to other sites.

Table 5 lists which sites used the preliminary and which used the final NVC classification for sand dune vegetation in the SDGB survey. Table 6 lists the categorisation used for sites mapped under the preliminary NVC and Table 7 lists the categorisation for sites mapped using the final NVC, and all the 2012 mapping. The categories were designed to allow as great a comparison between preliminary and final NVC categories as possible, focusing primarily on distinguishing likely wetting and drying trends in the vegetation. Data from the SDGB survey may be referred to as 1990 data for clarity and simplicity, although individual sites were surveyed in different years, ranging from 1987 - 1990.

Table 5. List of key sites surveyed, original survey year in the Sand Dune Survey of Great Britain (SDGB) and version of NVC used in the SDGB mapping.

Site	Year Surveyed	Version of NVC
Braunton Burrows	1990	Final
Ainsdale LNR	1989	Preliminary, converted to Final
Ainsdale NNR	1989	Preliminary, converted to Final
Birkdale Hills LNR	1989	Preliminary, converted to Final
Sandscale	1987	Preliminary
Lindisfarne	1989	Preliminary
Ross Links	1988	Preliminary
Holme	1989	Preliminary
Winterton	1989	Preliminary

N.B. Data from the SDGB survey may be referred to as 1990 data for clarity and simplicity, although individual sites were surveyed in different years, ranging from 1987 - 1990.

Table 6. Broad vegetation codes used for reporting of change in mapped area, using preliminary NVC classification

Code	Vegetation type
c	Calcareous slack type (Final NVC: SD13, SD14, SD15, SD16)
a	Acid slack type (Final NVC: SD17)
s/d	Slack to dry transitional
d	Dry habitats
sm	Salt marsh
wp	Wet pasture (usually frequent Juncus spp) (Final NVC: M23, MG8, MG10, MG11, MG12, OV28)
w	Other wetland type (including swamp, mire, open water, wet woodland, ponds etc.)
t	Trees or scrub (most sites this will be conifer plantations)

Table 7. Broad vegetation codes used for reporting of change in mapped area, using <u>final NVC</u> classification.

Code	Vegetation type
bs	Bare sand
ce	Early successional calcareous slack type (SD13, or transitions involving SD13)
cw	Wet Calcareous slack type (SD14, SD15)
cd	Dry Calcareous slack type (SD16)
a	Acid slack type (SD17)
s/d	Slack to dry transitional
d	Dry (SD6 to SD12; SD18; other non-wetland NVC communities e.g. MG1)
sm	Salt marsh
wp	Wet pasture (usually frequent Juncus spp, or inundation grasslands: M23, MG8, MG10, MG11, MG12, OV28)
w	Other wetland type (including swamp, mire, open water, wet woodland, ponds etc.)
sc	Scrub (additional category used at Braunton and Birkdale Hills LNR due to extensive scrub)
t	Trees or scrub (most sites this will be conifer plantations)
s/w	Slack to wet transitional

3.1.6.4 Change analysis of mapped area

The change analysis aimed to compare polygons of slack or other wetland vegetation mapped in the SDGB survey and which were revisited in 2012 to confirm whether they were still wetland or not, and incorporated newly formed primary or secondary slack, or other wetland areas not present in the SDGB survey. Corresponding polygons meeting these criteria were used in the change analysis. To clarify with some examples, new areas of primary slack in the northern part of Sandscale, mapped in 2012, were included in the change analysis as new slack, with no corresponding area in the SDGB survey; areas of slack on the Sefton Coast identified as slack in the SDGB survey but deemed to be dry dune vegetation in 2012 were also included in the analysis, but without any corresponding mapped area in 2012. This was due to the need to maintain a consistent mapping methodology, where only areas of wetland were mapped, and areas deemed to no longer be wetland vegetation were not mapped.

In summary, the following categories were included when conducting the change analysis:

- Locations mapped as wetland in the SDGB survey, but deemed no longer to be wetland vegetation in 2012 based on lack of slack vegetation indicator species. Note that only wetland vegetation types were mapped in 2012, so where vegetation had changed to a non-wetland type this was noted in a target note, but the extent was not mapped. These therefore represent a contraction in the area of wetland at the site.

- Locations mapped as wetland in both the SDGB survey and 2012.
- Newly formed or created wetland features mapped in 2012.

3.1.6.5 Quadrat analysis

Quadrat data from the SDGB survey were entered by hand for all dune slack or wetland quadrats that were available from the reports provided by Natural England. In some cases, tables of floristic data were missing.

Proxy explanatory variables
Proxy explanatory environmental data were calculated based on the floristic composition of species (presence/absence) in each quadrat for 1990 and 2012. Indices calculated were mean Ellenberg indices for Moisture (Ellenberg F), pH/Reaction (Ellenberg R), nutrients (Ellenberg N), light (Ellenberg L) and salinity (Ellenberg S). These indices used the UK-calibrated Ellenberg values for higher plants (Hill et al., 2004). Three climatic indices were also calculated, mean January temperature index, mean July temperature index and mean precipitation index, based on climate indices for the UK flora for higher plants (Hill et al., 2004).

Measured explanatory variables
In the 2012 survey, measured explanatory variables for each quadrat included: mean vegetation height (cm), slope (degrees), aspect (degrees from North=0), % bare ground and basic soil variables (pH, %moisture, %LOI). Species richness in each quadrat was also calculated. These explanatory variables were collated for each quadrat from 2012 in addition to the proxy explanatory variables described above.

Analysis of quadrat data
In total, data from 334 quadrats from 1990 was entered and checked, including a number of quadrats from dry dune grasslands and mobile dune habitats. In 2012, 185 quadrats were surveyed including quadrats associated with dipwells and a number of new quadrats, of these 175 had soils data, it was not possible to take soil samples from the remaining 10 quadrats, due to a variety of reasons, primarily where survey locations were under water in the wet summer at Sandscale. There were 131 quadrats in 2012 which were directly linked to quadrats surveyed in 1990, of which 119 had soils data). These 131 quadrats formed the basis of analysis of botanical change over time.

Botanical composition was analysed using the ordination analysis package CANOCO v4.5 (ter Braak and Šmilauer, 2002). Data from 1990 was analysed using proxy variables only. Data from 2012, recorded as percentage cover in the field were converted to the ten-point DOMIN scale for harmonisation with the 1990 data, and were interpreted using both proxy and measured environmental variables. When analysed together, a number of species had to be grouped to harmonise species between the two survey periods. Additional explanatory environmental variables were collated to describe year and site for the change analysis. For each ordination analysis (1990, 2012, combined data), the length of the first environmental gradient was established using detrended correspondence analysis to determine whether detrending methods were required. In all cases, the data did not require detrending therefore linear ordination methods were applied (Principal Components Analysis - PCA). Species cover data were log transformed within CANOCO as part of the analysis.

Statistical analysis - Analysis of change across and within sites over time
Statistical analysis of differences in explanatory variables across and within sites used the R package (R Development Core Team, 2011). We fitted a fixed effects and a mixed model to the individual quadrat differences between 2012 and 1990 data. The fixed effects analysis used site as a factor to estimate change by site. Due to differences in the number of quadrats recorded at each site, a joint analysis to estimate an underlying common change was best carried out using a mixed effects model. In this model we have assumed an overall change common to all sites, with a random deviation from that difference for each site.

3.2 *Hydrological study*

3.2.1 **Desk study**

For each of the 'key sites', we have prepared background information to describe the hydrogeological setting, average meteorological conditions, and other factors that will impact on the hydrological regime within the wetland and hence the ecohydrological conditions. At some sites (e.g. Braunton Burrows), a considerable amount of hydrological investigation has already been carried out and in most cases this has already been reported in other documents. We refer to those documents where appropriate. Where possible, results of previous studies are incorporated into the development of conceptual groundwater flow models.

3.2.2 **Hydrogeological Setting**

The geological settings for the sites are based on geological maps at the 1:50,000 scale published by the British Geological Survey. They show superficial strata over bedrock. Supporting evidence is drawn from a variety of published data including site management plans, overview documents and the technical literature.

3.2.3 **Aerial Imagery, topography and mapping hydrological measurement points**

NextPerspectives aerial photography (GeoTIFF) and 2m resolution digital elevation (ASCII) data for each key site have been downloaded via Geostore. These datasets were processed and manipulated in ArcGIS 9 (ESRI, 2004) in order to produce the basemaps upon which other datasets (topography, vegetation, and instrument layout) could be displayed.

Digital elevation data were used for topographic analysis which provided general information about each dune system (e.g. height and width of frontal dunes, number of dune ridges, elevation of base of slack areas). This additionally helped to inform the conceptual groundwater flow models.

3.2.4 **Climatic Setting**

Assessment of the long term meteorological conditions for each site has been conducted using the Met Office Rainfall and Evaporation Calculation System (MORECS). This system uses daily meteorological data to produce weekly estimates of rainfall and evapotranspiration for each square of a 40 x 40 km grid superimposed upon Great Britain. Each of the key sites falls into one of these grid squares (Table 8).

MORECS utilises a modified version of the Penman-Monteith equation to calculate evapotranspiration and a two-reservoir model to simulate the extraction of water in the Soil Moisture Deficit (SMD) calculations (Gardner and Field, 1983). Evapotranspiration is calculated at a 'potential' rate i.e. the amount of water that would be lost by evapotranspiration assuming that unlimited water is always available. This quantity is known as 'potential evaporation' (PE) and only reflects reality in situations where water is always freely available. In situations where this is not the case, PE is likely to be an over-estimate of the actual loss of water by evapotranspiration. Actual evaporation (AE) takes into account the soil moisture deficit (the amount of water held in the soil minus the amount of water that the soil can hold against the forces of gravity – a full explanation of this is given on pages 261 to 264 of Shaw (1994)) and reduces the PE rate accordingly to give a value that better reflects the actual amount of water lost through evapotranspiration. The analysis in this report uses AE not PE.

In addition to displaying the monthly time-series data (1961 to 2012) for the 40 x 40 km grid square containing each key site, we have also calculated rainfall minus actual evaporation at both a monthly (Net Monthly) and annual (Net Annual) time step. These data reflect the balance between rainfall and evaporation (positive values = rainfall exceeds evaporation, negative values = evaporation exceeds rainfall) and help both to identify generally wetter or drier sites, and also indicate which are more likely to be sensitive to climatic changes.

Table 8. Key sites and MORECS square numbers.

Site	MORECS Square
Lindisfarne	59
Ross Links	66
Sandscale	90
Ainsdale	96
Saltfleetby	110
Holme	119
Winterton	131
Braunton	165

3.2.5 Field Investigation

With the exception of Lindisfarne and Ross Links, each key site was visited at least once by staff from CEH and BGS. Visits to Lindisfarne and Ross Links were considered too costly and instead the background hydrological information for these sites was collected by the vegetation survey field team. The purpose of these visits was to:

- Meet with local staff involved in managing the site.
- Verify the information gathered during the desk study phase.
- Record any information that may help with developing the hydrological understanding of the site.
- Survey points of interest – surface water features, topographic features, dipwells (relocate where possible).
- Where possible, measure groundwater levels.

3.2.6 Topographic surveying

All topographic surveying was carried out using a Trimble R8 GNSS differential GPS system. This was operated in real-time Kinematic surveying mode which, with a single Baseline of <30 km, has a horizontal accuracy of 8 mm + 1 ppm RMS, and vertical accuracy of 15 mm + 1 ppm RMS.

3.2.7 Water level measurement

Manual water level measurements were made with a 30 m flat-tape water level meter (ITMSoil, UK) and are accurate to better than +/- 5 mm.

Automatic water level measurements are taken using either Diver® (Schlumberger, The Netherlands) or Levelogger® Gold (Solinst, USA) non-vented pressure transducers. The same principle of operation applies to both systems. Pressure transducers are suspended in the dipwells or piezometers where measurements are required (A in Figure 2). The pressure that these transducers measure is the sum of the pressure due to the column of water above the sensor plus atmospheric pressure. It is therefore necessary to have a similar logger measuring just atmospheric pressure (B in Figure 2) so that the difference between the two pressure readings can be calculated, with the result being just the pressure due to the column of water.

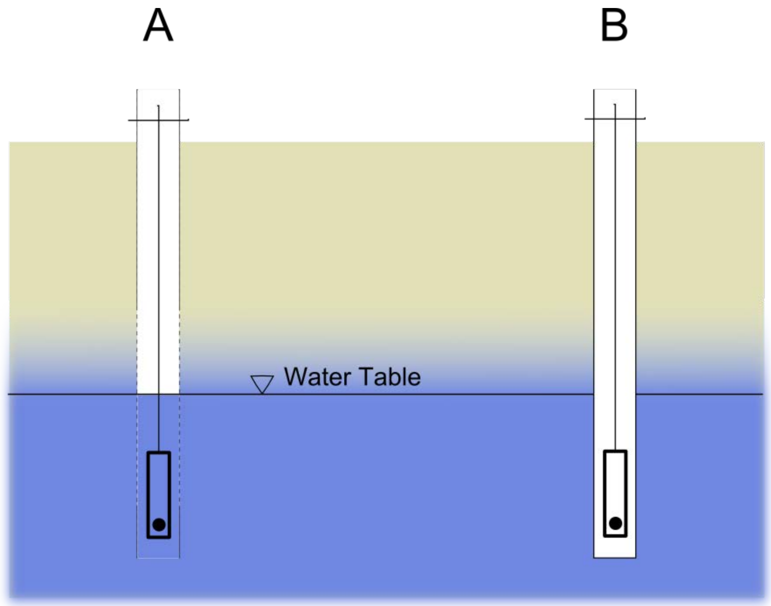

Figure 2. Non-vented water level monitoring system.

The accuracy of these systems is typically +/- 1 cm.

4 Synthesis of results from vegetation survey

4.1 *Analysis of change in mapped area, and quadrat characteristics at each site*

4.1.1 Braunton Burrows, change in mapped area of dune wetlands

In the Sand Dune survey of Great Britain (Radley, 1994), Braunton Burrows was mapped in 1990. Changes in mapped area of dune wetlands at Braunton between 1990 and 2012 are summarised in Table 9.

Table 9. Braunton Burrows. Mapped area (ha) of broad vegetation classes in 1990 and 2012, showing net change, and percentage change for classes with area > 1 ha in 1990.

Area summaries	1990	2012	Net change	%change
Bare sand and early successional	1.1	3.3	2.2	207.9
Wet slacks + slack/wet transitions	40.9	12.8	-28.1	-68.7
Dry slacks	62.8	38.5	-24.3	-38.7
Slack/dry transitions	6.7	27.9	21.2	315.4
Dry habitats, including scrub	16.5	12.5	-4.0	-24.0
Other wetlands	1.3	2.1	0.8	65.8
Total slacks	111.5	82.5	-32.2	-28.9
Total slacks and other wetlands	112.7	81.3	-31.4	-27.9
(Total Mapped Area)	129.2	96.6	-32.7	-25.3

There was a net decline in wetland area of around 30 ha, around 28% of the wetland area in 1990. Detailed change analysis using a change matrix was not possible within the scope of this study. However, based on Table 9 and interpretation of the maps and database (available electronically from Natural England), the following broad changes are apparent from this analysis.

There was a decrease of 28 ha in wet slack or slack transitions to other wetland types. There was also a decrease of 24 ha in dry slack area. However, there was a 21 ha increase in area of vegetation recorded as transitional between slack and other dry habitats, which at Braunton will include transitions to both scrub and woodland types, but also mesotrophic grassland types. It is likely that this pattern, combined with the total decrease in mapped area, represents a broad shift of wet slack types to dry slack types and a shift from dry slack types to dry non-wetland habitats, or transitions to them. This usually involves shrinkage of the wetland area within existing topographical slack or wetland features rather than a wholesale change of one community type to another, although there are instances where this has occurred.

There was a small increase in area of bare sand (in wetland areas) and early successional communities (SD13, or transitions involving SD13). This was largely a result of active management to create new scrapes or pools across the site, which also accounts for the small increase in area of other wetland types. These small increases in early successional and other wetland types amount to only 3 ha compared with a net loss of slack and wetland vegetation of 31 ha at this site.

4.1.2 Braunton Burrows, vegetation change revealed through analysis of repeated quadrats

In 2012, 55 quadrats were surveyed at Braunton Burrows. Of these, 53 could be used for analysis of vegetation change between 1990 and 2012. Changes in Ellenberg environmental and climate indicators are summarised in Table 10. There was a significant decline in Ellenberg Light scores, suggesting vegetation has become less open, probably linked to observed increases in scrub and taller vegetation.

Table 10. Braunton Burrows. Change in environmental and climatic indicators between 1990 and 2012.

N = 53	Indicator	1990	2012	Significance
Mean	**Light**	**7.42**	**7.32**	**
Mean	**Moisture**	**6.08**	**5.86**	*
Mean	pH	6.30	6.24	n.s.
Mean	Nutrients	4.03	4.05	n.s.
Mean	**Salinity**	**0.50**	**0.35**	***
Mean	**JanTemp**	**3.7**	**3.6**	***
Mean	JulTemp	14.7	14.6	n.s.
Mean	Precipitation	1064	1063	n.s.
Mean	**Spp Richness**	**17.92**	**23.08**	***
s.d.	Light	0.21	0.20	
s.d.	Moisture	0.71	0.80	
s.d.	pH	0.20	0.18	
s.d.	Nutrients	0.43	0.41	
s.d.	Salinity	0.21	0.13	
s.d.	JanTemp	0.09	0.04	
s.d.	JulTemp	0.09	0.10	
s.d.	Precipitation	18.58	23.13	
s.d.	Spp Richness	5.90	6.62	

Table shows mean, standard deviation (s.d.) for each year, and whether there was a significant difference over time (in bold, * <0.05, ** <0.01, *** < 0.001). N = number of quadrats. See methods for description of indicators.

There was also a significant decline in Ellenberg Moisture indicator score, which is consistent with the outcomes from change in mapped area of habitats, and indications of long-term fall in water levels at the site. Indicators for soil pH and nutrient levels did not change significantly. There were highly significant decreases in salinity and January temperature scores. The reasons for these two changes are unknown. Species richness increased, but the nature of the change in species composition has not been investigated. For example, there may be an increase in undesirable or weedy species.

4.1.3 Sefton Coast, change in mapped area of dune wetlands

In the Sand Dune survey of Great Britain (Radley, 1994), Ainsdale NNR, Ainsdale LNR and Birkdale Hills LNR were mapped in 1989.

Ainsdale NNR and Ainsdale LNR

Comparison of changes in mapped area of dune wetlands covered both Ainsdale NNR and Ainsdale LNR due to the difficulties in separating where individual mapped slacks lie across the site boundaries. Changes between 1989 and 2012 are summarised in Table 11 below.

Table 11. Ainsdale NNR and Ainsdale LNR. Mapped area (ha) of broad vegetation classes in 1989 and 2012, showing net change, and percentage change for classes with area > 1 ha in 1989.

Area summaries	1989	2012	Net change	%change
Bare sand and early successional	2.7	0.3	-2.5	-90.2
Wet slacks + slack/wet transitions	14.6	13.0	-1.7	-11.3
Dry slacks	15.5	16.8	1.3	8.5
Slack/dry transitions	15.7	1.3	-14.5	-92.0
Dry habitats, including scrub	3.6	0.7	-2.9	-81.3
Other wetlands	2.6	1.3	-1.3	-48.8
Total slacks	48.6	31.3	-17.3	-35.6
Total slacks and other wetlands	51.2	32.6	-18.6	-36.3
(Total Mapped Area)	55.4	33.3	-22.1	-39.9

There was a large decrease of 36% in wetland area between the two time points, with a net decrease in mapped area of 22 ha, 40%. This represents a substantial change at a large site. Detailed change analysis using a change matrix was not possible within the scope of this study. However, based on Table 11 and interpretation of the maps and database (available electronically from Natural England), the following broad changes are apparent from this analysis.

