University of Reading

Vegetation recovery of saltmarsh and sand dune habitat following cable and pipeline installation

Doctor of Philosophy

School of Biological Sciences

Louise Denning

December 2017

Acknowledgements

I wish to thank (and acknowledge) the following people for their cooperation, assistance and contributions to my thesis:

My supervisors, Dr Jonathan Mitchley and Dr Richard Carter, who I have been fortunate to have known for many years. Richard has played a major role in helping me develop my botanical skills, first through his teaching on the Vegetation Survey and Assessment Masters, but also while I worked with him at his environmental consultancy. During that time, I have had the opportunity to work on a wide range of botanical projects including many coastal developments, where the idea for this thesis was first conceived. It was also through my consultancy role that I first met Jonathan when he joined our botanical team. Jonathan has an enthusiasm for botany which is contagious. Jonathan has been the perfect PhD supervisor for me, letting me work to my own pace (especially while I was working part-time) and allowing me the freedom to develop my research. Richard's and Jonathan's support throughout my PhD has been so valuable, and whilst I am sure I could have accomplished it with different supervisors, I am sure it would have been a far less enjoyable experience.

I also wish to thank Dr Simon Mortimer and Dr Paul Hatcher who were part of my supervisory committee, they provided advice as to the direction of my research at critical periods and gave me the confidence that my research had value. Without their suggestions my PhD would have been much poorer in terms of its breath and content.

The following people have helped me to expand and develop my plant identification skills in particular with bryophytes recorded in sand dune areas - Jonathan Mitchley, Richard Carter and David Morris.

My use of QGIS was greatly assisted by a course on Geographical Information Systems for Ecologists and Conservation Practitioners, and also with assistance from Stephen Phillips from RSK Environment Ltd, and my friend Ben Fisher from McCarthy Green.

Help with producing the line drawings of vegetation communities and potential impacts was given by my mother Sherry Denning.

Proof reading of the chapters were provided by my parents Sherry and Paul Denning, Dr Jonathan Mitchley and Dr Richard Carter.

Advice on the statistical analysis of my data using CANOCO 5 was provided by Dr Jan Lepš and Dr Petr Šmilaur during an eleven-day course (Multivariate Analysis of Ecological Data) held at the

University of South Bohemia. General statistical advice was sought from the University of Reading, Statistical Advisory Service and from Dr Maria Christodoulou from the University of Oxford.

Survey assistance while undertaking the surveys at Walney Island was gratefully received from three members of the Cumbria Wildlife Trust Marine Trainee Scheme which was kindly organised by Maria-Ann Park (CWT Marine Training Programme Manager).

I am very grateful to the following organisations for allowing me access to their sites namely eni Liverpool Bay Operating Company, The RSPB, The Crown Estate, Kent Wildlife Trust, Buccleuch Estates, and Perenco UK.

Much of the available historical site data came from the local biological records offices, regional Natural England and Natural Resources Wales teams and the RSPB.

Finally, I wish to thank my parents Sherry and Paul Denning, sister Charlotte Hughes and my grandmother Mrs Jessie Kent for their continuing support during my PhD. Without their financial assistance, it would have been very difficult to complete my self-financed PhD. Similarly, the bequest left to me by my friend Dr William Pickering enabled me to focus and complete my PhD without having to continue with paid work.

Declaration

I confirm that this is my own work and the use of all material from other sources has been properly and fully acknowledged.

Louise Denning, December 2017

Contents

Abstract

This project focuses on post-construction vegetation recovery of saltmarsh and sand dunes following the installation of offshore cables and pipelines. With an increased reliance on renewable energy, sensitive coastal habitats are likely to be subject to future impacts. Past projects can provide a useful record of change to help determine vegetation recovery in terms of time frames and naturalness. The overall aim of the project is to provide evidence to aid the decision-making process.

Central to this research is determining which attributes of restored vegetation might best reflect recovery, how long does recovery take, and what are the likely recovery outcomes.

Detailed botanical surveys were completed on and off the pipeline and across different vegetation zones. Species data were initially analysed using a Generalised Linear Model, with subsequent ordination using Canonical Correspondence Analysis.