There was a substantial decline of 90% in the relatively small area of bare sand and early successional habitat, despite numerous small management scrapes of varying ages on both sites. Individually, and in total, these were all of very small area. With early successional habitat, or transitions from early successional (SD13) to other communities, usually SD14, occupying in total only 0.3 ha in 2012. There was an 11% decline in area of wet slacks and transitions to other wetland types. There was a substantial decline in area of communities in transition between slack and other dry habitats, of 14 ha (92% of the 1989 resource), coupled with a small increase of 1.3 ha in dry slacks. It is not possible to say for certain what each community has changed to, however, the large decline in mapped area suggests that much previous wetland habitat has now changed to dry habitat and was therefore not mapped in 2012. This was most apparent on the NNR in the vicinity of the pine plantation, or areas previously occupied by pine plantation, where features which were topographically dune slacks and which had been mapped as slack previously no longer contained any wetland or dune slack indicator species other than *Salix repens*. The extent of *S. repens* cover differed across these former slacks, varying from ~10% to 60% coverage in total of the former slack floor. However, survey notes suggest the majority of other species indicated communities of SD8 fixed dune grassland, SD12 decalcified fixed dune grassland or intermediates between them on the former slack floors. Detailed investigation of this was not possible in this study but is recommended for future work.

Birkdale LNR

Comparison of changes in mapped area of dune wetlands at Birkdale LNR between 1989 and 2012 are summarised in Table 12 below.

Table 12. Birkdale LNR. Mapped area (ha) of broad vegetation classes in 1989 and 2012, showing net change, and percentage change for classes with area > 1 ha in 1989.

Area summaries	1989	2012	Net change	%change
Bare sand and early successional	1.5	0.0	-1.5	-100.0
Wet slacks + slack/wet transitions	11.0	11.2	0.3	2.3
Dry slacks	7.0	1.3	-5.7	-81.0
Slack/dry transitions	7.1	0.3	-6.8	-96.4
Dry habitats, including scrub	0.4	0.0	-0.4	-
Other wetlands	3.7	4.0	0.3	8.2
Total slacks	26.6	12.8	-13.7	-51.7
Total slacks and other wetlands	30.3	16.8	-13.4	-44.4
(Total Mapped Area)	30.9	16.8	-14.0	-45.5

There was a large decrease of 44% in wetland area between the two time points, with a net decrease in mapped area of 14 ha, 45%. This represents a substantial change at a large site. Detailed change analysis using a change matrix was not possible within the scope of this study. However, based on Table 12 and interpretation of the maps and database (available electronically from Natural England), the following broad changes are apparent from this analysis.

At Birkdale, as at Ainsdale, there was a strong decline in area of early successional habitat. There were fringes of such habitat around management scrapes, but no discretely mapped units of this community type. The area of wet slack or transitions to other wetland communities did not change. There were 81% declines in dry slack community (SD16) and 96% declines in slack transitions to other dry communities, in total amounting to a loss of 12.5 ha. It is likely that this constituted the majority of slack area not mapped in 2012, and represents a change from dry slack types to non-wetland community. Although there was little change involving mapped areas of scrub within slacks it should be noted that this only covers partial areas of scrub occurring as mosaics within slacks. Slacks which are no longer slack vegetation but completely covered in scrub, which were fairly common at Birkdale, would not have been mapped in 2012. However, surveyor notes show that this was a frequent occurrence, and in many cases it was very difficult to penetrate the scrub to establish whether wetland indicator species were able to persist under the canopy or not.

Comparison of results with previous studies
The changes seen over the full time period 1988 – 2012 are consistent with those revealed in a previous survey (Gateley and MIchell, 2004). Analysis of change across the full extent of dune habitats within the wider Sefton Coast dune system over the period 1988-2004 (Sefton Coast Partnership, 2006) suggested an increase in dry slack vegetation at the expense of wet slack vegetation, with a net decline of 37% in wet dune habitat (SD15) and an increase in the drier slack vegetation (SD16) of 26%. Total slack area however only declined by 8%, compared with the decline in wetland area of 39 % observed in this study for combined area of wetlands surveyed at Ainsdale NNR, Ainsdale LNR and Birkdale LNR. Further analysis of the data, including change analysis of the 2004 data for the polygons surveyed in this study, and incorporating information on spatial context, hydrological data, and management history at the sites, and other recorded vegetation change (e.g. Smith 2006), would be required to understand these trends better.

4.1.4 **Sefton Coast, vegetation change revealed through analysis of repeated quadrats**

Ainsdale NNR
In 2012, 30 quadrats were surveyed at Ainsdale NNR. Of these, 29 could be used for analysis of change over time. Changes in Ellenberg environmental and climate indicators are summarised in Table 13. There was a small but significant decline in Ellenberg light scores, suggesting a move away from open communities with light demanding species to a more closed canopy. There was a reasonably large increase in Ellenberg nutrient scores, suggesting that the site has become more eutrophic. There are a number of reasons for this. Accumulated N in soils due to atmospheric N deposition may be one reason. A second reason may be natural successional development of soils over time, leading to increases in soil organic matter content. This would be exacerbated by tendencies to taller, scrubbier vegetation which lead to increased organic matter accumulation and greater soil fertility, particularly around N-fixing species such as gorse and sea buckthorn, but also more generally under scrub species such as birch, willow and hawthorn. Surprisingly, given the change in habitat area reported in the mapping comparison, there is no significant decline in Ellenberg moisture scores. This may be due to the lack of quadrats near to where the majority of observed changes occurred, which was near the pine plantation. There were no changes in the climate indicator scores or in species richness at Ainsdale NNR.

Table 13. Ainsdale NNR. Change in environmental and climatic indicators at Ainsdale NNR between 1989 and 2012.

N=21	Indicator	1989	2012	Significance
Mean	**Light**	**7.42**	**7.29**	*
Mean	Moisture	5.94	5.84	n.s.
Mean	pH	5.91	5.99	n.s.
Mean	**Nutrients**	**3.77**	**4.09**	**
Mean	Salinity	0.33	0.30	n.s.
Mean	JanTemp	3.61	3.60	n.s.
Mean	JulTemp	14.57	14.59	n.s.
Mean	Precipitation	1076	1074	n.s.
Mean	Spp Richness	24.14	23.33	n.s.
s.d.	Light	0.22	0.16	
s.d.	Moisture	1.32	0.90	
s.d.	pH	0.26	0.26	
s.d.	Nutrients	0.33	0.42	
s.d.	Salinity	0.15	0.18	
s.d.	JanTemp	0.08	0.03	
s.d.	JulTemp	0.12	0.07	
s.d.	Precipitation	31.77	15.60	
s.d.	Spp Richness	11.24	6.30	

Table shows mean, standard deviation (s.d.) for each year, and whether there was a significant difference over time (in bold, * <0.05, ** <0.01, *** < 0.001). N = number of quadrats. See methods for description of indicators.

Ainsdale LNR

In 2012, 4 quadrats were re-surveyed at Ainsdale LNR. These were all used for analysis of change over time. Changes in Ellenberg environmental and climate indicators are summarised in Table 14. There was no significant change in environmental indicator scores, climatic indicator scores or species richness.

Table 14. Ainsdale LNR. Change in environmental and climatic indicators at Ainsdale LNR between 1989 and 2012.

N=4	Indicator	1989	2012	Significance
Mean	Light	7.47	7.30	n.s.
Mean	Moisture	7.06	6.46	n.s.
Mean	pH	6.05	6.11	n.s.
Mean	Nutrients	3.90	4.18	n.s.
Mean	Salinity	0.42	0.38	n.s.
Mean	JanTemp	3.62	3.55	n.s.
Mean	JulTemp	14.49	14.54	n.s.
Mean	Precipitation	1102	1085	n.s.
Mean	Spp Richness	19.25	23.00	n.s.
s.d.	Light	0.15	0.18	
s.d.	Moisture	1.20	1.07	
s.d.	pH	0.12	0.14	
s.d.	Nutrients	0.39	0.36	
s.d.	Salinity	0.10	0.14	
s.d.	JanTemp	0.03	0.04	
s.d.	JulTemp	0.14	0.06	
s.d.	Precipitation	34.06	13.80	
s.d.	Spp Richness	2.22	3.92	

Table shows mean, standard deviation (s.d.) for each year, and whether there was a significant difference over time (in bold, * <0.05, ** <0.01, *** < 0.001). N = number of quadrats. See methods for description of indicators.

Birkdale Hills LNR

In 2012, 18 quadrats were surveyed at Birkdale Hills LNR. Of these, 14 could be used for analysis of change over time. Changes in Ellenberg environmental and climate indicators are summarised in

Table 15. There was a highly significant decrease in Ellenberg light scores, suggesting a shift towards taller more rank vegetation. This matches the observed increase in scrub across many of the Birkdale slacks. There was a concurrent increase in Ellenberg nutrient scores which is also consistent with greater levels of organic matter under taller vegetation and scrub. There was also quite a large decline in Ellenberg moisture scores, suggesting some drying out of the vegetation in the quadrats. There was no significant change in climate indicator scores or species richness.

Table 15. Birkdale Hills LNR. Change in environmental and climatic indicators at Birkdale LNR between 1989 and 2012.

N=14	Indicator	1989	2012	Significance
Mean	**Light**	**7.51**	**7.27**	***
Mean	**Moisture**	**7.79**	**7.01**	*
Mean	pH	5.99	6.03	n.s.
Mean	**Nutrients**	**3.68**	**4.24**	**
Mean	Salinity	0.38	0.30	n.s.
Mean	JanTemp	3.62	3.60	n.s.
Mean	JulTemp	14.56	14.58	n.s.
Mean	Precipitation	1085	1079	n.s.
Mean	Spp Richness	15.64	15.86	n.s.
s.d.	Light	0.12	0.18	
s.d.	Moisture	0.81	0.88	
s.d.	pH	0.24	0.23	
s.d.	Nutrients	0.29	0.45	
s.d.	Salinity	0.14	0.19	
s.d.	JanTemp	0.04	0.05	
s.d.	JulTemp	0.11	0.08	
s.d.	Precipitation	31.75	19.11	
s.d.	Spp Richness	4.34	5.59	

Table shows mean, standard deviation (s.d.) for each year, and whether there was a significant difference over time (in bold, * <0.05, ** <0.01, *** < 0.001). N = number of quadrats. See methods for description of indicators.

4.1.5 **Sandscale, change in mapped area of dune wetlands**

In the Sand Dune survey of Great Britain (Radley, 1994), Sandscale was mapped in 1987. Changes in mapped area of dune wetlands at Sandscale between 1987 and 2012 are summarised in Table 16 below.

Table 16. Sandscale. Mapped area (ha) of broad vegetation classes in 1987 and 2012, showing net change, and percentage change for classes with area > 1 ha in 1987.

Area summaries	1987	2012	Net change	%change
Slacks + slack/wet transitions	23.7	25.5	1.8	7.8
Slack/dry transitions	7.9	3.0	-4.9	-62.2
Dry habitats	0.0	0.8	0.8	-
Other wetlands	30.2	38.4	8.2	27.2
Total slacks	31.6	28.5	-3.1	-9.7
Total slacks and other wetlands	61.8	66.9	5.1	8.3
(Total Mapped Area)	61.8	67.7	5.9	9.5

There was a small net increase in wetland area of around 5 ha, around 8% of the wetland area in 1987, however this is within the error of mapping (Hearn et al. 2011). Detailed change analysis using a change matrix was not possible within the scope of this study. However, based on Table 16 and interpretation of the maps and database (available electronically from Natural England), the following broad changes are apparent from this analysis.

There was a decrease of around 5 ha in slack/dry transitions, and an increase of 8 ha in the area of other wetlands. This relates primarily to areas of M23 Juncus pasture which covers relatively large areas of the eastern half of the site, and which was indistinctly mapped in 1987. Overall, we feel there has been little net change in area of wetland communities, and the small changes observed are likely to be due to differences in interpretation of surveyors.

4.1.6 **Sandscale, vegetation change revealed through analysis of repeated quadrats**

In 2012, in total 35 quadrats were surveyed at Sandscale. Of these, 6 could be used for analysis of change over time. 24 quadrats were recorded adjacent to previous piezometer locations. Some of these were deeply flooded at the time of recording, so quadrats were recorded nearby. A further 5 new quadrats were recorded, either in new secondary or embryo slacks, or in other older vegetation types. This analysis concerns the 6 repeat quadrats only. Changes in Ellenberg environmental and climate indicators are summarised in Table 17. There was no significant change in environmental indicator scores. There was a significant increase in the July temperature indicator and a significant decline in the precipitation indicator. Species richness increased, but the nature of the change in species composition has not been investigated. For example, there may be an increase in undesirable or weedy species.

Table 17. Sandscale. Change in environmental and climatic indicators between 1987 and 2012.

Table shows mean, standard deviation (s.d.) for each year, and whether there was a significant difference over time (in bold, * <0.05, ** <0.01, *** < 0.001). N = number of quadrats. See methods for description of indicators.

N=6	Indicator	1987	2012	Significance
Mean	Light	7.46	7.35	n.s.
Mean	Moisture	6.54	6.47	n.s.
Mean	pH	5.66	5.60	n.s.
Mean	Nutrients	3.34	3.63	n.s.
Mean	Salinity	0.37	0.31	n.s.
Mean	JanTemp	3.54	3.55	n.s.
Mean	**JulTemp**	**14.34**	**14.46**	*****
Mean	**Precipitation**	**1127**	**1102**	*****
Mean	**Spp Richness**	**14.00**	**23.33**	******
s.d.	Light	0.23	0.10	
s.d.	Moisture	0.70	0.61	
s.d.	pH	0.30	0.19	
s.d.	Nutrients	0.54	0.36	
s.d.	Salinity	0.07	0.05	
s.d.	JanTemp	0.03	0.04	
s.d.	JulTemp	0.06	0.05	
s.d.	Precipitation	11.21	11.34	
s.d.	Spp Richness	5.22	3.93	

4.1.7 Lindisfarne, change in mapped area of dune wetlands

In the Sand Dune survey of Great Britain (Radley, 1994), Lindisfarne was mapped in 1988. Changes in mapped area of dune wetlands at Lindisfarne between 1988 and 2012 are summarised in Table 18 below.

Table 18. Lindisfarne. Mapped area (ha) of broad vegetation classes in 1988 and 2012, showing net change, and percentage change for classes with area > 1 ha in 1988.

Area summaries	1988	2012	Net change	%change
Slacks + slack/wet transitions	22.2	27.5	5.3	23.8
Slack/dry transitions	7.1	2.3	-4.8	-67.8
Dry habitats	2.7	0.7	-2.1	-75.3
Other wetlands	1.3	1.0	-0.3	-19.8
Total slacks	29.3	29.8	0.5	1.7
Total slacks and other wetlands	30.6	30.9	0.2	0.8
(Total Mapped Area)	33.4	31.5	-1.8	-5.5

There was no net change in wetland area between the two time points. Detailed change analysis using a change matrix was not possible within the scope of this study. However, based on Table 18 and interpretation of the maps and database (available electronically from Natural England), the following broad changes are apparent from this analysis.

There was an increase of around 5 ha in dune slacks and slack/wet transitions, with a corresponding decrease in area of the drier habitats and slack/dry conditions. These changes equate to a 24 % increase in slack area. This may partly be due to differences in interpretation of vegetation community by surveyors, and interpretation can be guided by analysis of change for repeated quadrats.

4.1.8 Lindisfarne, vegetation change revealed through analysis of repeated quadrats

In 2012, in total 24 quadrats were surveyed at Lindisfarne. Of these, 16 could be used for analysis of change over time. Six quadrats were recorded adjacent to new piezometer locations. This analysis concerns the 16 repeat quadrats only. Changes in Ellenberg environmental and climate indicators are summarised in
Table 19. There was no significant change in environmental indicator scores, climate indicator scores or species richness at this site.

Table 19. Lindisfarne. Change in environmental and climatic indicators between 1988 and 2012.

N=16	Indicator	1988	2012	Significance
Mean	Light	7.619	7.599	n.s.
Mean	Moisture	6.483	6.758	n.s.
Mean	pH	5.849	5.929	n.s.
Mean	Nutrients	3.416	3.432	n.s.
Mean	Salinity	0.6241	0.5474	n.s.
Mean	JanTemp	3.632	3.612	n.s.
Mean	JulTemp	14.41	14.46	n.s.
Mean	Precipitation	1117	1106	n.s.
Mean	Spp Richness	14.31	14.81	n.s.
s.d.	Light	0.229	0.1256	
s.d.	Moisture	1.0437	0.8872	
s.d.	pH	0.2665	0.3177	
s.d.	Nutrients	0.3966	0.4469	
s.d.	Salinity	0.367	0.3749	
s.d.	JanTemp	0.12477	0.09391	
s.d.	JulTemp	0.11344	0.05766	
s.d.	Precipitation	25.66	14.26	
s.d.	Spp Richness	4.85	4.39	

Table shows mean, standard deviation (s.d.) for each year, and whether there was a significant difference over time (in bold, * <0.05, ** <0.01, *** < 0.001). N = number of quadrats. See methods for description of indicators.

4.1.9 Ross Links, change in mapped area of dune wetlands

In the Sand Dune survey of Great Britain (Radley, 1994), Ross Links was mapped in 1988. Changes in mapped area of dune wetlands at Ross Links between 1988 and 2012 are summarised in Table 20 below.

Table 20. Ross Links. Mapped area (ha) of broad vegetation classes in 1988 and 2012, showing net change, and percentage change for classes with area > 1 ha in 1988.

Area summaries	1988	2012	Net change	%change
Slacks + slack/wet transitions	24.9	7.3	-17.5	-70.5
Slack/dry transitions	0.2	5.3	5.1	-
Dry habitats	1.9	2.6	0.7	35.0
Other wetlands	1.8	10.2	8.4	456.7
Total slacks	25.0	12.7	-12.4	-49.4
Total slacks and other wetlands	26.9	22.9	-4.0	-14.8
(Total Mapped Area)	28.8	25.5	-3.3	-11.5

There was a small net decrease in wetland area between the two time points of 4 ha, around 15% of the area mapped in 1988. Detailed change analysis using a change matrix was not possible within the scope of this study. However, based on Table 20 and interpretation of the maps and database (available electronically from Natural England), the following broad changes are apparent from this analysis.

There was a decrease of 17 ha (70%) in wet slacks and transitions to other wetlands, with an increase in area of 8 ha in wetland habitats. This may represent a change from slack communities to M23 Juncus pasture. There was a 5 ha increase in transitions to dry habitats. The interpretation of area change suggests a small net loss of wetland types in favour of dry habitats. This may partly be due to differences in interpretation of vegetation community by surveyors, and interpretation can be guided by analysis of change for repeated quadrats.

4.1.10 Ross Links, vegetation change revealed through analysis of repeated quadrats

In 2012, 6 quadrats were surveyed at Ross Links. These were all repeat quadrats and could be used for analysis of change over time. Changes in Ellenberg environmental and climate indicators are summarised in Table 21. There was no significant change in environmental indicator scores, climate indicator scores. However, there was a significant increase in species richness at this site. The reason for this, and the conservation significance has not been evaluated, for example it may represent an increase in undesirable species rather than typical dune species.

Table 21. Ross Links. Change in environmental and climatic indicators between 1988 and 2012.

N=6	Indicator	1990	2012	Significance
Mean	Light	7.444	7.425	n.s.
Mean	Moisture	6.9	6.904	n.s.
Mean	pH	5.434	5.534	n.s.
Mean	Nutrients	3.329	3.541	n.s.
Mean	Salinity	0.4465	0.33	n.s.
Mean	JanTemp	3.552	3.555	n.s.
Mean	JulTemp	14.37	14.43	n.s.
Mean	Precipitation	1129	1114	n.s.
Mean	**Spp Richness**	**11**	**21.67**	*****
s.d.	Light	0.1402	0.1819	
s.d.	Moisture	0.7549	1.0336	
s.d.	pH	0.5376	0.3398	
s.d.	Nutrients	1.0193	0.423	
s.d.	Salinity	0.3264	0.1305	
s.d.	JanTemp	0.04264	0.03233	
s.d.	JulTemp	0.07153	0.04722	
s.d.	Precipitation	19.37	13.14	
s.d.	Spp Richness	3.58	9.03	

Table shows mean, standard deviation (s.d.) for each year, and whether there was a significant difference over time (in bold, * <0.05, ** <0.01, *** < 0.001). N = number of quadrats. See methods for description of indicators.

4.1.11 **Holme Dunes, change in mapped area of dune wetlands**

In the Sand Dune survey of Great Britain (Radley, 1994), Holme Dunes was mapped in 1989. Changes in mapped area of dune wetlands at Holme Dunes between 1989 and 2012 are summarised in Table 22 below.

Table 22. Holme Dunes. Mapped area (ha) of broad vegetation classes in 1989 and 2012, showing net change, and percentage change for classes with area > 1 ha in 1989.

Area summaries	1990	2012	Net change	%change
Slacks + slack/wet transitions	3.6	0.3	-3.3	-92.9
Slack/dry transitions	0.0	0.2	0.2	-
Dry habitats	1.5	3.5	2.1	143.3
Other wetlands	0.1	0.1	0.0	-
Total slacks	3.6	0.5	-3.1	-87.1
Total slacks and other wetlands	3.7	0.6	-3.1	-84.2
(Total Mapped Area)	5.1	4.1	-1.0	-19.7

There was some change in wetland area between the two time points. Detailed change analysis using a change matrix was not possible within the scope of this study. However, based on Table 22 and interpretation of the maps and database (available electronically from Natural England), the following broad changes are apparent from this analysis.

Slacks and slack/wet transitions declined, with a roughly similar increase in area of dry habitats. The total area of slack and wetland declined by 84%. Of the wetland areas identified as slack, these generally had a poor fit to NVC slack communities, most closely resembling SD17 due to the lack of *Salix repens.* This represents a shift in slack community type from the allocations of many of these areas to SD16 in the 1989 survey.

4.1.12 Holme Dunes, vegetation change revealed through analysis of repeated quadrats

In 2012, 6 quadrats were surveyed at Holme Dunes. These were all repeat quadrats and could be used for analysis of change over time. Changes in Ellenberg environmental and climate indicators are summarised in Table 23. There was a significant decrease in Ellenberg salinity, and a significant increase in species richness, but no significant changes in other environmental indicator scores, or climate indicator scores at this site. The conservation implications of the increase in species richness have not been evaluated.

Table 23. Holme Dunes. Change in environmental and climatic indicators between 1989 and 2012.

N=6	Indicator	1989	2012	Significance
Mean	Light	7.42	7.22	n.s.
Mean	Moisture	5.49	5.78	n.s.
Mean	pH	6.18	6.34	n.s.
Mean	Nutrients	4.51	4.78	n.s.
Mean	**Salinity**	**0.88**	**0.66**	*
Mean	JanTemp	3.73	3.70	n.s.
Mean	JulTemp	14.65	14.72	n.s.
Mean	Precipitation	1070	1052	n.s.
Mean	**Spp Richness**	**15.00**	**23.00**	**
s.d.	Light	0.19	0.14	n.s.
s.d.	Moisture	0.50	0.62	n.s.
s.d.	pH	0.20	0.32	n.s.
s.d.	Nutrients	0.30	0.52	n.s.
s.d.	Salinity	0.39	0.27	n.s.
s.d.	JanTemp	0.10	0.07	n.s.
s.d.	JulTemp	0.12	0.13	n.s.
s.d.	Precipitation	21	22	n.s.
s.d.	Spp Richness	5.22	6.00	n.s.

Table shows mean, standard deviation (s.d.) for each year, and whether there was a significant difference over time (in bold, * <0.05, ** <0.01, *** < 0.001). N = number of quadrats. See methods for description of indicators.

4.1.13 Winterton, change in mapped area of dune wetlands

In the Sand Dune survey of Great Britain (Radley, 1994), Winterton was mapped in 1989. Changes in mapped area of dune wetlands at Winterton between 1989 and 2012 are summarised in Table 24 below.

Table 24. Winterton. Mapped area (ha) of broad vegetation classes in 1989 and 2012, showing net change, and percentage change for classes with area > 1 ha in 1989.

Area summaries	1989	2012	Net change	%change
Slacks + slack/wet transitions	0.8	0.0	-0.8	-
Slack/dry transitions	0.0	0.0	0.0	-
Dry habitats	6.7	2.8	-3.9	-57.8
Other wetlands	3.1	5.7	2.5	80.0
Total slacks	0.8	0.0	-0.8	-
Total slacks and other wetlands	3.9	5.7	1.7	44.0
(Total Mapped Area)	11.0	8.5	-2.5	-23.0

There was a 44% increase in wetland area between the two time points, with a net increase of 1.7 ha. Detailed change analysis using a change matrix was not possible within the scope of this study. However, based on
Table 24 and interpretation of the maps and database (available electronically from Natural England), the following broad changes are apparent from this analysis.

There was a decrease of around 4 ha in dry habitats, with increases in non slack wetland habitats. However, these may partly be due to differences in interpretation of vegetation community by surveyors, and further information can be provided by analysis of change for repeated quadrats.

4.1.14 Winterton, vegetation change revealed through analysis of repeated quadrats

In 2012, 6 quadrats were surveyed at Winterton. Of these, 5 were repeat quadrats and could be used for analysis of change over time. Changes in Ellenberg environmental and climate indicators are summarised in Table 25. There was no significant change in environmental indicator scores or climate indicator scores. There was however a significant decline in species richness at this site. The reasons for this have not been evaluated.

Table 25. Winterton. Change in environmental and climatic indicators between 1989 and 2012.

N=5	Indicator	1990	2012	Significance
Mean	Light	7.29	7.44	n.s.
Mean	Moisture	6.25	6.00	n.s.
Mean	pH	3.97	4.11	n.s.
Mean	Nutrients	2.92	2.75	n.s.
Mean	Salinity	0.30	0.28	n.s.
Mean	JanTemp	3.61	3.67	n.s.
Mean	JulTemp	14.38	14.38	n.s.
Mean	Precipitation	1132	1131	n.s.
Mean	**Spp Richness**	**10.60**	**6.00**	*****
s.d.	Light	0.26	0.53	
s.d.	Moisture	0.57	0.54	
s.d.	pH	0.93	1.02	
s.d.	Nutrients	0.81	1.38	
s.d.	Salinity	0.11	0.14	
s.d.	JanTemp	0.02	0.12	
s.d.	JulTemp	0.07	0.11	
s.d.	Precipitation	21.19	25.84	
s.d.	Spp Richness	1.83	1.30	

Table shows mean, standard deviation (s.d.) for each year, and whether there was a significant difference over time (in bold, * <0.05, ** <0.01, *** < 0.001). N = number of quadrats. See methods for description of indicators.

4.2 *Analysis of change in mapped area, and quadrats across sites*

4.2.1 **Overview of change in mapped area of dune wetlands across all sites**

Change in mapped area of wetlands across all surveyed sites is shown in Table 26. For Braunton and the Sefton Coast which were mapped using the final NVC classification in the SDGB survey, or subsequently converted to it, there was a net decline in all dune slack and wetland categories except slack/dry transitions. The decline in wet slack types (-44%) was greater than the decline in dry slack types (-34%). Across all sites, the coarser analysis shows that there was a net decline in dry and wet slack types, with a change of -32%, comprising 74 ha. There was a 19 ha increase in area of other wetland types, but overall, there was a net decline in the total area of slacks and other wetlands of 57 ha (-18%). The percentage change in total slack area across all sites was -28%. The total mapped area also declined, by 72 ha (-20%).

Table 26. Overview of change in mapped area of dune wetlands, showing detailed summary for Braunton and Sefton Coast based on final NVC, and coarser summary for all sites.

Area summaries	1990	2012	Net change	%change
Braunton and Sefton Coast				
Bare sand and early successional	5.3	3.5	-1.8	-33.6
Wet slacks + slack/wet transitions	66.6	37.0	-29.5	-44.4
Dry slacks	85.2	56.6	-28.6	-33.6
Slack/dry transitions	29.5	29.4	-0.1	-0.4
Dry habitats, including scrub	20.4	13.2	-7.2	-35.3
Other wetlands	7.5	7.4	-0.1	-1.8
Total slacks	186.7	126.6	-60.0	-32.2
Total slacks and other wetlands	194.2	130.7	-63.4	-32.7
All sites				
Dry and Wet Slacks + slack/wet transitions	232.3	157.9	-74.4	-32.0
Slack/dry transitions	44.7	40.2	-4.5	-10.1
Dry habitats	33.3	23.6	-9.7	-29.0
Other wetlands	44.0	62.8	18.8	42.6
Total slacks	277.0	198.1	-78.9	-28.5
Total slacks and other wetlands	321.1	257.6	-63.4	-19.8
(Total Mapped Area)	355.6	284.0	-71.6	-20.1

4.2.2 **Overview of change in quadrats across all sites**

Statistical significance of change in variables across all sites, and an overview of change by site, summarised from section 4.1, are shown in Table 27.

Across all sites, there was no significant change in Ellenberg moisture (F) scores across all sites, but there were declines at Braunton and Birkdale LNR. There was a significant decline in Ellenberg Light (L) scores across all sites, suggesting a general shift towards less open vegetation, with declines at Braunton, Ainsdale NNR and Birkdale. There was a significant increase in Ellenberg nutrient (N) scores across all sites, with increases at Ainsdale NNR and Birkdale. There was no change in Ellenberg R scores, but there was a significant decline in Ellenberg salinity (S) scores across all sites, with declines at Braunton and Holme.

For the climatic indicators, there was a significant decline in Precipitation scores, also significant at Sandscale, but no consistent change in January or July temperature scores across sites, although there was a decline in January temperature score at Braunton and an increase in July temperature score at Sandscale. Species richness increased at Braunton, Sandscale, Ross and Holme, but showed no overall significant change. Percentage bare ground increased at Braunton but decreased at Lindisfarne and Ross, showing no significant overall change.

Table 27. Overview of significant changes across and within sites.

	EbF	EbL	EbN	EbR	EbS	Prec	Tjan	Tjul	Spp rich	Bare sand
All sites		**--**	**+**		**--**	**-**				
Brau	**-**	**--**			**---**		**---**		**+++**	**++**
AinN		**-**	**++**							
AinL										
Birk	**---**	**---**	**+++**							
Sand						**-**		**+**	**++**	
Lind										**---**
Ross									**+++**	**--**
Holm					**-**				**++**	
Wint										

Significant differences over time in indicator variables across all sites, and within individual sites. Symbols represent significant increases (+) or decreases (-) over time, at levels of + ($p < 0.05$), ++ ($p < 0.01$), or +++ ($p < 0.001$) respectively.

4.3 *Analysis of vegetation change across all sites*

4.3.1 Multivariate interpretation of 1990 quadrat data

Ordination by Principal Components Analysis (PCA) ordination showed that the first three axes explained 11.6%, 8.3% and 5.4% respectively of the total species variance, giving a cumulative total of 25.3% of variance explained by the three axes. Figure 3 shows that the primary axis, axis 1, represents a wetness gradient from wet (left) to dry (right), while axis 2 represents a combination of fertility and pH, with higher nutrient values and higher pH values at the top, and more acidic (lower pH) and more open (higher light values) to the bottom. The species in Figure 5 generally confirm this pattern, with wetter species to the left (*Carex nigra, Ranunculus flammula*) and drier species to the right (*Festuca rubra, Holcus lanatus*), while base-loving or circum-neutral species (*Epipactis palustris, Prunella vulgaris*) sit at the top of the diagram, and acid loving species (*Erica tetralix, Agrostis canina*) generally found nearer the bottom. Ordination of the sites (Figure 4) shows that Birkdale is the wetter of the Sefton Coast sites, with slacks at Ainsdale NNR spanning the full range from dry to wet and calcareous to acidic. Winterton is not surprisingly one of the more acidic sites. Although not fully parallel with axis 1, the Precipitation index is aligned with high Ellenberg moisture values, indicating that the wetter sites contain species assemblages adapted to receiving higher rainfall. Similarly the July temperature index is broadly aligned with the drier sites, which typically have warm summers.

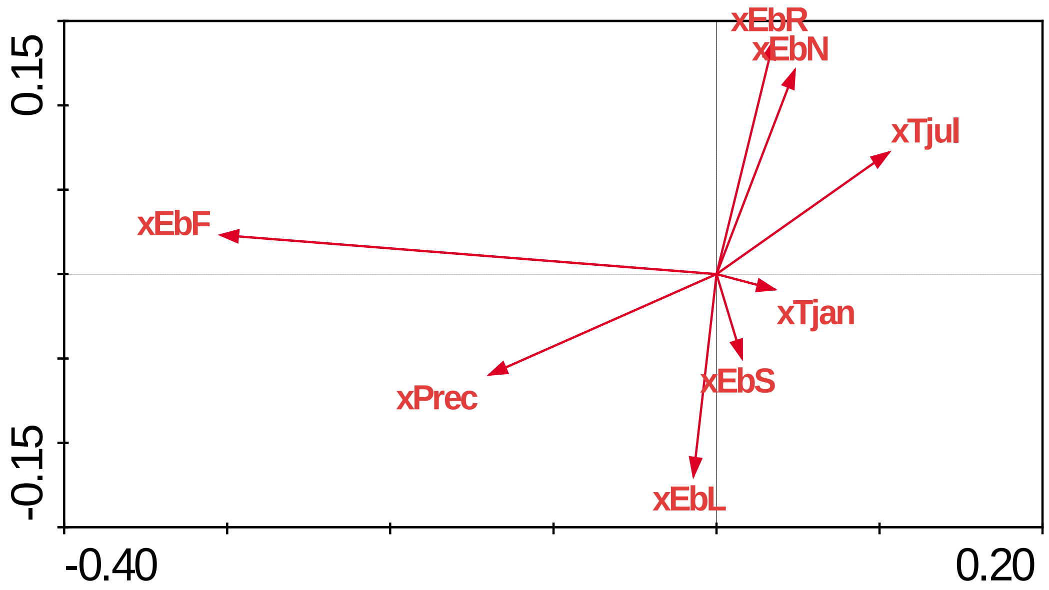

Figure 3. Explanatory proxy variables overlain on the ordination for 1990.
EbF – Ellenberg moisture, EbR – Ellenberg pH/reaction, EbN – Ellenberg nutrients, EbL - Ellenberg light, EbS – Ellenberg salinity, Tjan – January temperature index, Tjul - July temperature index, Prec – Precipitation index.

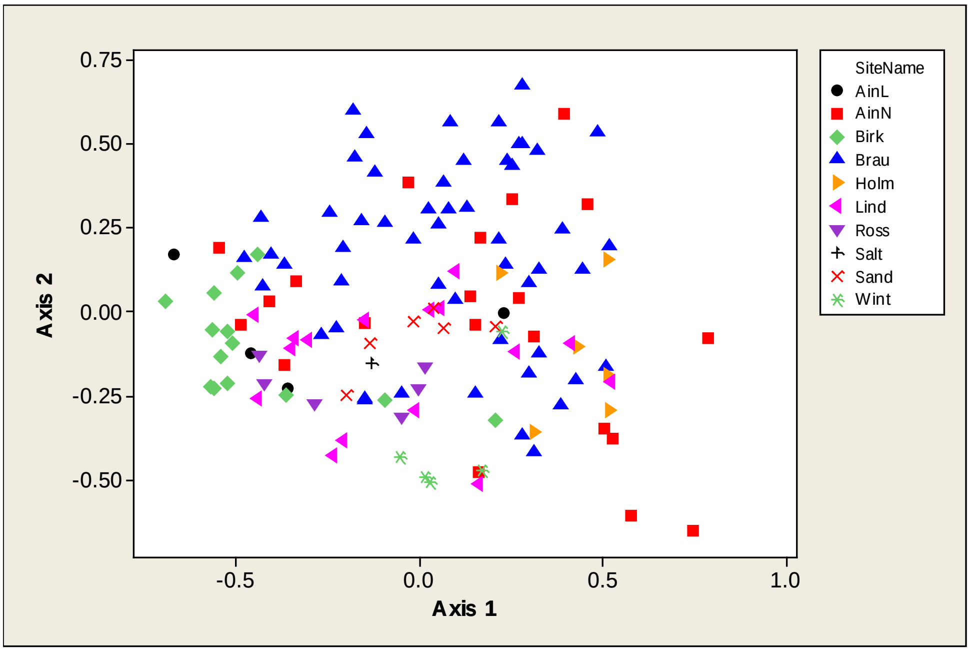

Figure 4. PCA ordination of slack and wetland quadrats in 1990.
Site codes are AinN – Ainsdale NNR, AinL – Ainsdale LNR, Birk – Birkdale, Brau – Braunton, Holm – Holme dunes, Lind – Lindisfarne, Ross – Ross Links, Salt – Saltfleetby, Sand – Sandscale, Wint – Winterton.

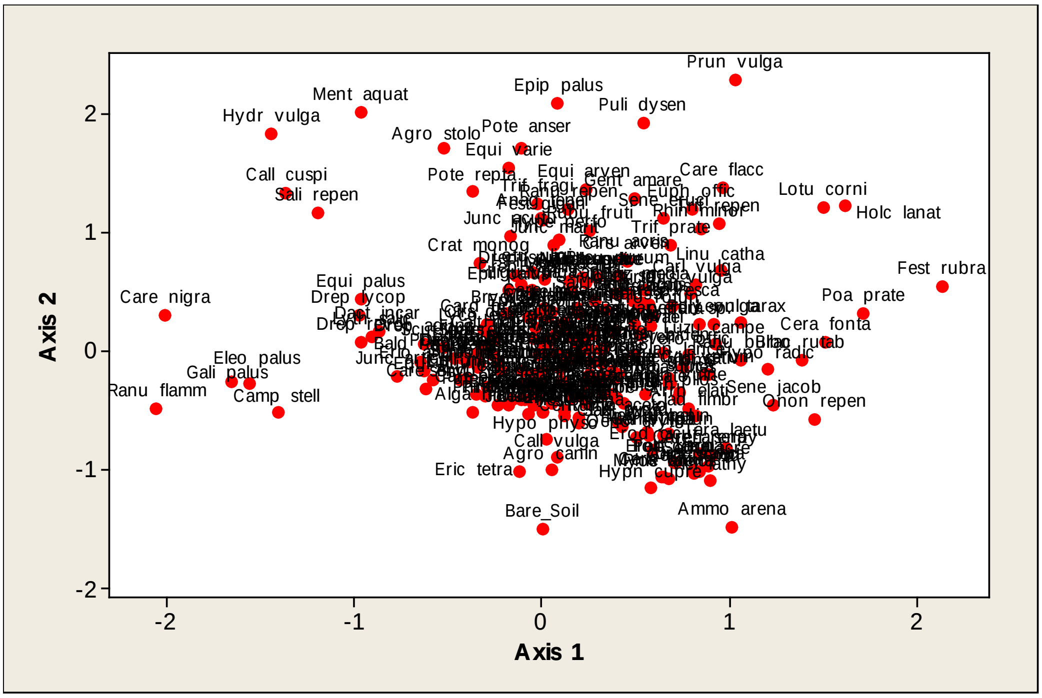

Figure 5. PCA ordination of species in 1990.
The further species are from the origin, the greater influence they contribute to the ordination.