Tentative recovery times are provided. These time frames are indicative as each site and construction project is dependent on the vegetation zones and community types present, construction methods, severity of impact and restoration techniques used. With recovery taking anything from 10 years where impacts are less severe (*i.e.* in the driftline, low-mid marsh, and pioneer marsh) to much longer recovery times >25 years in sensitive vegetation types (*i.e.* mid-upper marsh, dune slacks) or where there have been greater impacts.

The study found that sand dunes were generally more resilient to construction than saltmarsh, with the exception of dune slacks which typically became drier resulting in a loss of wet-tolerant herbs. In sand dunes there are opportunities to have a positive impact *e.g.* creating scrapes, or open areas with bare sand supporting early successional species. In saltmarsh, impacts associated with construction tended to be more severe (*e.g.* compaction, changes in topography and modification of creeks), often resulting in atypical development of early successional marsh.

INTRODUCTION

Chapter 1 Introduction

1.1 Overview

This PhD proposal came about having worked as a botanist for 15-years in an environmental consultancy. During that time I worked on several large-scale linear coastal developments and it was evident that there was insufficient, readily available published information to help determine the impact of the proposed schemes on likely vegetation recovery and future habitat integrity. Early discussions with the main nature conservation bodies in the UK has supported the need for better information and a stronger evidence base, especially as there are many coastal renewables and energy projects currently being developed and consented around UK waters.

The basis for this PhD therefore follows the evidence-based approached for conservation *e.g.* Sutherland et al. (2012) and Sutherland and Freckleton (2012) with the aim of reviewing the assessment process and developing a tool-box of materials to aid decision making.

1.2 Saltmarsh and Sand Dunes in the UK

1.2.1 Saltmarsh Distribution

A comprehensive account of the saltmarshes in the UK was undertaken by the Nature Conservancy Council (Burd, 1989), who initiated the Saltmarsh Survey in 1981. The main aims of the study were to determine the distribution and abundance of saltmarsh in Great Britain focusing on areas of saltmarsh over 0.5ha. At each location, the vegetation types were mapped and described. The survey identified 557 separate sites covering an area of 44,370ha.

England has the largest area of saltmarsh in the UK, around 34,500ha[1] found across 120 sites (Burd, 1989). The majority of this (70%) is found in seven counties; Cumbria, Essex, Kent, Hampshire, Lancashire, Lincolnshire and Norfolk. The average area of each site is 270ha; and nearly half (59 sites) are over 100ha.

In Wales, Burd (1989) identified 6000ha of saltmarsh across 57 sites[1]. Nearly half of the saltmarsh (2876ha) was found in Llanelli and West Glamorgan, although the study found that saltmarsh vegetation was found in all the major estuaries and inlets around the Welsh coast.

In Scotland, Burd (1989) identified 6,089ha of saltmarsh vegetation across 380 sites, of which 280 supported an area of vegetation smaller than 10ha. This survey was updated between 2010-2012

---

1 The JNCC webpage specifies 32,462ha in England and 5800ha in Wales- assessed 01/10/17 http://jncc.defra.gov.uk/page-5379 page updated 27/01/16

(Haynes, 2016). The updated survey focused on areas of saltmarsh (over 3ha or longer than 500m) across the Scottish mainland and offshore Islands. In total 249 sites were surveyed, with more than 5,800ha of saltmarsh recorded and mapped.

In Northern Ireland, limited information is available regarding the total area of saltmarsh habitat. The JNCC has identified 250ha (recorded from protected saltmarsh sites) which is similar to that published by Burd (239ha), who identified 15 individual sites.

In 2011, the saltmarsh resource in England and Wales was calculated at 40,522ha, using aerial photography (Phelan et al., 2011). Phelan suggests a net annual change in saltmarsh extent between 1989 and 2006-2009 as between +1 and -82ha yr^{-1}. Saltmarsh losses vary around the UK coast; Baily and Pearson (2007) estimate that losses of up to 50% along the south coast have been recorded between 1971 and 2001; while Cooper et al. (2001) recorded saltmarsh losses of between 17-59% in estuaries in the south-east of England. These losses have occurred through reclamation, erosion of the marsh frontage, widening of existing channels, which are at least in part attributed to sea level rises and coastal squeeze.

1.2.2 Sand Dune Distribution

Sand dunes are widely distributed around the UK coastline with different dune types developing as a result of climatic and geological variations. Scotland has the largest dune resource covering approximately 50,000ha. The sand dune resource in England, Wales and Northern Ireland is smaller; *c.* 11,900ha, 8,150ha and 1,500ha respectively (as defined by the JNCC[1]). Pye et al. (2007) identified 112 dune sites, with more than 50% of these being less than $1km^2$.

Hindshore dunes develop in the most exposed locations where huge amounts of sand are driven inland, these are most common in Scotland and Wales, although in England one of the largest dune systems at Sefton Coast (*c.* $20km^2$) was formed this way. More commonly in England, dunes develop between two headlands, known as bay dunes, or form spit dunes at the mouths of estuaries. The dune systems of the south coast of England are the least well developed. In north-west Scotland, the calcareous sediments of shell fragments have allowed extensive areas of Machair to develop.

1.3 Description and Classification

1.3.1 Approaches

Saltmarsh and sand dune habitats in the UK have been subject to numerous classification systems developed in an attempt to categorise and simplify the composition of vegetation and its structure. Two of the key approaches *i.e.* dominant species versus total floristic composition (phytosociology) are pertinent to this study. A useful summary, along with references to other reviews is given in Jennings et al. (2003) used in describing a US National Vegetation Classification.

The use of dominant species (often the most conspicuous) to classify and name vegetation types, is the most widely used system in the UK and forms the basis of the National Vegetation Classification (NVC). One of the original studies using dominant species was undertaken by Tansley (1939) in his work *The British Islands and their Vegetation.* The use of dominant species to classify vegetation has two main benefits. It is easier for non-specialists to use as it draws on a smaller number of plant species and the number of communities identified is relatively limited. However, there is often considerable variation in less abundant species (which are often in themselves very characteristic); and there are also problems associated with surveyors' under-recording non-dominant species as this is not seen as the focus of the survey. The use of the dominant species approach can lead to discrepancy in determining the vegetation types between surveyors as much of the interpretation of survey data is based on a review of the proportions of the constant species. Difficulties arise when these key species are missing or found at uncharacteristic levels of abundance when compared to the published floristic tables as found in Rodwell (2000).

In comparison, using a total floristic composition (phytosociology) approach based on the work by Braun-Blanquet (developed in the 1920's) and described in Westhoff and van der Maarel (1973), uses all the species present to define plant communities along with environmental and biotic factors. This works on the basis that some species (diagnostic species) are better indicators of a given community than others. These diagnostic species are used to organise vegetation communities into a hierarchical classification. The hierarchical classification identifies stand-types known as associations. These associations are grouped into alliances, orders and classes, of increasingly broad floristic character (Barkman et al., 1986). This approach is widely used across Europe and forms the basis of the classification used in defining those habitats listed on The Habitats Directive (European Commission, 2013). Rodwell (2000) includes a complete list of all the NVC communities arranged within the hierarchical framework.

1.3.2 National Vegetation Classification

For this study, vegetation communities are described following the National Vegetation Classification (NVC) developed by (Rodwell, 2000) which is based on the dominant species approach, grouping plant communities by informal categories. It was intended to provide 'standardised descriptions of named and systematically arranged vegetation types from all natural, semi-natural and major artificial habitats in England, Scotland and Wales' (Rodwell et al 2000). For both saltmarshes and sand dunes the NVC is typically based on the dominance of a few grass species *e.g. Ammophila arenaria*, *Festuca rubra*, *Puccinellia maritima* and *Spartina anglica*, which resulted in relatively few broad vegetation types. In addition, these vegetation types relate to successional stages *e.g.* pioneer, low-mid marsh, or mobile, fixed and 'grey' dunes, or were based on descriptive terms *i.e.* dune slacks which were not supported by detailed floristic descriptions (Rodwell, 2000). The relative coarse nature of these NVC communities means that additional types are often required to describe the variations found at individual sites. There are also gaps in the coverage of the ecological range of variation covered in the classification and some of these may encompass types that are significant on a European scale (Rodwell et al., 2000).