4.3.2 **Multivariate interpretation of 2012 quadrat data**

Ordination by Principal Components Analysis (PCA) ordination showed that the first three axes explained 11.1%, 7.2% and 5.4% respectively of the total species variance, giving a cumulative total of 23.7% of variance explained by the three axes. As illustrated by Figure 6 the primary axis in the 2012 data is similar to that for 1990 and represents a wetness gradient from left (wet) to right (dry). However, interpretation of axis 2 is less clear, with some explanatory elements along axis 2 inverted compared with 1990. Higher nutrient values appear low on axis 2 while higher soil pH values (but less so Ellenberg Reaction scores) show high values along axis 2. The measured explanatory soil and vegetation variables provide little further information, except that vegetation height is closely aligned with Ellenberg nutrients. Ordination of the quadrats (Figure 7) shows that Braunton remains generally the drier and more calcareous of the sites, while Birkdale is the wetter of the three Sefton Coast sites, but also the more nutrient rich and with taller vegetation.

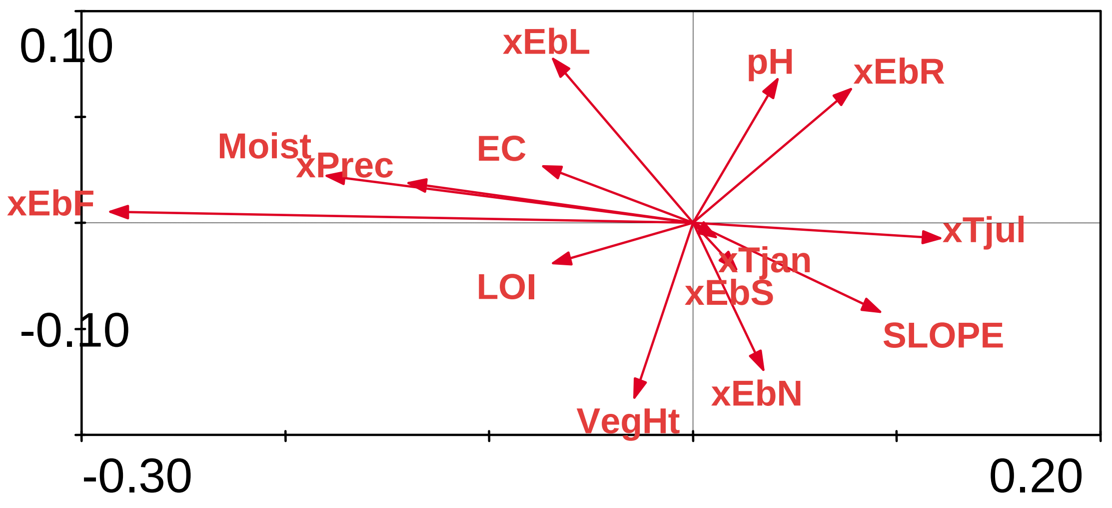

Figure 6. Measured and proxy explanatory variables overlain on the ordination for 2012.
Codes as in Figure 3, additional codes are: Moist – soil moisture content, LOI – soil organic matter content, EC – soil conductivity, VegHt – vegetation height, SLOPE – slope angle.

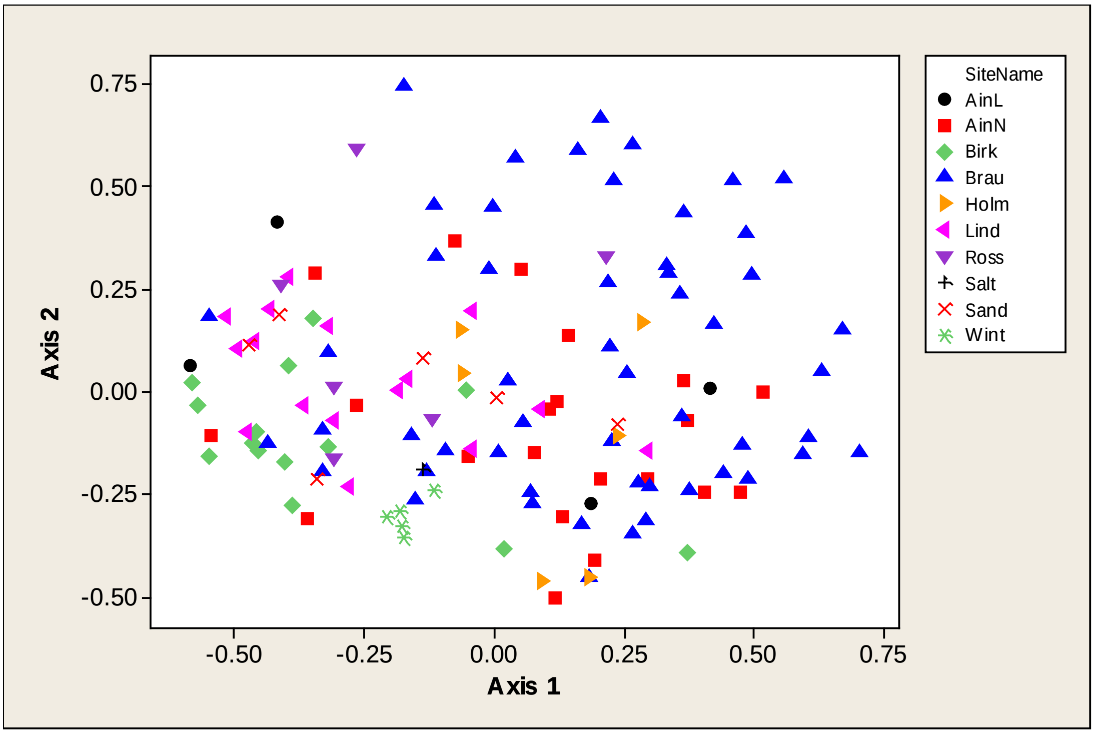

Figure 7. PCA ordination of slack and wetland quadrats in 2012.
Site codes as Figure 4.

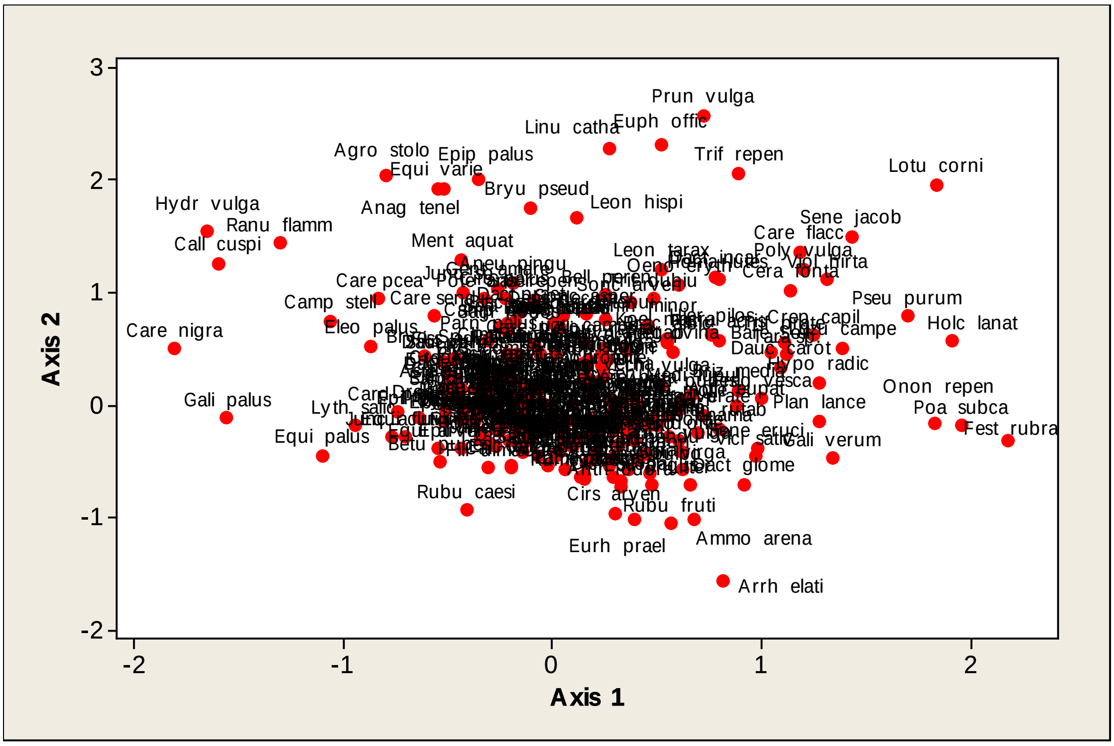

Figure 8. PCA ordination of species in 2012.
Interpretation as Figure 5.

4.3.3 Multivariate interpretation of change from 1990 to 2012

In a PCA ordination of the combined 1990 and 2012 data, the first three axes explained 10.7%, 6.8% and 4.4% respectively of the total species variance, giving a cumulative total of 21.9% of variance explained by the three axes. The spatial pattern with the combined datasets (not shown) is similar to that in 2012, while Figure 9 shows how the explanatory variables overlie the ordination. Figure 10 below plots the centroids of quadrats within each site for each time point, with arrows showing where they have moved in the ordination space.

Braunton, Birkdale LNR and Ainsdale LNR show strong shifts in species composition towards drier conditions, partly reinforcing the individual site analysis (Section 4.1) where Braunton and Birkdale showed significant declines in Ellenberg moisture scores, although the decline was not significant for Ainsdale LNR, possibly due to the low sample size. Both Lindisfarne and Sandscale show movement upwards and left in the diagram, possibly reflecting a shift towards slightly more open vegetation, while Ross Links moves upwards and right, suggesting a shift towards more calcareous vegetation, or perhaps also more open vegetation. In the latter cases, an understanding of the management history over the last few decades may aid in interpretation of change.

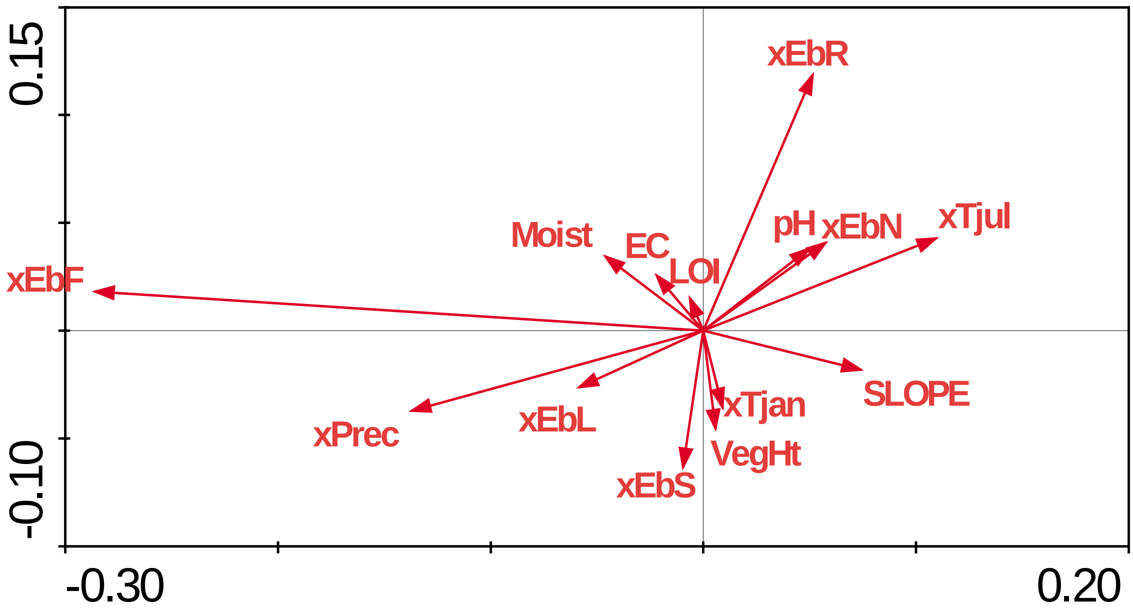

Figure 9. Measured and proxy explanatory variables overlain on the ordination for combined 1990 and 2012 quadrat data.
Codes as in Figure 6.

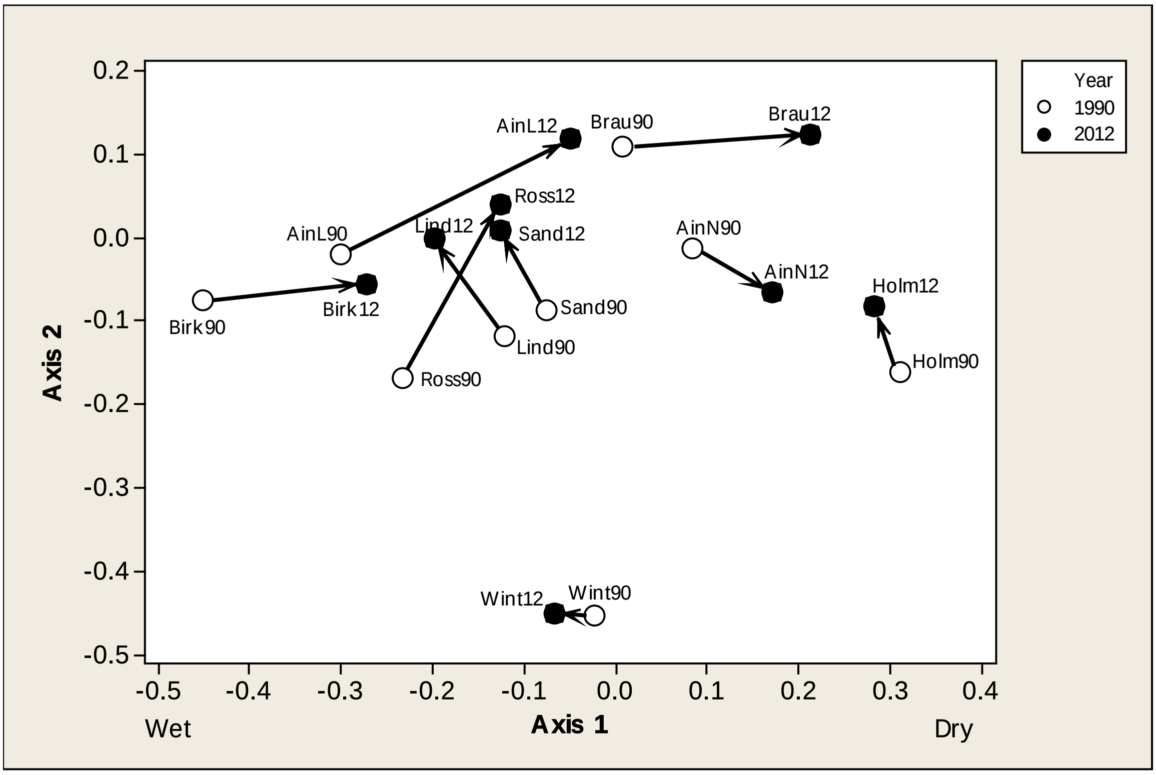

Figure 10. Combined PCA of 1990 and 2012 quadrat data.
Symbols show centroids for each site and year. Arrows show direction of movement over time.

4.4 *Overview of soil characteristics across all sites*

Within the 2012 survey 175 soil cores were taken. Results are categorised by broad community type in Figure 11 and Figure 12. Mean soil pH (Figure 11) varied from relatively acidic soils <pH 5.5 in scrub and wet pasture to pH levels around the decalcification limit of pH 6.5 in acid slack types and transitions to acid slack types, as well as some wetland communities. In the majority of calcareous slack types and in dry habitats, mean pH was around 7.5. Mean %LOI (Figure 12) varied from under 1% in the early successional communities to around 4% in dry dune communities. It increased to a mean of around 8% in the calcareous and acidic wet slack communities, and showed the highest means of around 10% in wetland and scrub communities.

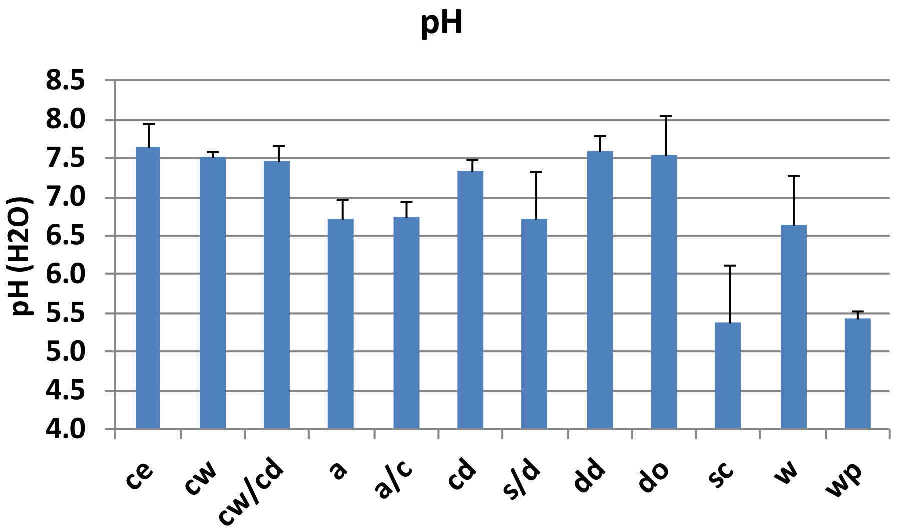

Figure 11. Soil pH in all soil cores, averaged by community type.
For codes see, additional codes: dd=dry dune habitats, do=dry non-dune habitats.

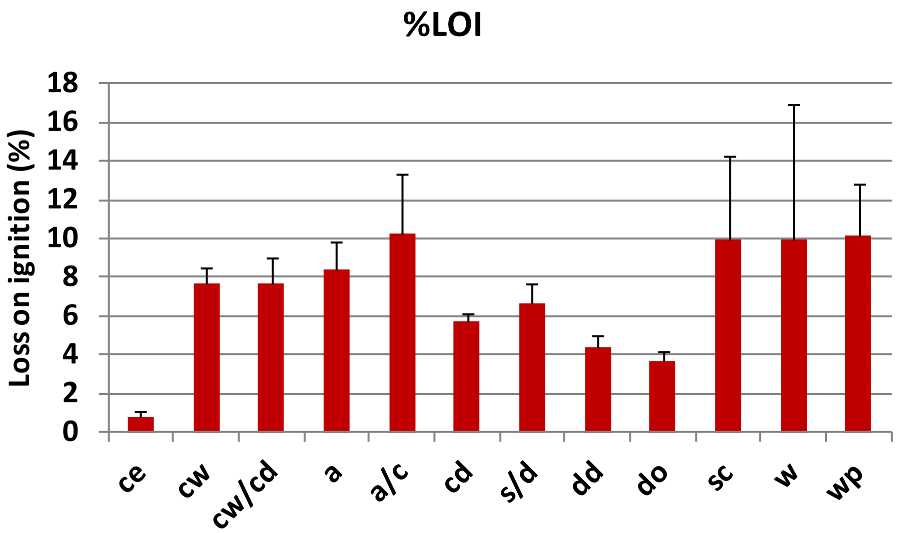

Figure 12. Soil organic matter content (as %LOI) in all soil cores, averaged by community type.
For codes see Table 7, additional codes: dd=dry dune habitats, do=dry non-dune habitats.