Despite the problems associated with the NVC approach, it has become the widely accepted classification system when describing vegetation in the UK used by statutory bodies, conservation agencies, as well as environmental consultants (Rodwell et al., 2000). It has been used to interpret and implement key aspects of national and international site designation legislation. For example it is used to classify terrestrial habitats for the designation of Sites of Special Scientific Interest (SSSI) (Bainbridge et al., 2013a, 2013b), and interpreting Annex I habitats for the selection of Special Areas of Conservation (SAC) (Brown et al., 1997). It is also used in assessing habitat condition through its incorporation in the JNCC Common Standards Monitoring Guidance.

Much of the work on saltmarshes that would form the basis of the saltmarsh NVC was undertaken by Adam (1978, 1981). Adam undertook a review of the various botanical studies of saltmarsh vegetation while developing a dichotomous key using a phytosociological classification. As part of that work, Adam collected almost 3000 new samples of vegetation from 133 saltmarshes around the UK. This was followed by the UK wide saltmarsh survey completed by Burd (1989).

The NVC system for sand dunes and shingle habitat was developed through survey work focusing on representative dune systems across England, Scotland and Wales. The NVC project also drew upon existing survey data collected as part of the Sand Dune Vegetation Survey of Great Britain by Dargie (1993, 1995), Birse (1980), Birse et al. (1976) and Radley (1994). In total 2304 samples were used in the analysis to determine vegetation types.

Tables 2 and 3 (*Section 2.2.3*) provides a summary of the saltmarsh and sand dune vegetation zones (used as the main classification system for my data analysis) with their equivalent NVC types and European Union Habitat Directive types.

1.4 Protection

1.4.1 The Value of Sand Dunes and Saltmarsh Habitats

In a report by the Natural Capital Committee (2015) the value of coastal habitats was clearly identified. The report states "*an area of intertidal habitat on the coast, for example, can act as a buffer against flooding. It can also provide areas for recreation; act as a nursery ground for* *commercial fish species; sequester and store carbon from the atmosphere and maintain itself*". There have been many studies on the monetary value of coastal habitats, and a summary was compiled by the UK National Ecosystem Assessment (Jones et al., 2011, Turner et al., 2014). This report notes, "*the six Coastal Margin habitats (Sand Dunes, Machair, Saltmarsh, Shingle, Sea Cliffs and Coastal Lagoons) make up only 0.6% of the UK's land area, but are far more important to society than their small area might suggest. The total value of the ecosystem services provided by the UK's coast is estimated at £48 billion (adjusted to 2003 values), equivalent to 3.46% of Global National Income*". Ecosystem services provided by coastal habitats include tourism, coastal defence, carbon sequestration, and high biodiversity.

The Environment Bank (2015) notes that saltmarsh creation and restoration is identified as one of five priority habitats for the likely high positive cost-benefit ratios it delivers.

1.4.2 Legislation and Protected Sites

A number of legislative Acts and Directives provide legal protection to habitats that, together with national and local planning policies, aim to conserve biodiversity and nature conservation interest in the UK[2]. Currently, much of the UK's saltmarsh and sand dune resource is designated through statutory conservation legislation.

Habitat designations at a European level centre around Natura2000 sites through the designation of SAC. Jones et al. (2011) notes that *c.* 20% of sand dunes and machair, and 50% of saltmarsh are under SAC protection. SACs aim to establish and protect a network of important high-quality conservation sites that make a significant contribution across Europe to conserving habitat and species identified in Annexes I and II of the EC Habitats Directive. Annex I list 89 habitat types (78 of which are found in the UK). Of these, eleven are coastal sand dunes and four are coastal saltmarshes habitats. Appendix Table 1 gives the regional extent in hectares of each of the sand dune and saltmarsh Annex I habitat types in the UK. The Habitats Directive Article 6 (2) requires member states to avoid the deterioration of natural habitats within SACs, other articles oblige states to undertake surveillance and reporting of the conservation status.

In the UK, the best examples of flora and fauna are protected through the SSSI statutory designation. These sites are also used to underpin other national and international nature conservation designations, with *c.* 75% of the area covered by SSSIs recognised as being of EU importance (JNCC, 2013a).

[2] The EU Habitats Directives (Council Directive 92/43/EEC on the Conservation of Natural Habitats and of Wild Fauna and Flora), The Wildlife and Countryside Act 1981 (as amended), The Countryside and Rights of Way Act, 2000 (England and Wales), The Nature Conservation (Scotland) Act 2004, The Natural Environment and Rural Communities Act, 2006, Conservation of Habitats and Species Regulations, 2010 (as amended) and the Water Framework Directive.

The original selection criteria for biological SSSIs was developed in 1989 as a means of defining the scientific rationale for site selection (Nature Conservation Council, 1989). This was based on the ten primary and secondary criteria identified by Ratcliffe (1977). In 2013, this document was revised by the Joint Nature Conservation Committee (JNCC[3]) to take into consideration new European and UK legislation as well as incorporating new understanding of ecological processes, climate change and the whole ecosystem approach (JNCC, 2013a, JNCC, 2013b). The 2013 guidelines identified two additional criteria, ecological coherence and potential value.

In addition, National Nature Reserves contain examples of some of the most important natural and semi-natural ecosystems in Great Britain. They are managed to conserve their habitats and to provide special opportunities for the scientific study of the habitats and species represented within them. Various lower level habitat designations may also provide protection to coastal habitats *e.g.* Local Nature Reserves, County Wildlife Sites or Sites of Importance for Nature Conservation *etc.*

Two UK Priority Habitat types, Coastal Sand Dunes and Coastal Saltmarsh are recognised under the 2007 review of the UK Biodiversity Action Plan (Biodiversity Reporting and Information Group, 2007). Both habitats are also included on the list of Habitats of Principal Importance.

1.5 Consideration of the Threats

Jones et al. (2011) provides a detailed summary of the key threats to coastal habitats, namely climate change, sea level rise, air pollution, tourism, coastal access, coastal development and sea defence.

While much of the UK's sand dune and saltmarsh resource is designated through statutory designations at an international, European or national level, there have been considerable habitat losses (16.8% between 1945 and 2010) which are still continuing[4] (Jones et al., 2011). Habitat loss and fragmentation has occurred from land-take (primarily industry and agricultural expansion on saltmarsh, and housing and tourism infrastructure on sand dunes and shingle), coastal squeeze and sea-level rise[5].

1.5.1 Energy Production

Coastal habitats have been subject to disturbance as a result of energy production for decades. Historically this centred around the development of oil and gas facilities and associated pipelines making landfall (the location of which is determined by the position of the reserve and onshore processing terminals). However, with declining oil/ gas reserves in the North Sea, and increased

[3] Note documents authored by the Joint Nature Conservation Committee are abbreviated to JNCC.
[4] although at a slower rate since the 1980s when stronger protection came into force
[5] estimated at 2% for sand dunes and 4.5% for saltmarsh over the past 20 years

awareness of the effects of climate change with the need to decarbonise energy production (Committee on Climate Change, 2016) there has been a move away from these traditional energy methods to an increased use of renewable sources.

Guidance documents have been produced to inform developers and consultants of the environmental impacts associated with pipeline and cable installation *e.g.* (BERR, 2008, Department of Trade and Industry, 1992, European Commission, 2010, IEEM, 2010, John et al., 2016, John et al., 2015, OSPAR, 2017) and the Environmental Impact Assessment (EIA) process (CIEEM, 2016a).

Over the last year, the press has recorded the shift in energy production with headlines such as "*Wild is the wind: the resource that could power the world*" (The Guardian, 2017), "*Offshore wind power cheaper than new nuclear*" (The BBC, 2017), "*Record-breaking Hornsea Two wind farm will cut cost of green energy*" (The Times, 2017), "*Britain powered 24 hours without coal for first time in 135 years in watershed moment*" (The Independent, 2017), "*World's largest offshore windfarm to be built off Yorkshire coast*" (The Guardian, 2016).