5 Discussion of vegetation survey results

5.1 *Application of the NVC to dune slack vegetation*

The National Vegetation Classification (NVC) is designed to classify vegetation into distinct categories. There are long-running theoretical debates about whether there is such a thing as a ‘plant community’ or whether consistent assemblages of plant species exist. That aside, vegetation classification serves a purpose. It allows us to make sense of complex assemblages of individual plant species, and place them in more tractable defined classes for the purposes of recording and inventory. The use of consistently defined vegetation units also facilitates mapping of vegetation types at fine scale.

However, some types of vegetation are better suited to classification than others. It could be argued that sand dune vegetation communities are not that well suited to classification. There are a number of reasons for this. Variation in dune vegetation is underpinned by a number of environmental gradients, which perhaps exhibit more variation and a greater ecological range than many other plant communities. Wetness gradients range from near-permanently flooded wet dune slacks to dry dune crests or sand sheets. Soil pH gradients range from high pH young shell sand to strongly acidic, older, silica sand-based soils. Fertility gradients range from very low to highly fertile, and organic matter gradients range from bare sand lacking almost any organic matter to deep organic-rich soils. Many of these gradients can operate independently of each other, leading to multiple combinations of ecological niche. Perhaps more importantly, the morphology of dune systems leads to fairly continuous variation along these gradients, without sharp ecotones which might otherwise lead to sharper boundaries between species assemblages. Additional factors such as salt spray and disturbance caused by blowing sand (Yura and Ogura, 2006), recreational access, or animals such as rabbits (Burggraaf-van Nierop and van der Meijden, 1984), and the wide range of land forms (dunes, slacks, hummocks), add to the habitat heterogeneity at a site-scale.

The NVC methodology (Rodwell, 2006) recommends surveying ‘typical’ stands of vegetation. In a dune landscape comprising mosaics of small and large-scale land forms exhibiting the gradients described above, distinct stands of vegetation are often the exception rather than the norm.

Lastly, the data used to derive the classification for the dune habitats was based on a relatively limited set of quadrats. The classification was finalised around the time of the Sand Dune Survey of Great Britain (SDGB) circa 1989, although the volume was not published until 2000 (Rodwell, 2000). Thus the classification did not take advantage of the considerable data collected under that survey across the whole of GB. As a result, the sand dune classification is widely regarded as not particularly representative of the UK dune resource, and the fit to many current vegetation communities is poor. A further complication is that some plant assemblages have changed, with some community types found in the past e.g. at Newborough Warren in the 1950s, no longer have current analogues (Rhind et al. 2013).

All of these factors mean that allocation of any particular stand of vegetation, or set of quadrats, to an NVC community carries an element of subjectivity, is better classed as intermediate or transitional between two different communities, or in some cases is just not possible.

5.2 *Caveats on the repeatability and interpretation of mapping*

Mapping is an art as much as a science. Hearn et al. (2011) tested experimentally the differences in mapping between trained professional and agency surveyors, who all surveyed the same landscape of heterogenous vegetation. There were differences in the size, shape and location of polygon boundaries between surveyors, and differences in allocation of polygons to NVC communities. Hearn et al. (2011) concluded that the variability inherent in mapping the same piece of land was as much as 30 % between surveyors. It is likely that re-surveying the same area after an extended time period, as in this study, is likely to involve additional error to due to visual change in the character of vegetation, even if underlying vegetation assemblages remain broadly similar.

On the basis of the Hearn et al. study, we are therefore reluctant to attribute too much significance to changes in mapped area below 30 % for any individual site. Changes in mapped area below 30 % are as likely to be due to differences in interpretation of polygon boundary or NVC allocation, as they are to reflect real change over time. However, interpretation of change across multiple sites, combined with analysis of change in repeat vegetation quadrats and their associated measured and proxy environmental variables adds considerably to the interpretive power of the analysis, and allows a broad picture of the change in dune wetlands in England to be derived.

5.3 *Mapping methodologies for detecting change*

There are two main approaches in mapping to detect change over time, but we discuss an additional option of using remote sensing. The first takes previously mapped polygons/vegetation units and assigns an NVC community to the vegetation in them. This will only show changes in allocation from one community type to another over time, but could capture more subtle shifts in the proportions of mosaics within a polygon, where these are mapped. A variant of this approach has been used by Tom Dargie (Dargie, 1992) to interpret change over time, where polygons are standardised between time periods, and the overall allocations to community categories are assessed over time. This approach is less sensitive to minor shifts in the vegetation, but is relatively easy to interpret. However, it is still subject to differences in surveyor interpretation as to allocation of vegetation to one community or another.

The second approach, which we have taken in this study, is to redefine vegetation unit boundaries in a new mapping exercise. This can potentially capture shifts in the size of vegetation units as species assemblages move up and down environmental gradients, in addition to changes in community type. However, due to often large differences in the shape and boundaries of mapped units, it is more difficult to analyse, and is sensitive to the additional subjectivity of surveyor interpretation as to where boundaries between communities occur, as well as allocation of mapped polygons to NVC types.

Analysis of net change in both cases would be easiest where all communities on a site are mapped. The selective mapping of individual components of a site make interpretation of change over time more difficult where individual polygons/vegetation units change into, or out of, the selection criteria. E.g. in this case where former wetlands become dry vegetation or new wetlands are created.

Remote sensing of vegetation from aerial photography combined with analysis of additional information such as LIDAR promises a more automated approach to vegetation monitoring over time. This approach has benefits but also a number of draw backs. The benefits include more rapid processing of data across large areas using automated routines developed with the aid of ground-truthing of satellite imagery. The classification to vegetation types is probably more objective than the use of surveyors on the ground, but still retains an element of subjectivity in developing the ‘rule base’ for assigning vegetation types and care needs to be taken that the rules are developed across the wide range of vegetation types and variants across the UK in order to be applicable to other sites. Disadvantages include the resolution of the mapping to vegetation type – it will be possible to assign communities to broad vegetation types (e.g. slack, dry grassland, dune heath) but is not likely to be able to reliably assign vegetation to NVC community, with the possible exception of vegetation types dominated by more distinctive species such as *Hippophae rhamnoides*. For example, *Salix repens* can be dominant in a wide variety of NVC communities in dunes and cannot reliably be used to distinguish between slacks and dry dune communities. Additional topographic information can be used to help define locations which are geomorphological slacks, but these may no longer support slack vegetation, as evidenced in findings from this survey on the Sefton Coast.

As the technology advances, it may be possible to achieve more, although it is worth noting that these ideas have been trialled since at least the early 1990s. At present, they are useful in identifying change between broad community types, but not to the level required to reliably interpret vegetation change in dune wetlands. Similar studies in the Netherlands have been used to interpret broad changes over time in dune vegetation, but show large variability when classifying vegetation at finer phytosociological detail. A project is currently ongoing to explore the potential of remote sensing-based mapping techniques for monitoring dune vegetation. Early results shown at a dune wetland conference suggest they have potential to help inform conceptual flow models for dune systems.

5.4 *Discussion on causes of change in vegetation over time*

The data suggest a consistent climate signal of drying across all sites. While the decline in precipitation score was significant across sites, there was no consistent decrease in the Ellenberg moisture score. However, the decline in Ellenberg moisture score was significant at two of the largest sites (Braunton Burrows and Birkdale Hills LNR), with another two sites Ainsdale NNR and Ainsdale LNR showing clear shifts in the ordination analysis towards drier conditions over time. In addition, the mapping analysis showed a net loss of dune slack habitat at all sites except Lindisfarne, with loss at three of the large sites (Braunton, Ainsdale NNR+LNR and Birkdale) ranging from 28 – 52 % of slack area in 1990, above the error threshold for interpreting mapping (Hearn et al., 2011). The losses appear greatest at sites in the southern and western part of England, rather than those considered more northerly (e.g. Sandscale, Lindisfarne), or easterly. Certainly, a long-term decline in precipitation has been identified at Braunton (Robins, 2007; Stratford et al. 2013). Further analysis is required to see if this reflects a change in the quantity of effective rainfall at these sites, and whether any climate shifts might be compounded by local circumstances such as the rapid development of scrub at Birkdale. The effect of vegetation on dune water tables is little studied. Evapotranspiration by pines may lower dune water tables by 0.7 m or more (Stratford et al., 2006), but other than large scale lysimeter work on drier dune vegetation in the Netherlands in the 1960s (Minderman and Leeflang, 1968), very little has been done on relative rates of evapotranspirative losses by different dune vegetation types typical for the UK. This topic is a focus for some of the work conducted under this study, but more needs to be done.

The increase in Ellenberg nutrient scores and decrease in Ellenberg light scores in the quadrat analysis both suggest nutrient loads are increasing and vegetation is becoming taller and less open with a loss of light-demanding species. This is consistent with what we would expect from elevated nitrogen deposition in dunes (Jones et al. 2004; Remke et al. 2009). Although annual nitrogen deposition loads have declined slightly since their peak around 1990 (ROTAP, 2012), around the time of the SDGB survey, current average annual deposition to the sites surveyed here is 13.1 kg N ha^{-1} yr^{-1}, within the critical load range for dune slacks of 10 – 20 kg N ha^{-1} yr^{-1} and towards the upper bound of the critical load range for dry dune vegetation of 8 – 15 kg N ha^{-1} yr^{-1} (Bobbink and Hettelingh 2011). Much of the deposition above the lower bound of the critical load range will accumulate in plants and soils (Plassmann et al. 2009; Rowe et al. 2013), with potential long-term consequences for vegetation change and soil development (Rowe et al. 2011, Jones et al. 2008).

Similar changes are also caused by scrub development (Hodgkin 1984), or natural successional development of vegetation and soils (Jones et al. 2010). However, the significant increase in nutrient scores at two sites with contrasting management history over the last few decades: Birkdale where management has been minimal, and Ainsdale where active site management has sought to remove pines, control scrub and introduce grazing, suggest a national trend, although this may be exacerbated by local site factors.

The lack of significant change in indicator scores at a number of the sites (Lindisfarne, Ross Links, Holme and Winterton), despite movement of these sites along the secondary ordination axis over time, suggests that the measured and proxy variables are failing to capture some drivers of change. Similarly, the large changes in species richness at many of the sites are currently unexplained. Further analysis, including collation of management history at these sites over the last few decades, may help explain the reason for some of these changes, and whether they are linked to locally applicable on- or off-site activities including site management, or larger scale factors such as nitrogen deposition.

There are errors involved in any repeat survey exercise. Part of the variability between time periods is due to the element of surveyor interpretation in mapping, variability inherent in mapping, and to the difficulty in accurately relocating quadrats over time. However, this error was minimised through the following procedures: A team of 6 individuals was involved in mapping and surveying repeat quadrats in this survey, they were trained by some of the original surveyors in the SDGB survey, and the original SDGB surveys were undertaken by different individuals at different sites. Therefore we feel this is unlikely to cause systematic bias.

5.5 *Relevance to eco-hydrological guidelines (hydrology and nutrients)*

5.5.1 Context to development of ecohydrological guidelines

Putting these findings in the context of the ongoing development and refinement of eco-hydrological guidelines for dune slacks, we first provide some context to the research needs in this area. The Wetland Framework (Wheeler *et al.*, 2009) doesn't cover coastal dune wetlands, and identifies in section 25.5 'Furthering the Framework' the following future objective – *'Expand and enhance the Framework by integrating information and mechanisms from other wetland habitats (wet grassland, wet woodland, wet heath and dune slacks)'*. This area of work was subsequently developed by Davy *et al*. (2010) and reported in the 'Ecohydrological guidelines for wet dune habitats Wet dunes - phase 2' report, which until recently represented the most complete UK based summary of this science area. Davy et al. (2010) identified the following knowledge gaps and information requirements in order to move this area forward:

'The problems in marrying ecological and hydrological information at higher resolution highlight the gaps in current knowledge. More precise eco-hydrological guidelines for the management of wet dune slacks will require substantial additional field investigation:

1. *Long-term monitoring of suitably replicated dipwells, placed strategically at a range of sites within unequivocally identified dune-slack community types.*

2. *Sites should be chosen to include the whole range of community types (including rare ones such as SD13), and to reflect different physiographic settings, substrate, climatic conditions and depositional environments.*
3. *Changes in the communities should be monitored, along with seasonal and long-term changes in water level and water chemistry.*
4. *Fluctuations in groundwater level in different communities could be best characterised in terms of the probability of exceeding set maxima for winter and summer periods, as well as understanding the magnitude of water table fluctuation and the persistence of wet and dry periods on habitat condition.*
5. *Such investigations ideally need to be part of larger scale hydrological investigations of whole dune systems to determine water flow and hydrochemical gradients through the slacks.*
6. *The results of these studies should be integrated to assess likely impacts of climate change, particularly resulting from sea-level rise and changing patterns of rainfall, on the eco-hydrology of wet dune systems.'*

5.5.2 **Hydrological guidelines**

Recent work has considerably improved the knowledge of hydrological guidelines for dune wetlands. A study by Curreli et al. (2013) has published the first set of robust ecohydrological guidelines for a range of NVC dune slack vegetation types, covering SD14, SD15, SD16 and SD17 communities. The work was based on extensive data collection on co-located vegetation and hydrology data, with dipwell and associated quadrat elevations established by DGPS to within 1 cm vertical accuracy. Water table summary metrics were based on hydrological regime over a four year period, longer than in any other primary study. Data were drawn from four west coast UK sites and the guidelines, which include water level and soil chemistry conditions are deemed most robust for SD14 (3 subcommunities), SD15 (1 subcommunity) and SD16, but less robust for SD17 and other subcommunities of SD 14, SD15, SD16, due to smaller sample sizes for these communities, SD13 was not sufficiently represented to develop indicative guidelines. Despite recent advances in this area, considerably more needs to be done, particularly for SD13 and SD17 communities, and drawing on a wider evidence base across the UK.

Results from this report show that understanding the hydrological regimes which govern plant communities in dune wetlands is critical to their management. Sanitwong na Ayutthaya and Clarke (2010) predict a drop in dune water tables at the Sefton coast of > 1m over the next 50 years. Based on this, Curreli et al. (2013) suggest that hydrological conditions will only be able to support dry dune grassland over this timescale, implying a complete loss of all dune slacks at Ainsdale. This is because only 40 cm difference in average summer minimum water table separates the driest and the wettest dune slack communities. Findings from this report of a 30% loss in dune wetland area since 1990 suggest there may already be evidence on the ground of significant drying out of this habitat, and is extremely worrying.

5.5.3 **Nutrient chemistry guidelines**

A further component of the ecohydrological guidelines relates to nutrient levels in groundwater. Currently nutrient levels in groundwater have been little studied, and are not included in critical load approaches to assessing nutrient loads to wetland systems, although the potential for input from these sources is acknowledged (Bobbink and Hettelingh, 2011). The potential sources of off-site nutrients have been investigated in two groundwater-dependent terrestrial ecosystems (GWDTEs) known to be impacted by groundwater nutrient contamination, a lowland fen on Anglesey and the Merthyr Mawr dune system in South Wales (SWS 2010). At Merthyr Mawr the likely fluxes of N into the site from a seasonal stream, its relative magnitude in comparison to atmospheric deposition inputs, and the complexity of the groundwater chemistry had previously been studied by Jones et al. (2005; 2006). However, for the majority of sites relatively little is known about groundwater N inputs and any consequences of that nutrient input. Davy et al. (2010) collated from published and grey literature and from unpublished studies some data on groundwater chemistry at suspected impacted and unimpacted dune sites. They suggested a reference condition of total inorganic nitrogen (TIN) concentrations < 0.2 mg N L^{-1}, with concentrations up to 0.4 mg N L^{-1} indicating potential contamination and concentrations > 1.0 mg N L^{-1} indicating probable contamination. These guidelines are considerably lower than guidelines of 3 mg NO_3-N L^{-1} propsed by the UKTAG Wetlands Task force (UKTAG 2012) which took a catchment based approach to assessing risk of impact from nutrient contamination to dune wetlands. The discrepancy may arise because many dune systems are hydrologically isolated from the surrounding land, therefore catchment inputs are unlikely to have an influence on dune wetlands in those situations. The tentative but more stringent nutrient guidelines for nitrogen suggested by Davy et al. (2010) have been confirmed by recent work on Aberffraw dunes in Anglesey, North Wales (Rhymes et al. 2014). That study showed a significant impact of groundwater nitrate on plant species composition and on soil chemistry at TIN concentrations below 0.2 mg N L^{-1}. The study took a gradient survey approach, investigating vegetation and soils at distances away from a known contamination source, intensively fertilised agricultural pastures which surround the site. Rhymes et al. (2014) showed that nitrate levels were elevated in groundwater beneath the site, that groundwater nitrate explained an additional 7% of variation in plant species composition after hydrological variation had been accounted for, favouring nitrophilous species, and that soil chemistry was also affected becoming more eutrophic. An earlier gradient study looking at signals of N deposition across a UK gradient showed a non-significant trend ($p = 0.055$) of increasing groundwater dissolved organic N (DON) and total N concentrations with increasing N deposition (Jones et al. 2002). While not significant in that study, the developing body of evidence increasingly suggests that both atmospheric deposition and groundwater-based sources of nutrients are having an impact on dune slack vegetation.

Results from this report also suggest a significant eutrophication signal in dune wetland vegetation, consistent with large-scale drivers such as N inputs from atmospheric deposition, but potentially compounded by local site-based contamination issues, and possible interactions between drying out of wetland soils and increased nutrient availability. This is a further research area which represents a major knowledge gap.

In the context of the findings of recent published work, the results reported in this vegetation survey and hydrological study start to address some of the issues raised by Davy et al. (2010), and focus on points 5 and 6 – integrating the field-based evidence and interpreting those findings in the context of climate change and nitrogen deposition. Specifically we have established the current extent and quality of the English dune slack resource, analysing how this has changed over the past 22 years. Where possible, we have developed a hydrological conceptualisation for each site. This information will guide the collection of further site data suitable for further developing and improving eco-hydrological thresholds for dune wetland communities.

6 Synthesis of results from hydrological work

The focus of the hydrological work in this study is the relationship between land cover and water availability.

First we investigate the relationship between water table and available moisture at the surface. This area is of interest because water table level is normally taken as the most relevant hydrological measure when looking for a relationship with surface vegetation. Under certain conditions, such as dry periods in which small rainfall events may be sufficient to irrigate the root zone of the vegetation but not penetrate to the water table, there may be justifiable reason to think that this relationship does not apply.

Secondly we investigate the water use of different types of dune land cover, and review both the current literature and techniques available for monitoring. Whilst extensive work has been conducted in the Netherlands, little has been done in the UK. Better information in this area would help with dune management planning decisions.

6.1 *Exploration of potential for root zone moisture regime to influence understanding of links between vegetation community and groundwater regime.*

Efforts to establish a link between vegetation species abundance and diversity on dunes date back to the 1950s (Ranwell 1959, Willis 1963). Water table elevation is relatively easy to measure and provides a direct observation method for quantifying the hydrological differences between parts of the dune system. Ranwell (1959) was the first to assign seasonal water table elevations to wet, transitional and dry dune slacks. This approach has been successfully applied to a range of wetland plant communities (Wheeler et al., 2004) and in its most advanced form, provides a monthly water table elevation prescription for some NVC communities.