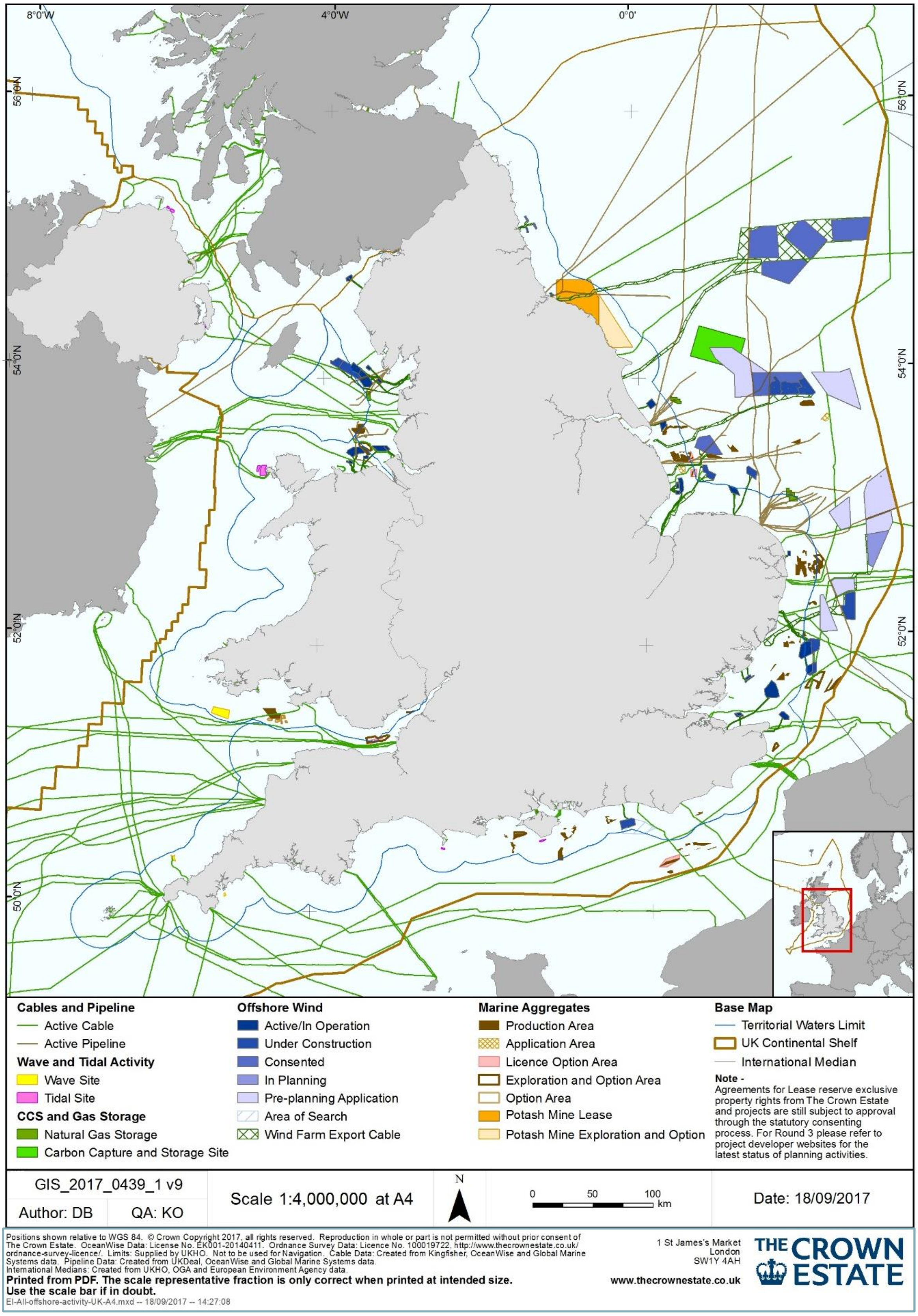
As part of the Clean Growth Strategy the UK government has committed to ensuring at least 15% of UK energy comes from renewable energy sources by 2020, of which 10% will be met by offshore wind. By the end of 2016, renewable energy represented 25% of the UK's electricity generation, of which 5% was provided by offshore wind.

Since 2000, The Crown Estate has leased areas of seabed for the commercial development of offshore wind farms in UK waters. As of 2016, there were 29 fully operational offshore wind farms, with construction activity commencing on a further 5.3GW of new capacity (The Crown Estate, 2017b). The first 13 sites, developed as part of Round 1, were typically small-scale (with less than 30 turbines), located close to the shore and had a small generating capacity. In contrast, the 16 Round 2 sites, are larger in scale and are located further offshore *i.e.* projects in the Greater Wash, the Thames Estuary and Liverpool Bay. Between 2009 and 2010, both Round 1 and 2 areas were extended to further increase operational capacity, and nine Round 3 areas were released. There are currently eleven sites under construction or subject to planning. In November 2017, The Crown Estate (2017a) announced that it was considering additional seabed rights to provide further opportunities for offshore wind deployment in the 2020s. This review would be taken in consultation with stakeholders and the offshore wind sector. All of these existing and new projects require cable connection to the mainland, and some of these projects as illustrated in *Chapters 3* and *4* cross saltmarsh and sand dune habitats. The Crown Estate Offshore Activity map (Figure 1) shows all the current cables, pipelines, wave, tidal, offshore wind and gas storage sites around the UK coast.

One of the main issues on reducing our reliance on carbonised energy sources, is that renewable energy is intermittent in terms of production, which can lead to an energy deficit. To overcome this deficit, the UK is increasingly reliant on Europe (who use a broader range of power sources *e.g.* hydro-electric, nuclear and coal) to maintain electricity supply. The use of interconnectors (cross-border power cables) crucially allow electricity from across Europe to be shifted from where it is being over-produced to where it is needed. In a recent article in The Times newspaper it listed four existing subsea power links (to France, the Netherlands, Northern Ireland and the Irish Republic) and twelve future interconnector projects (Gosden, 2017). Interconnector cables may also require access to sand dune and saltmarsh habitats to make landfall.

Other future energy sources that may result in impacts on sand dunes and saltmarshes (through cable installation) include tidal and shoreline wave energy. As of 2016, there were 14 wave and tidal sites in the UK, producing 13.5MW (Department for Business, 2017). However, since 2014, the Crown Estate has leased over 40 sites for tidal and wave projects. The Crown Estate note that "*the waters around our coast contain some of the best wave and tidal energy resources in the world. In order to contribute to maintaining a diverse and secure energy mix, and realise renewable energy and carbon reduction targets, there is a strong case to develop these resources at an appropriate scale*".

Figure 1 - The Crown Estate offshore activity map shows proposed and constructed cable, pipeline, wave, tidal and offshore wind developments around the English and Welsh coast.



1.5.2 Climate Change and Sea-level Rise

The Climate Change Adaption Manual (Natural England and RSPB, 2014) aims to assess the adaptation responses of UK habitats to climate change, providing an overall sensitivity rating and identifying potential climate change impacts. The scientific evidence behind the manual draws on published reports produced for the Intergovernmental Panel on Climate Change (IPCC)[6], and UK climate change data from the UK Climate Projections 2009 report[7,8]. The IPCC (2013) states "*human influence has been detected in warming of the atmosphere and the ocean, in changes in the global water cycle, in reductions in snow and ice, in global mean sea level rise, and in changes in some climate extremes…... It is extremely likely that human influence has been the dominant cause of the observed warming since the mid-20th century*".

It is estimated that sea level around the UK rose by about 1.4mm yr^{-1} over the 20^{th} century (Woodworth et al., 2009). Predicted rates of sea-level rise will greatly exceed isostatic readjustment on all UK coasts, but in particular in the south and east which have the greatest rate of isostatic readjustment. By 2095 relative sea level is predicted to have increased in London by 21-68cm and in Edinburgh by 7-54cm[9] (Jenkins et al., 2009). In the last 20 years, habitat losses due to sea-level rise have been relatively small, estimated at 2% for sand dunes and 4.5% for saltmarsh. However, future, sea-level rise is predicted to result in habitat losses of around 8% by 2060 (Jones et al., 2011).

Mossman et al. (2013) based on Jenkins et al. (2009) notes that there are large uncertainties in predicting storminess. In contrast to previous predictions (which showed increased storm surges in parts of the UK), the seasonal mean and extreme waves are generally expected to increase slightly to the south-west of the UK, reduce to the north and experience little change in the North Sea. However, predictions do show that the UK will be subject to increased winter rainfalls, and heavy rainfall events, while rainfall in the summer will decrease.

Specifically relating to coastal habitats, saltmarshes are ranked as having a high sensitivity to climate change. Natural England and RSPB (2014) notes that they are "*particularly sensitive to the combined effects of sea level rise, storm events and human responses to these*". Appendix Table 2 outlines the main causes, consequences and potential impacts of climate change on saltmarsh habitats.