The soil types in many of these studies, which would be categorised as a depth (>50cm) of clays/silts/organics, tend to either retain moisture and/or exert a capillary force that can maintain a supply of water to the root zone. In the dunes, where the soil profile might typically consist of 5 to 25 cm of organic/sandy soil underlain by sand, the capillary action is minimal and the vertical movement of water by this process is limited. It is therefore possible that the water table may no longer reflect the availability of water to the plant root zone. In these cases, a relationship between water table and vegetation may be misleading.

To investigate this further, field monitoring and sampling were undertaken in order to quantify:

- The difference in moisture holding capacity between the near-surface organic/sand soils and deeper sand layers.
- The moisture response to rainfall events through the soil column.

6.1.1 **Organic matter content**

Soil samples were collected from Braunton Burrows. The first set was collected from multiple depths in order to quantify the organic matter content of different layers. The second set consisted of replicate samples from two depths, the near surface organic layer and from the deeper sand layer, in order to quantify the moisture retention in each layer.

For measurement of organic matter content, the samples were first dried in the oven for 2 days at 60° C. The samples were weighed and then heated to 500 ° C for 4 hours in a muffle furnace. At this temperature all the organic portion of the sample is burned off. The samples were then weighed again, and the difference between the weights equates to the mass of organic matter in the sample.

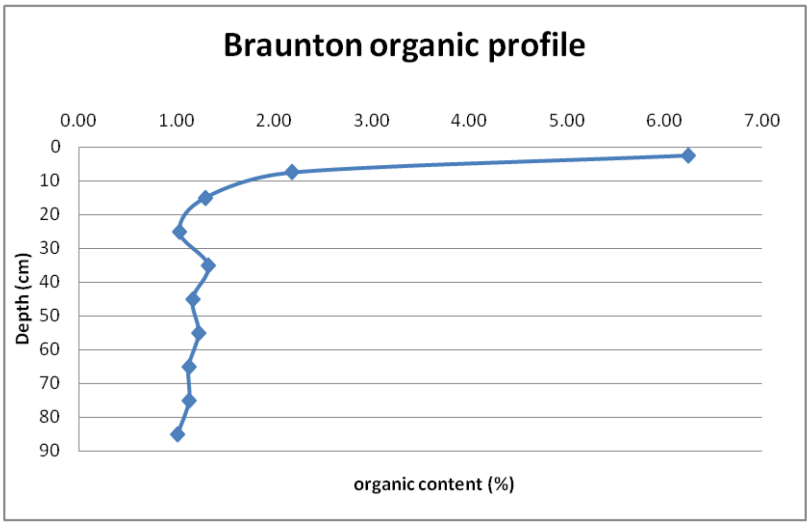

Figure 13. Variation in soil organic matter content with depth.

These results indicate that the organic layer is almost entirely contained within the top 10 cm of the soil profile, and roots penetrating beneath this are in sand (Figure 13).

6.1.2 **Soil moisture release**

In order to quantify the moisture holding capacity at different depths in the soil profile, replicate (3 of each) samples were collected from the top 0 to 10 cm (organic) layer and deeper 15 to 25 cm (sand) layer. Great care was taken collecting these samples in order to keep disturbance of the soil column to a minimum, however difficulties were encountered due the thick roots present (particularly in the top organic layer samples). The samples were transported back to the soil physics lab facilities at CEH Wallingford and were prepared for analysis on the ‘Sandbox’ equipment.

Table 28. Results of soil moisture release experiment.

		Braunton 1			Braunton 2			Braunton 1			Braunton 2			
		0 - 10			0 - 10			15 - 25			15 - 25			
	Sample number	A	B	C	A	B	C	A	B	C	A	B	C	
	Comments	Hole in base of sample	OK	OK	OK	Missing a big piece in the base of sample	OK	Small hole in the top	Top: not totally full; bottom: missing sample all around the ring border	Top not totally full	Sample disturbed during the first measurement	OK	OK	Date
pF: Saturated Cm Water colum: 0	Weight (g)	1362.5	1354.5	1469.2	1580	1469.6	1547.6	1729.3	1657.5	1720.4	1720.2	1780.1	1809.4	07/08/2012 17:10
pF: 0.4 Cm Water colum: 2.5	Weight (g)	1357.4	1367.7	1468.5	1573.8	1464.3	1547.6	1725.2	1650.9	1715.1	1721.6	1776.8	1807.8	09/08/2012 17:00
pF: 1 Cm Water colum: 10	Weight (g)	1310.9	1320.6	1449.3	1556.4	1439.1	1525.1	1713.2	1637.9	1704.9	1709.9	1768.7	1798.5	10/08/2012 17:00
		1298.9	1312.1	1444.6	1552.8	1434.7	1521.7	1710.9	1635.3	1703.6	1705.6	1767.1	1794.9	13/08/2012 10:00
pF: 1.5 Cm Water colum: 36.5	Weight (g)	1190.9	1217.3	1359.7	1502.5	1379.3	1453.9	1681.1	1587	1684.2	1700	1758.4	1789.3	15/08/2012 10:10
		1187.7	1214.7	1357.4	1499.7	1374.5	1451.3	1679.4	1584.5	1682.5	1697.5	1754.5	1786	16/08/2012 10:00
		1182.4	1209.4	1351.9	1494.7	1369.8	1446.4	1678.1	1582.7	1682.1	1695.5	1752.8	1784.8	20/08/2012 12:00
		1181.7	1208.7	1350.9	1493.8	1368.5	1445.4	1677.4	1582.1	1681.7	1693.9	1751.5	1784.1	21/08/2012 10:40
pF: 1.8 Cm Water colum: 63.1	Weight (g)	1087	1113.8	1222	1335.8	1226	1294.3	1508.8	1431	1517.7	1510.4	1555.1	1586.8	24/08/2012 17:00
		1076.3	1104.7	1208.5	1320.4	1211.9	1279.6	1504.8	1426.1	1512.6	1507.2	1552.7	1583.4	05/09/2012 16:38
		1075.7	1104	1207.8	1319.6	1210.9	1278.8	1504.3	1425.3	1512	1506.5	1551.9	1582.7	06/09/2012 15:21
pF: 2 Cm Water colum: 100	Weight (g)	1052.3	1086.9	1184.5	1287.2	1184.7	1253	1471.6	1388.1	1473.2	1478.6	1522.2	1549.5	18/09/2012 17:41
		1051	1085.6	1183	1285.5	1183	1251.2	1470.8	1387.6	1472.7	1477.4	1521.1	1548.8	21/09/2012 17:47
		1050.3	1085.3	1182.5	1284.8	1182.3	1249.8	1471.5	1388.1	1473.2	1476.9	1521.7	1549.1	24/09/2012 16:53
		1045.1	1081.7	1179.5	1281	1178.6	1246.3	1470.2	1386.9	1471.9	1476.6	1521.1	1548.6	03/10/2012 09:36
		1041.4	1074.3	1175.6	1275.2	1172.5	1239.7	1469.5	1386.7	1471.5	1475	1520.8	1547.6	23/10/2012 16:59

Once setup on the sandbox, the samples are saturated with water and then gradually exposed to increasing suction pressure, simulating a drop in water table. The weight of the samples is measured regularly and the resulting data set describes the change in weight of the sample (which is directly related to the change in moisture content) resulting from changes in water table elevation.

Our interest in this experiment was to see whether the top organic layers held onto moisture more effectively than the deeper sand layers. If this was found to be the case then it indicates that the surface layer is better able to retain water as the water table declines, increasing the amount of available water in the root zone. The raw results of the experiment are shown in Table 28.

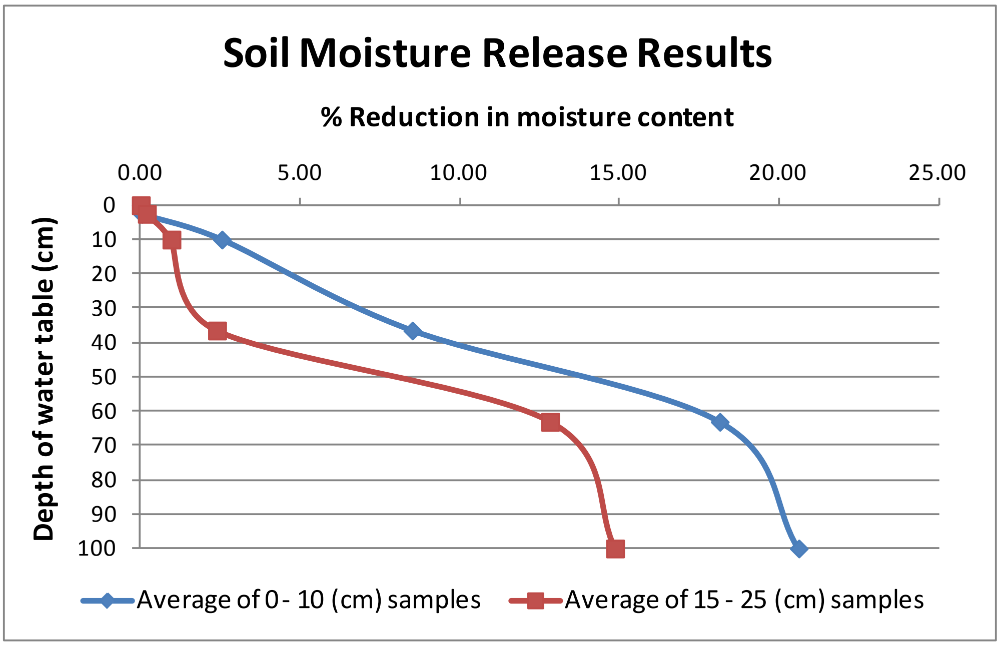

Figure 14. Results of soil moisture release tests.

The percentage change in water content was then calculated using the formula:

$$\%\ change\ in\ moisture\ content = \frac{mass\ of\ saturated\ sample - mass\ of\ sample\ in\ test}{mass\ of\ saturated\ sample} \times 100\%$$

The results from this are surprising (Figure 14) and suggest that for the samples tested, the surface organic layer is in fact less effective at retaining moisture than the deeper sand layer. With the water table at a depth of 1 m, the organic layer has lost ~ 20% of its saturated moisture content, whilst the sand layer has lost ~ 14%. This may indicate a greater proportion of fine material in the sand layer. These results merit further investigation and should be accompanied by detailed grain size analysis.

6.2 *Field experiment designed for a key site to quantify evapotranspiration rates from a range of dune vegetation in order to refine conceptual hydrological models for dune systems.*

Evapotranspiration is the total amount of water that is transferred from the land surface to the atmosphere. This includes evaporation from open water bodies, interception and reevaporation of moisture captured on the surface of vegetation and water transpired by the plant-root system. Evaporation can be time-consuming and costly to measure accurately. Methods to calculate evaporation rates based on meteorological drivers have been developed over the years and include Thornthwaite, Blaney-Criddle, Penman and Penman-Monteith (see Shaw (1994) for more details). All of these methods give an indication of the 'potential evaporation' (PE) rate that could occur, and assume that there is an adequate supply of water available to the plant. In the site reports that accompany this report, long term average MORECS rainfall and potential evaporation values are used to compare conditions between sites. Whilst rainfall varies considerably between sites, potential evaporation varies much less (Table 29).

Table 29. Summary MORECS data for each grid square containing a key site.

Square	Sand Dune Key Site	Average Annual Rainfall (mm)	Average Annual Evaporation (mm)	Average Annual Net rainfall (mm)
59	Lindisfarne	663	511	152
66	Ross Links	824	508	316
90	Sandscale	1153	573	580
96	Ainsdale	861	598	263
110	Saltfleetby	637	551	86
119	Holme	630	556	74
131	Winterton	622	530	92
165	Braunton	1037	585	453

In reality, various factors (including water availability) affect the rate at which the plant evaporates and it is more accurate to use 'actual evaporation' (AE) in the water balance calculation. However AE is more difficult to measure and the instruments required to do this are expensive to purchase and costly to operate. Techniques such as Bowen ratio (Peacock and Hess, 2004), Eddy Covariance (Acreman et al., 2003) and Scintillometry (McJannet, 2011) have been used very effectively to measure AE.

The most famous experiments to quantify water use by different types of dune land cover are the Castricum lysimeters in The Netherlands. Four 25m x 25m drainage lysimeters were maintained with different types of land cover; bare sand, dune shrub, oak trees, pine trees. The summary results of this experiment are shown in Table 30, (Stuyfzand, 1993). Each lysimeter receives the same annual gross precipitation, but four times as much water infiltrate to depth under bare sand compared to surface covered by pine trees. The role of evaporation and transpiration in this are important, but just as important is interception.

Table 30. Summary results from the Castricum lysimeter experiments, 1957 to 1981. (From Stuyfzand, 1993.)

Vegetation Type		Bare dune sand	Dune shrub (Hippophae)	Oaks (Quercus robur)	Pines (Pinus nigra)
P	Gross precipitation (mm/yr)	820	820	820	820
I	Interception (mm/yr)	0	162	230	360
S	Soil evaporation (mm/yr)	197	313	285	320
T	Transpiration (mm/yr)	0			
R	Excess precipitation (mm/yr)	623	345	305	140

Choosing a suitable method for measuring evapotranspiration in a wetland will depend on the characteristics of the wetland. For example, the size, topographic variation in the vegetated and non-vegetated surface, homogeneity of vegetation will guide the choice of technique. Dune fields have their own particular characteristics that limit the techniques that can be applied. Eddy covariance requires a fairly large open and flat area of homogeneous vegetation. Trees or large topographic variation can cause additional turbulence and complicate of the evaporation calculation. Eddy covariance was successfully applied to Wicken Fen (Kelvin, 2011) in a large open area of reeds, but is unlikely to perform well in a dune system.

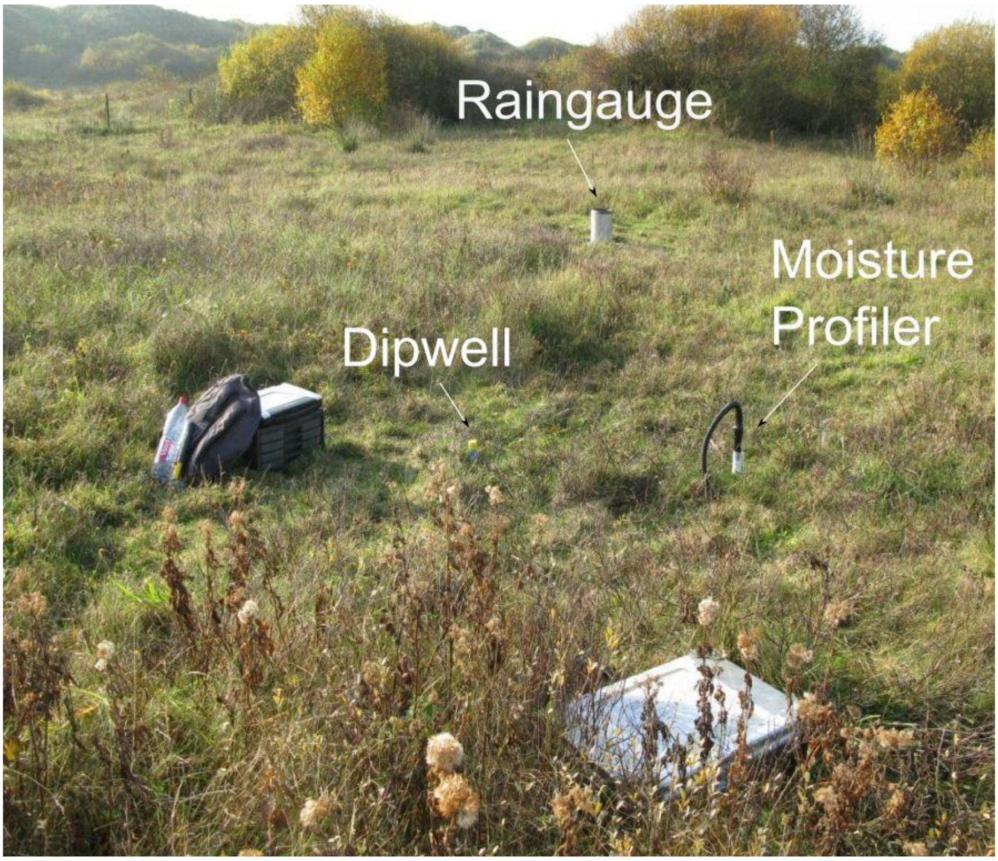

Figure 15. Soil moisture profiler, water level monitoring and rain gauge setup at Braunton Burrows.

Scintillometry, which involves an emitter and receiver placed either side of the study area (likely to be a distance of 500 m to 1 km) may deal with the topographic variation in the dunes more successfully, as current studies in urban landscapes suggest that the system can cope with housing of varying height. It will however only give a 'bulk' measurement for all of the vegetation in the sensor path, so where multiple land cover types exist it will be difficult to apportion the evaporative demand between them. This system also needs to be mounted between 5 and 10 m above the highest point in the path (this generally means building a tower for support, and this brings with it various security and safety issues) and requires a good power supply, which can be problematic at dune sites.

As a result of these issues CEH has investigated a different approach using a combination of field measurement, lab analysis and computer modelling. In the field, soil moisture is measured at several depths down through the soil profile (all measured below the ground surface: 10 cm, 20 cm, 30 cm, 40 cm, 60 cm and 100 cm) using a PR2 soil moisture profiler (Delta-T Instruments, UK). Also measured within a few metres of the moisture profile are water table elevation and rainfall (Figure 15).

The system was installed in August 2012 and happened to coincide with an unusually wet summer. This is significant because the ground surface remained consistently wetter than in 'normal' summer conditions. In addition, the cooler weather stunted plant growth and the usual rapid uptake of water in the root zone was reduced. Nevertheless, the initial data (Figure 16) show how the moisture profile and water table to respond to medium to large rainfall events, whilst smaller rainfall events not cause an increase in soil moisture in the top 10 cm, suggesting that in small rainfall events in dry conditions make very little contribution to groundwater levels.

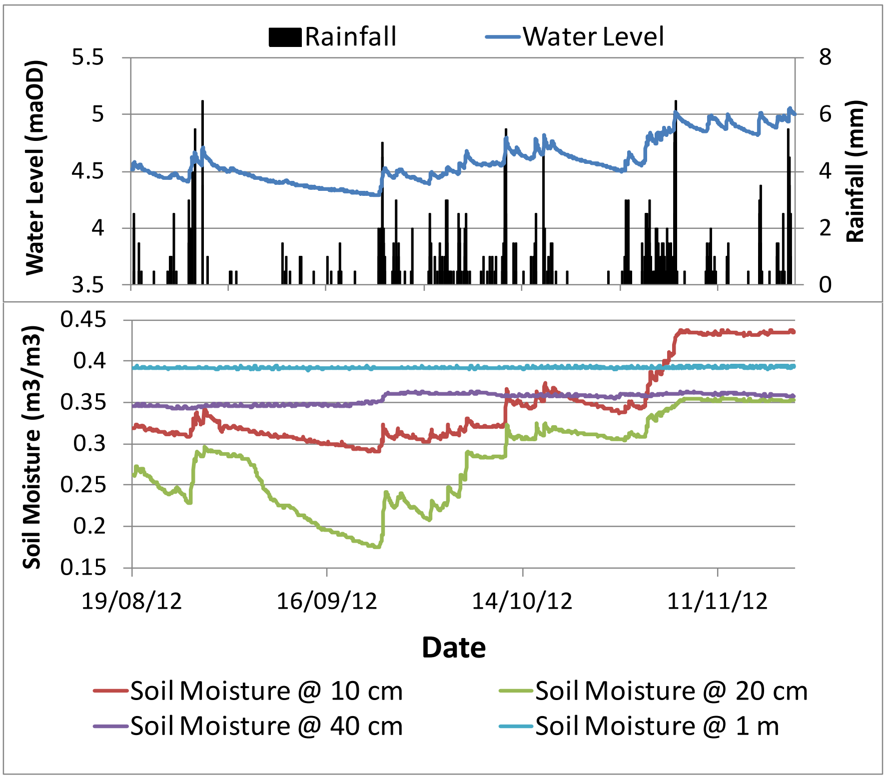

Figure 16. Rainfall, water level and soil moisture profile data.

Data collection is ongoing and it is hoped that the data collected during the summer of 2013 will facilitate the computer modelling, which will help us to understand the rainfall recharge of groundwater.

6.3 *Summary of hydrological investigations*

Interest in the sensitivity of dune slack vegetation communities to hydrological conditions has fuelled various research studies over the past 40 years. The key findings of these studies have highlighted, amongst other things, the importance of land cover in affecting groundwater recharge, the importance of understanding groundwater movement and factors that affect its flow across a dune site, the importance of long-term data sets in understanding variability and change in the hydrological system, and the ecologically important aspects of the hydrological regime (such as timing and duration of inundation). The work carried out in this study has conceptualised the groundwater flow system of seven English dune wetland systems – in some cases this was informed by existing water level data whilst in others it was inferred from the hydrogeological setting and topographic data. An important next step is to look across sites in order to develop a groundwater flow typology based upon available information. This will help to inform future dune management and hydrological investigations, identifying the optimum locations for observation.

This study has also focused in the role of vegetation in affecting the hydrological regime, largely through changes to rainfall interception and transpiration of groundwater. As demonstrated by the Castricum lysimeter experiments (Table 30), changing land cover has a dramatic impact on the amount of water beneath the ground. The magnitude of this exceeds many predictions of declining rainfall due to climate change. Management of vegetation in order to influence a hydrological regime that would support dune wetland species should be investigated further through field trials and accompanying scientific measurement. If carried out rigorously, this would provide much needed justification and guidance for future site management activities. For further discussion of linked vegetation and hydrology responses, see discussion in sections 5.4 and 5.5.

7 Recommendations for further work

- Further work is recommended to install dipwells, and co-located permanent vegetation quadrats at a number of new sites, and to extend existing vegetation and hydrological monitoring points at other sites (e.g. Birkdale, Lindisfarne) to capture a wider range of dune wetland types, and to cover the spatial context required to interpret the impact of local drivers of hydrological and vegetation change such as the prograding green beach at Birkdale, or extensive site management programmes. Vegetation quadrats should be accurately surveyed and marked to allow repeat survey at appropriate intervals.

- Further work is recommended to collate data on historical site management (e.g. grazing history including stocking densities, winter stock feeding, scrub clearance, water abstraction, alterations or additions to surface drainage or ditches etc.) at each of these sites, and to jointly analyse hydrological, management and vegetation data sets in order to understand the drivers of change in dune wetland vegetation across England.

- Active site management should work to create areas of early successional slack and wetland habitat. It should also consider reinstatement of natural dune dynamics to facilitate natural creation of secondary dune slacks.

- Site management activities should be suitable recorded and monitored so that experience can be gained and lessons can be learnt from application of practices across sites. Ongoing resources should support collation of such information.

- Permanent vegetation quadrats should be established, co-located with complimentary hydrological measurements, using accurate surveying/marking techniques such that re-survey of quadrats can be undertaken.

- Carefully designed experiments should be carried out to investigate the impact of changing land management (e.g. grazing, large-scale scrub clearance) or habitat restoration on hydrology, hydrochemistry, biogeochemistry and ecology. Such experiments should be designed in collaboration with researchers to make best use of the results, and should involve replication and sufficient measurement and monitoring over realistic time scales to allow definitive conclusions to be drawn from any changes which might occur.

- Primary research should also be carried out in a number of areas which include:
    - Characterisation of the hydrological and nutrient guidelines for currently understudied dune wetland communities, including the transitions from dune slacks to other wetland types focusing in particular on transitions to wetter permanently inundated communities and transitions to more eutrophic communities.
    - Establishing groundwater nutrient concentration thresholds and critical loads of nutrients from groundwater.
    - Studying how eutrophication and changing hydrological regimes interact to affect nutrient availability in soils and the consequences for plant species composition.

8 List of site reports

Jones, L., Stratford, C., Robins, N., Mountford, O., Amy, S., Peyton, J., Hulmes, L. & Hulmes S. (2013). **Braunton Burrows**. Site report for “Survey and analysis of vegetation and hydrological change in English dune slack habitats” project. Report to Natural England, May 2013.

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Appendix 1. Sand dune wetlands in England and their extent.

This table includes all wetlands recorded on English dunes as part of the Sand Dune survey of Great Britain (Radley, 1994). In NVC terms, therefore, not only are all the dune slack communities included (SD13-SD17) but also a range of swamp communities (predominantly S4, S6, S1O, S12, S21, S25 and S26), mire communities (M15, M16 and M23), and the inundation grassland community MG11. It demonstrates that 83% of the habitat is concentrated on just 7 sites. Those in bold were surveyed in this study, in consultation with Natural England project officers.

County	**Site name**	**Extent in 1990 (ha. approx)**
Northumberland	North Northumberland coast	4
	Alnmouth	<1
	Druridge Bay	1
	Amble/Haxley	<1
	Lyne Sands/Newbiggin	5
	Lindisfarne	**47**
	Bamburgh	1
	Ross Links	**38**
	Beadnall/Newton	1
	Embleton	2
Cleveland/Durham	Hart Dunes	<1
	Seaton/North Gare	<1
	South Gare/Coatham	2
Humber	Holderness	1
	Cleethorpes	5
Lincolnshire	North Lincolnshire Coast	3
	Saltfleetby Theddlethorpe Dunes	7
	Gibraltar Point/Skegness	2
Norfolk	**Hunstanton/Holme**	**9**
	Thornham/Brancaster	<1
	Holkham	2
	Winterton/Horsey	**43**
Kent	Sandwich Bay*[1]	10
Devon	Dawlish Warren	2
	Braunton Burrows	**128**
Cornwall	Rock Dunes	<1
	Penhale Dunes	14
	Gwithian/Mexico Towans	<1
Somerset	Berrow Dunes	17
Merseyside	**Sefton Coast**	**181**
Lancashire	Fylde Coast	6
Cumbria	Silloth/Maryport	1
	Seascale/Drigg*[2]	35
	Eskmeals	6
	Haverigg	9
	Sandscale*[2]	**42**
	North Walney	11
	South Walney	1

*[1] Sandwich Bay was considered for inclusion via a PhD currently underway on this site, but in practice this was not feasible.
*[2] There was a choice of two sites (Seascale/Drigg or Sandscale) as the Cumbrian 'key site'. Sandscale had the better slack resource, together with historic dipwell data, and was therefore surveyed in this study.

Reasoning for site selection

Selection of final list of sites for vegetation survey was conducted through detailed discussion with Natural England at a meeting in Peterborough on 12th January 2012. The criteria considered for site selection were:

- Sites with extensive dune wetland resource
- Sites with existing hydrological data or understanding
- Even geographical spread around the country
- A mix of calcareous and acidic dune types
- Resources available for field survey work (given that it was not possible to exactly estimate the nature of the task)

The final wish-list of sites to survey included the following:

Devon & Cornwall
Braunton Burrows
(Dawlish Warren – if time permitted)
(Penhale Dunes – if time permitted)

Merseyside
Ainsdale NNR
Ainsdale LNR
Birkdale Hills LNR
(Formby – if time permitted)
(Other satellite sites – if time permitted)

Cumbria
Sandscale Haws
(Seascale/Drigg – considered, but dropped in favour of Sandscale)

Northumberland
Lindisfarne
Ross Links

Lincolnshire
Saltfleetby/Theddlethorpe dunes – small area surveyed, but subsequently not deemed worth analysing

Norfolk
Hunstanton/Holme
Winterton/Horsey

Kent
(Sandwich Bay – if time permitted)

Appendix 2. Collated information from initial site reports provided by Natural England.

N.B. Subsequently it was decided to add Ross Links and Holme Dunes to the list of surveyed sites, so these site reports are not included in the initial batch of reports received. It was also decided not to analyse the minimal survey data from Saltfleetby, so this site does not feature in the reporting within the main report, and does not have an individual site report.

Braunton Burrows
1990 [ca 50 pp] as an unbound copy of the 1992 report loose in the box: preamble about survey programme and agencies; methods; site description; standard site recording form; constancy table summarising quadrats (490 quadrats apparently recorded of which 113 were in slacks –types SD14, SD15 and SD16); NVC types recorded; 21 pages of target notes explaining context of individual quadrats etc; species list for whole site; lengthy bibliography

Lindisfarne
In 1989 [ca 50+ pp]: methods (supported by a fuller description in Annex 1); general description; vegetation description; site assessment; comments & suggestions; Annex 2 (site recording form); Annex 3 (vegetation types); 17 pages of target notes; Annex 6 containing quadrat data (55 quadrats of which at least 17 were in slacks – types SD15 & SD16) in constancy tables; and detailed vegetation map for site.

Saltfleetby
In 1989 [≥ 100 pp] conducted on behalf of National Rivers Authority (Anglian) and covering Saltfleetby-Theddlethorpe Dunes NNR: General description; vegetation description; 7 vegetation maps; vegetation types; ca 40 pages of target notes; and an appendix containing the quadrat data (ca 230 quadrats of which 60 were in slacks – types M22, S6 and S26) in constancy tables and location maps.

In 1990 [20 pp] for Saltfleet Dunes: Methods; general site description; standard site recording form; vegetation types present; constancy table summarising quadrats (15 quadrats recorded – only one in a slack – SD17); 6 pages of target notes explaining context of individual quadrats; detailed vegetation map for site.

Sandscale
In 1987 [20 pp] Site Report #2: Methods; vegetation types (NVC and non-NVC); discussion (by habitat); 3 pages of target notes explaining context of individual quadrats; constancy table summarising quadrats (21 quadrats recorded – only 6 in slacks – types SD15, SD16, M23 and M28); detailed vegetation map for site.

Sefton Coast
As well bound editions of the final reports, there is a folder containing the original MS and figures for all the reports listed below. This should make Xeroxing (if necessary) much easier. With (but not in) the folder there are also loose copies of all the detailed vegetation maps for the nine Divisions of the Sefton Coast.

In 1988/89 [28 pp] 2 copies: Methods; general description (including maps of location, Divisions (see following reports), drift geology and erosion/accretion; vegetation description (NVC types and others); site assessment; protection and management; rarity; diversity; review of existing surveys; bibliography. Note that a revised NVC community listing for the whole coast was tucked (loose) into this introductory report based upon the understanding of NVC types in 1989.

1988 [17 pp] covering Division 1 (Seaforth to Hightown): Methods; general vegetation description (including standard site record, map of main features – site plan); vegetation communities (NVC types); constancy table summarising quadrats (24 quadrats recorded – SD15 only – 1 quadrat); 9 pages of target notes explaining context of individual quadrats; detailed vegetation map for division.

1988/89 [10 pp] covering Division 2 (Altcar Firing ranges): as Division 1 but only 13 quadrats (of which 3 are in slacks – SD15 and SD16) and 3 pages of target notes.

1988/89 [16 pp] covering Division 3 (Cabin Hill NNR, Ravenmeols LNR, Lifeboat Road, St Joseph's Hospital and associated land): as Division 1 but 33 quadrats (of which 4 are in slacks – SD15 and SD16) and 9 pages of target notes.

1988/89 [14 pp] covering Division 4 (National Trust and associated fields): as Division 1 but 25 quadrats (of which only 1 is in a slack – SD15) and 8 pages of target notes.

1988/89 [14 pp] covering Division 5 (Formby Golf Club to Woodvale Airfield): as Division 1 but only 14 quadrats (none in slacks, though SD15 present) and 6 pages of target notes.

1988/89 [ca 200 pp] covering Division 6 (Ainsdale Sand Dunes NNR): as Division 1 but 91 quadrats (of which 15 are in slacks – SD15 and SD16), 6 pages of target notes and copies of all 91 quadrat sheets.

1988/89 [13 pp] covering Division 7 (Ainsdale LNR and outlying dunes): as Division 1 but only 6 quadrats (of which 4 are in slacks – SD15 and SD16) and 4 pages of target notes.

1988/89 [29 pp] covering Division 8 (Birkdale Hills LNR and 3 gold clubs; Royal Birkdale Golf, Hillside Golf Club and Southport & Ainsdale): as Division 1 but 54 quadrats (of which 15 are in slacks – SD15 and SD16) and 19 pages of target notes.

1988 [10 pp] covering Division 9 (Southport Dunes & Northern outliers): as Division 1 but without quadrat summary (SD15 & SD16 said to be present) and 6 pages of target notes.

Winterton

In 1989 [43 pp]: Methods (plus detailed annexes); general site description; vegetation description (NVC types); rare species; assessment; standard site recording form; annex of vegetation types; constancy table summarising quadrats (34 quadrats recorded – no SD slacks but 5 mire quadrats – M16e, M23a/b); 17 pages of target notes explaining context of individual quadrats; overall species list for site; detailed vegetation map (2 sheets) for site.

Folder of loose material dated from 1982-1989, and evidently including the raw data-sheets for the 34 quadrats from the final report. Also quite a lot of correspondence, field notebooks and background information on the site.

Appendix 3. Field KEY to the majority of NVC communities found in dune wetlands.

(Adapted from Rodwell 1991-2000)

1 Generally species-poor and often open vegetation of more mobile sand on fore-dunes and dunes with one or more of *Elytrigia juncea* ssp. *boreoatlantica* (*Elymus farctus*), *Leymus arenarius* and *Carex arenaria* constant and dominant .... **Fore-dune and Mobile Dune communities**

1 Generally closed vegetation of less mobile and fixed sand on dunes and sand plains with *Ammophila* sometimes frequent but typically moribund, *Festuca rubra* common and at least some of *Galium verum, Plantago lanceolata, Trifolium repens, Lotus corniculatus, Poa pratensis, Festuca ovina* and *Agrostis capillaris* frequent...**29** (**Fixed Dune communities)**

1 Dune grasslands without *Ammophila* but with *Arrhenatherum elatius, Elytrigia* species or *Festuca rubra* dominant... **30 (MG)**

1 Scrub with an open or closed canopy of *Hippophaë rhamnoides* ....**Dune scrub communities**

1 Open or closed grassy or bushy vegetation in dune slacks, often with *Salix repens*, and at least some of *Hydrocotyle vulgaris, Agrostis stolonifera, Mentha aquatica, Potentilla anserina, Epipactis palustris, Carex flacca, C. oederi* (*C. serotina*), *C. nigra, C. panicea, Juncus articulatus, Campylium stellatum, Bryum pseudotriquetrum* and *Aneura pinguis* ....**2 (True dune-slacks)**

1 Open or closed herbaceous vegetation of depressions within dune systems, with at least some of *Schoenus nigricans, Juncus acutiflorus, J. effusus, Filipendula ulmaria* and *Iris pseudacorus* prominent and with *Salix repens* rare or absent ....**19** (**Mires occasionally found in dune systems**)

1 Mainly closed herbaceous vegetation of depressions within dune systems, often species poor and dominated by one of *Phragmites australis, Bolboschoenus maritimus, Schoenoplectus tabernaemontani, Equisetum fluviatile* or *Eleocharis palustris* ....**23** (**Swamps occasionally found in dune systems**)

1 Open or closed vegetation with prominent halophytic or coastal species, and often with some wet mud exposed; *Puccinellia, Juncus maritimus* or *J. gerardii* prominent.................. **28 (Salt-marsh communities)**

TRUE DUNE SLACKS

2 *Salix repens* cover very short and often patchy or sparse with constant *Sagina nodosa, Juncus articulatus, Leontodon hispidus, Bryum pseudotriquetrum* and *Aneura pinguis*...**3** (**SD13**)

2 *Salix repens* can be frequent and often abundant but, if so, then not with the other listed associates...**4**

3 *Poa annua, Hydrocotyle vulgaris, Blackstonia perfoliata* and *Moerckia hibernica* frequent, *Campylium stellatum* and *Petalophyllum ralfsii* occasional ....

⇒ **SD13a** *Sagina nodosa-Bryum pseudotriquetrum* dune-slack (*Poa annua-Moerckia hibernica* sub-community)

3 *Agrostis stolonifera, Holcus lanatus, Poa pratensis, Festuca rubra, Lotus corniculatus* and *Anthyllis vulneraria* constant...

⇒ **SD13b** *Sagina nodosa-Bryum pseudotriquetrum* dune-slack (*Holcus lanatus-Festuca rubra* sub-community)

4 *Salix repens* constantly associated with *Campylium stellatum, Equisetum variegatum, Carex flacca* and usually *Juncus articulatus* and *Epipactis palustris* **5** (**SD14**)

4 *Salix repens* frequent but not with above associates constant.......................................**8**

5 *Lotus corniculatus, Poa pratensis, Holcus lanatus* and *Prunella vulgaris* all very frequent with *Carex arenaria* less common **6**

5 *Carex arenaria* constant with above listed associates more occasional **7**

6 *Leontodon hispidus, Pellia endiviifolia, Aneura pinguis* and *Bryum pseudotriquetrum* constant ....
⇒ **SD14c** *Salix repens-Campylium stellatum* dune-slack (*Bryum pseudotriquetrum-Aneura pinguis* sub-community)

6 *Festuca rubra, Pulicaria dysenterica, Trifolium pratense* and *T. repens* all very frequent with above associates not consistently common ....
⇒ **SD14d** *Salix repens-Campylium stellatum* dune-slack (*Festuca rubra* sub-community)

7 *Carex serotina* and *Drepanocladus sendteri* frequent, *Epipactis palustris* occasional ....
⇒ **SD14a** *Salix repens-Campylium stellatum* dune-slack (*Carex serotina-Drepanocladus sendteri* sub-community)

7 *Epipactis palustris* constant with *Scorzoneroides autumnalis, Ranunculus flammula, Rubus caesius* and *Galium palustre* frequent ....
⇒ **SD14b** *Salix repens-Campylium stellatum* dune-slack (*Rubus caesius-Galium palustre* sub-community)

8 *Salix repens* only occasional but *Potentilla anserina, Carex nigra* and *Agrostis stolonifera* constant associates. **9** (**SD17**)

8 *Potentilla anserina* and *Carex nigra* can occur but *Salix repens* is a constant and often abundant plant **12**

9 *Festuca rubra* and *Ranunculus repens* very frequent, *Bellis perennis* occasional **10**

9 Above species not consistently present **11**

10 *Trifolium repens, Carex flacca, Poa pratensis* and *Prunella vulgaris* all frequent...
⇒ **SD17b** *Potentilla anserina-Carex nigra* dune-slack (*Carex flacca* sub-community)

10 Above species not consistently present ....
⇒ **SD17a** *Potentilla anserina-Carex nigra* dune-slack (*Festuca rubra-Ranunculus repens* sub-community)

11 *Hydrocotyle vulgaris, Ranunculus flammula, Eleocharis palustris* and *Galium palustre* frequent ....
⇒ **SD17d** *Potentilla anserina-Carex nigra* dune-slack (*Hydrocotyle vulgaris-Ranunculus flammula* sub-community)

11 *Caltha palustris, Cynosurus cristatus, Rhinanthus minor* and *Silene flos-cuculi* frequent ....
⇒ **SD17c** *Potentilla anserina-Carex nigra* dune-slack (*Caltha palustris* sub-community)

12 *Salix repens* constantly associated with *Hydrocotyle vulgaris, Mentha aquatica* and *Calliergonella cuspidata, Lotus corniculatus* scarce **13** (**SD15**)

12 *Salix repens* constantly associated with *Lotus corniculatus, Carex flacca, Holcus lanatus* and *Festuca rubra* in drier vegetation **16** (**SD16**)

13 *Agrostis stolonifera, Equisetum variegatum* and *Carex arenaria* frequent **14**

13 Above species occasional at most **15**

14 *Rubus caesius, Galium palustre* and *Carex nigra* frequent..
⇒ **SD15b** *Salix repens-Calliergonella cuspidata* dune-slack (*Equisetum variegatum* sub-community)

14 *Carex flacca, Epipactis palustris* and *Pulicaria dysenterica* frequent ....
⇒ **SD15c** *Salix repens-Calliergonella cuspidata* dune-slack (*Carex flacca-Pulicaria dysenterica* sub-community)

15 *Rubus caesius, Galium palustre* and *Carex nigra* frequent..
⇒ **SD15a** *Salix repens-Calliergonella cuspidata* dune-slack (*Carex nigra* sub-community)

15 *Holcus lanatus, Angelica sylvestris, Phragmites australis, Molinia caerulea* and *Succisa pratensis* frequent
⇒ **SD15d** *Salix repens-Calliergonella cuspidata* dune-slack (*Holcus lanatus-Angelica sylvestris* sub-community)

16 *Leontodon hispidus, Equisetum variegatum, Pyrola rotundifolia* and *Trifolium pratense* frequent..............
⇒ **SD16c** *Salix repens-Holcus lanatus* dune-slack (*Prunella vulgaris-Equisetum variegatum* sub-community)

16 Above species not consistently present..**17**

17 *Ononis repens, Carex arenaria, Hypochaeris radicata* and *Salix caprea* frequent.......................................
⇒ **SD16a** *Salix repens-Holcus lanatus* dune-slack (*Ononis repens* sub-community)

17 Above species not consistently present..**18**

18 *Agrostis stolonifera, Hydrocotyle vulgaris, Juncus articulatus* and *Leontodon saxatilis* frequent.................
⇒ **SD16d** *Salix repens-Holcus lanatus* dune-slack (*Agrostis stolonifera* sub-community)

18 *Rubus caesius* frequent but above species not consistently present ....
⇒ **SD16b** *Salix repens-Holcus lanatus* dune-slack (*Rubus caesius* sub-community)

MIRES

19 *Schoenus nigricans* a constant and abundant feature of the vegetation, often with *Anagallis tenella, Campylium stellatum* and *Aneura pinguis*..
⇒ **M13** *Schoenus nigricans–Juncus subnodulosus* mire

19 *Schoenus* at most locally prominent in a taller vegetation with abundant rushes (*Juncus*) and tall-herbs such *Filipendula ulmaria* and *Iris pseudacorus*....................... **20**

20 Big rushes always a prominent feature of the vegetation, with Juncus effusus and Juncus acutiflorus (or occasionally J. articulatus) constant and dominant; *Molinia* and *Filipendula ulmaria* can be frequent but are subordinate in cover..................................
⇒ **M23** *Juncus effusus/acutiflorus–Galium palustre* rush pasture

20 Big rushes can be frequent but are typically not dominant and often at most locally abundant.. **21**

21 *Molinia* always a prominent feature of the vegetation and generally strongly dominant; *Filipendula* can be frequent but is typically subordinate in cover*Molinia* vegetation (**M24-M26**)

21 *Molinia* can be frequent but is typically not dominant and often at most locally abundant, but with *Filipendula ulmaria* constant and usually abundant **22**

22 *Iris pseudacorus* and *Oenanthe crocata* constant, the former sometimes exceeding *Filipendula* in cover, with *Lycopus europaeus, Stellaria alsine, Rumex crispus* and *Scutellaria galericulata* common ....
⇒ **M28** *Iris pseudacorus-Filipendula ulmaria* mire

22 *Iris* and *Oenanthe* occasional at most and usually not abundant or with the above associates...
⇒ **M27** *Filipendula ulmaria-Angelica sylvestris* mire

SWAMPS

23 *Phragmites australis* dominant with or without an understorey of low-growing associates.. **24** (**S4**)

23 *Phragmites australis* absent of only scattered with *Bolboschoenus maritimus, Schoenoplectus tabernaemontani, Equisetum fluviatile* or *Eleocharis palustris* dominant instead (usually with low-growing associates).. **25**

24 *Phragmites australis* overwhelmingly dominant with sparse understorey of low-growing associates; *Atriplex* species and *Puccinellia* species absent ....
⇒ **S4a** *Phragmites australis* swamp [*Phragmites australis* sub-community]

24 *Phragmites australis* dominant but often open over understorey of scattered *Atriplex prostrata* often with *Agrostis stolonifera* or *Puccinellia maritima* ....
⇒ **S4d** *Phragmites australis* swamp [*Atriplex prostrata* sub-community]

24 *Phragmites australis* dominant over understorey of *Galium palustre or Menyanthes trifoliata* and where *Atriplex* species and halophytes (*e.g. Puccinellia maritima*) are absent ....
⇒ **S4** *Phragmites australis* swamp [Other sub-communities – generally NOT found in dune wetlands]

25 Swamp dominated by club-rushes *Bolboschoenus* and/or *Schoenoplectus* **26**

25 Swamp dominated by spike-rushes or horsetails (*Eleocharis* and/or *Equisetum*)........ **27**

26 *Bolboschoenus maritimus* dominant with a species-poor understorey where *Schoenoplectus tabernaemontani* is rare and never abundant.......................................

⇒ **S21** *Scirpus (Bolboschoenus) maritimus* swamp [4 sub-communities]

26 *Schoenoplectus tabernaemontani* dominant with *Bolboschoenus maritimus* occasional but not exceeding 25% cover⇒ **S20** *Schoenoplectus tabernaemontani* swamp [2 sub-communities]

27 Swamp dominated by *Eleocharis palustris* and with *Equisetum fluviatile* (if present) subordinate ....
⇒ **S19** *Eleocharis palustris* swamp [3 sub-communities]

27 Swamp dominated by *Equisetum fluviatile* and with *Eleocharis palustris* rare or absent .
⇒ **S10** *Equisetum fluviatile* swamp [2 sub-communities]

Salt-Marshes

28 Vegetation dominated by tall dense clumps of *Juncus maritimus* with understorey of *Agrostis stolonifera, Festuca rubra, Glaux maritima* and *Juncus gerardii* ....
⇒ **SM18** *Juncus maritimus* salt-marsh community [3 sub-communities]

28 Grassland dominated by *Agrostis stolonifera* and *Festuca rubra* with *Juncus gerardii* usually abundant (even co-dominant) growing with *Glaux maritima, Armeria maritima, Plantago maritima* and *Triglochin maritima* – *Juncus maritimus* absent ....
⇒ **SM16** *Festuca rubra* salt-marsh community [6 sub-communities]

28 Grassland dominated by *Puccinellia maritima* but where *Festuca rubra, Agrostis stolonifera* and *Juncus gerardii* may be sub- or co-dominant and *Armeria maritima, Plantago maritima* and *Triglochin maritima* can again be frequent – *Juncus maritimus* absent..
⇒ **SM13** *Festuca rubra* salt-marsh community [6 sub-communities]

Fixed Dunes

29 *Ammophila arenaria* generally dominant and vigorous with *Festuca rubra* constant though usually subordinate in cover; *Poa pratensis* and *Hypochaeris radicata* frequent but *Lotus corniculatus, Trifolium repens* and *Galium verum* not common throughout......
⇒ **SD7** *Ammophila arenaria-Festuca rubra* semi-fixed dune community [4 sub-communities]

29 *Ammophila arenaria* constant and vigorous but accompanied by and often co-dominant with *Arrhenatherum elatius* as well as frequent *Festuca rubra* and *Poa pratensis* ....
⇒ **SD9** *Ammophila arenaria-Arrhenatherum elatius* dune grassland [2 sub-communities]

29 *Ammophila arenaria* very frequent but usually moribund and exceeded in cover by *Festuca rubra*; *Poa pratensis* also constant and generally accompanied by *Lotus corniculatus, Trifolium repens* and *Galium verum*..
⇒ **SD8** *Festuca rubra-Galium verum* fixed dune grassland [5 sub-communities]

MESOTROPHIC GRASSLANDS

30 Coarse and usually dry grassland dominated by *Arrhenatherum elatius* often associated with *Elytrigia repens, Festuca rubra* and *Dactylis glomerata* [halophytes and obligate dune species absent]..
MG1 *Arrhenatherum elatius* grassland [5 sub-communities]

30 Grassland shorter, often a turf, dominated by *Agrostis stolonifera* and *Festuca rubra* with *Arrhenatherum* rare or absent and with *Potentilla anserina* characteristically prominent..
⇒ **MG11** *Festuca rubra-Agrostis stolonifera-Potentilla anserina* grassland [3 sub-communities]

Appendix 4. Resources and equipment provided to field surveyors.

Hardware	Getac portable tablet PC Garmin GPS Digital camera
Software	ArcPad 10.0 Microsoft Office 2007 TABLEFIT 1.0
Digital information	NVC floristic tables (interactive Excel spreadsheet) Abbreviated NVC key & dune-slack vascular plant crib NVC slack community descriptions Site reports from 1990 survey
Geo-referenced digital information	Aerial photographs 1990 NVC survey maps Locations of other quadrats recorded by CEH previously Locations of dip wells recorded by CEH or NE previously Any information from other surveys
Hard copies of paperwork	1990 NVC survey maps; wetland/slack habitats highlighted Abbreviated NVC key & dune-slack vascular plant crib NVC dune-slack community descriptions
Field equipment	Fold-out rulers and plastic markers for delineating quadrats Solid plastic tubes and plastic bags Mallet, pliers and trowel, marker pens OS maps for locating sites Weather-writers/ Floras/ Compass

Appendix 5. Correspondence between draft and final NVC sand dune vegetation types.

Draft NVC detailed in SSSI guidelines (Nature Conservancy Council, 1989) and Final NVC in British Plant Communities Vol 5 (Rodwell 2000)

NVC community in table 2b of SSSI guidelines (NCC 1989)	**NVC communities in British Plant Communities Vol 5 (Rodwell 2000)**	**Comment**
1. Strandline		
SD1 *Crambe maritima-Glaucium flavum* shingle community	SD1 *Rumex crispus- Glaucium flavum* shingle community	Revised definition
SD2 *Cakile maritima-Honkenya peploides* strandline	SD2 *Honkenya peploides- Cakile maritima* strandline community	
SD3 *Atriplex hastata-Beta vulgaris* ssp. *maritima* strandline	MC6 *Atriplex hastate-Beta vulgaris* ssp. *maritima* sea bird cliff community	MC6 similar, though definition not revised
SD4 *Atriplex hastata-Galium aparine* strandline	SD3 *Matricaria maritima-Galium aparine* strandline community	
2. Mobile (yellow) dune		
SD5 *Elymus farctus* foredune	SD4 *Elymus farctus* ssp. boreali atlanticus foredune community	Revised definition
SD6 *Ammophila arenaria* dune	SD6 *Ammophila arenaria* mobile dune community	Revised definition
SD7 *Leymus arenarius* dune	SD5 *Leymus arenarius* mobile dune community	Revised definition
SD8 *Leymus arenarius-Ammophila arenaria* dune	No equivalent	Incorporated into SD5 and SD6
3. Dune grassland (fixed dune)		
SD9 *Ammophila arenaria-Ononis repens* dune	SD7 *Ammophila arenaria-Festuca rubra* semi-fixed dune community	Revised definition
SD10 *Festuca rubra-Galium verum* dune	SD8 Festuca rubra-Galium verum fixed dune grassland	Revised definition
	SD9 *Ammophila arenaria-Arrhenatherum elatius* dune grassland	New community
4. Acid dry dune grassland		
SD11 *Ammophila arenaria-Festuca ovina-Agrostis capillaris* dune	SD12 *Carex arenaria- Festuca ovina-Agrostis capillaris* dune grassland	Revised definition
SD12 *Carex arenaria* dune	SD10 *Carex arenaria* dune community	Revised definition
SD13 Carex arenaria-Cladonia spp. dune	SD11 *Carex arenaria-Cornicularia aculeata* dune community	

5. Dune Heath		**No changes (all are H types)**
6. Dune Slack		
SD 15 Salix *repens-Holcus lanatus* dune-slack community	SD16 *Salix repens-Holcus lanatus* dune-slack community	Revised definition
SD16 *Potentilla anserina-Carex arenaria* dune –slack community	SD17 *Potentilla anserina-Carex arenaria* dune –slack community	Revised definition
	SD13 *Sagina nodosa-Bryum pseudotriquetrum* dune-slack community	New community
	SD14 *Salix repens-Campylium stellatum* dune-slack community	New community
	SD15 *Salix repens-Calliergon cuspidatum* dune –slack community	New community
7. Dune scrub		
SD 17 *Hippophae rhamnoides* dune scrub	SD18 *Hippophae rhamnoides* dune scrub	Revised definition

Appendix 6. GIS Standards for vegetation mapping.

The following are Natural England's standards for converting National Vegetation Classification (NVC) survey information into a format that can be used in a Geographical Information System (GIS).

The components of this specification required for particular surveys are clarified in the contract specification for that survey.

- Standard data model for vegetation data

The following outline the standard method of managing different types of data.

- Vegetation data

NVC vegetation boundaries are represented as a single GIS layer of polygons.

NVC mosaics, where unavoidable owing to scale of mapping, are represented as a single polygon with a unique polygon ID.

All polygons have been digitised according to the standards in Section 4.1in MOA.

Each polygon has the following attributes (the data type for each attribute is shown in brackets):

site_code (character 16) - each polygon is attributed with the agreed site code for the site surveyed; this code is repeated for different polygons relating to the same site; the site codes were provided by the project officer.

GID (integer) - for designated sites or site units the corresponding GID is stored. This was supplied by Natural England. Where possible vegetation boundaries were digitised against individual site units.

polygon_ID (character 16) - each polygon within a site is given a unique sequential numeric value.

vegetation_type (character 16) - this represents the NVC coding (e.g. CG2d, H8c, MG5a) for the polygon.

bap_habitat (character 64) - the corresponding BAP priority habitat, where applicable.

If the vegetation type consists of a mosaic then the proportion of each community is represented as a percentage in brackets. The communities of a mosaic is separated by a ‘+' e.g. MG5a (40%) + MG5b (60%).

Where it is determined that stands consist of intermediate communities, these were indicated in the vegetation codes by a ‘/’ e.g. MG5/MG4.

Where the same vegetation type occurs at more than one location on a site, these were digitised as a multi-part polygon or region with a single *polygon_ID*.

The exact wording, including upper and lower case, follows the standard NVC codes as outlined in the Natural England's Field Survey Standards for Phase II Habitat Surveys.

The following table summarises the approach:

Site_code	Poly_ID	Vegetation_type
31WHJ	1	M19
31WHJ	2	H20
31WHJ	3	U21/U22
32WHJ	4	CG2d (30%) + H8c (20%) + MG5a (50%)

Appendix 7. The Sand Dune and Shingle Network.

It is worth mentioning at this stage the Sand Dune and Shingle Network, based within the Geography Department in the Faculty of Sciences and Social Sciences at Liverpool Hope University http://coast.hope.ac.uk/. In March 2010 a 'Hydrology thematic group' was formed, under the umbrella of the Network, with the objective of improving understanding of the interactions between hydrology and vegetation in dunes. Core members of this are Natural England, CEH, British Geological Survey (BGS), University of Southampton and University of Groeningen.

The group held an inaugural meeting in Southport in March 2010 and at this, a list of priority needs was identified. These were:

- Better information required on the water requirements of dune species.
- A need to develop our understanding of what a ‘reference condition’ is.
- Analysis of the ecosystem services provided by sand dunes.
- Better exchange of information between researchers and managers.
- An ongoing need for more extensive biological and hydrological records.
- Future discussions should include geomorphologists and coastal engineers.
- Further promotion of dune slack hydrology and identification of mechanisms through which to achieve this.
- Overall, we should be aware that whilst research and management will continue we should always try to prevent things being done which we will regret in the future.

This meeting was followed by a visit in May 2011, to three dune systems (Braunton Burrows, Whiteford Burrows and Kenfig Burrows) to look in more detail at the current pressures and research needs. This helped the group to formulate a research plan to address the priority needs. The core members of the group have been involved in implementation of this plan and in the case of this study, Natural England, CEH and BGS worked together to take this forward.

Most recently, the group held a second meeting in September 2013, in South Wales. This provided an opportunity for reporting back on the progress over the past three years and for revisiting and, where appropriate, revising the priority needs.

Appendix 8. Supporting information produced as part of this study.

Dataset Name	Description	Size	Restrictions
Previous studies	Scanned pdfs of previous reports, including the 1988/1989 Sand Dune Vegetation Survey.	Approx. 70 files. Each ~ 1 Mb	None, but should reference main report (Stratford et al. 2014) if used in further studies.
Soil organic matter profile at Braunton Burrows	Results of loss on ignition experiment carried out on soil profile samples from Braunton Burrows.	< 1Mb	None, but should reference main report (Stratford et al. 2014) if used in further studies.
Soil moisture release of Braunton Burrows samples	Results of sand table soil moisture release experiments carried out on surface (0 to 10 cm) and sub-surface (15 to 25 cm) samples from Braunton Burrows.	< 1 Mb	None, but should reference main report (Stratford et al. 2014) if used in further studies.
Dipwell locations	dGPS surveyed locations of dipwells at Braunton Burrows, Ainsdale and Sandscale. Estimation of previous dipwell locations at Sandscale.	< 1 Mb	No restriction for Braunton data or Sandscale. Ainsdale data is property of Derek Clarke at University of Southampton and will require his approval.
MORECS	Monthly long term rainfall and evaporation data for the 40 km x 40 km grid square that each dune site falls within.	< 1 Mb	Summary information (as included in the report are unrestricted). The underlying data are copyright of the UK Met Office.
Vegetation quadrats	Percentage cover in 2x2m quadrats, from 2012	< 1 Mb	Contact Laurence Jones at CEH. Reference main report (Stratford et al. 2014) if used in further studies.
Vegetation quadrats (historical)	DOMIN cover in quadrats from ~1990	< 1 Mb	None, but should reference main report (Stratford et al. 2014) if used in further studies.
Soil parameters	Basic physical parameters (pH, moisture, Loss On Ignition) associated with vegetation quadrats.	< 1 Mb	Contact Laurence Jones at CEH. Reference main report (Stratford et al. 2014) if used in further studies.
Mapped dune wetlands, 2012	Mapped polygons, assigned to NVC for dune wetlands at all surveyed sites. ArcGIS shapefiles.	~100 Mb	None, but should reference main report (Stratford et al. 2014) if used in further studies.
Mapped dune wetlands, ~1990	Mapped polygons from 1990 survey, corresponding to dune wetlands at all surveyed sites. ArcGIS shapefiles.	~100 Mb	None, but should reference main report (Stratford et al. 2014) if used in further studies.