---

[6] IPCC assessments provide a scientific basis for governments at all levels to develop climate related policies, and they underlie negotiations at the UN Climate Conference – the United Nations Framework Convention on Climate Change (UNFCCC).
[7] This is currently being reviewed in light of the Paris Agreement on Climate Change in December 2015
[8] http://ukclimateprojections.metoffice.gov.uk/
[9] Based on 5^{th} to 9^{th} percentile, medium emissions scenario

A similar review of the likely impacts of climate change for sand dunes are set out in Appendix Table 3. Sand dune habitats are classified as having a medium sensitivity to climate change. In theory they are capable of adapting to some of the impacts from climate change through natural sediment regimes, however human interventions along the coast have often constrained these processes, in particular constraining landward migration through development (Natural England and RSPB, 2014).

1.6 Restoration and Recovery

1.6.1 Definitions of Recovery and Restoration

The focus of this PhD is vegetation recovery of saltmarsh and sand dune habitats following pipeline and cable installation, and often this is achieved through some level of ecological restoration. This is driven for the most part by planning requirements which set out conditions with regard to restoration, monitoring and ultimately recovery. Understanding the definitions of recovery and restoration are therefore important.

The Society for Ecological Restoration (SER) defines recovery as "*the state or condition whereby all the key ecosystem attribute categories closely resemble those of the reference model*" (McDonald et al., 2016).

While ecological restoration is defined as the "*process of assisting the recovery of an ecosystem that has been degraded, damaged or destroyed*" (SER 2004). The SER goes on to say "*ecological restoration therefore seeks the highest and best recovery outcomes practicable to both compensate for past damage and to progressively effect an increase in the extent and healthy functionality of the planet's imperilled ecosystems*" (McDonald et al., 2016).

Perrow and Davy (2002) provides the philosophy and rationale for the need of restoration.

1.6.2 Criteria of Restoration Success

Determining the success of ecological restoration has long been studied, scrutinised and perhaps criticised as the term success is imprecise. Much of the problem is caused by an initial lack of restoration targets and a clear idea as to what should be achieved; or by setting unrealistic or unachievable project goals.

The SER recognises six key ecosystem attribute targets for determining the success of ecological restoration, these are; an absence/ cessation of threats; restoration of physical conditions; presence of desirable species; reinstatement of spatial habitat diversity; recovery of ecosystem functionality; and restoration of external exchanges with the wider unaffected environment (McDonald et al., 2016, Society for Ecological Restoration International, 2004).

In a review by Kentula (2000), three terms of restoration success are defined; compliance, functional and landscape success. This builds on the work by Quammen who defined compliance and functional success when considering wetland restoration. The results cannot be a simple yes or no evaluation but a process towards ecological goals (Zedler and Callaway, 2000). Zedler and Callaway (2000) notes that the ultimate measure of success is an evaluation of ecosystem resiliency. Rather than focusing on a species presence and abundance perhaps the focus should be on whether the target species is sustained or increased over the time.

There have been a number of reviews on the criteria used to determine restoration success. Ruiz-Jaen and Aide (2005) undertook a review of published articles in the journal *Restoration Ecology* to determine what measures of ecosystem attributes were widely assessed and how these were used to determine restoration success. The study focused on sites where planting or seeding had occurred to aid restoration. They found that most studies used three main ecosystem attributes 1) diversity; 2) vegetation structure; and 3) ecological processes (three of the six key attributes identified by the SER). Most measures of diversity focused on plant species-richness. Vegetation structure measures included cover, density, biomass and height. Less frequently recorded were measures of ecological processes; but when considered they focused on biological interactions, nutrient pools and soil organic matter. The review showed that no study measured all six of the SER attributes.

A similar study was undertaken by Lithgow et al. (2013), who focused specifically on large coastal dune systems. The review categorised the measures used to assess restoration success which included integrity (species composition and ecosystem structure), health (ecological process) and sustainability (occurrence of natural regeneration and resilience after the impact of additional disturbances).

Matthews and Endress (2008) undertook a review of the success of compensatory mitigation across 76 wetland sites in Illinois, USA. The study focused on determining which goals and measures of restoration success were used. The study found most goals were focused on plant communities (in particular abundance measures). Compliance goals were also used, with criteria related to survival of planted vegetation or were based on the dominance of non-native or weed species. The study noted that some goals were too lenient to be of value, whereas others were unachievable; making the judgement of success difficult. It concluded that more appropriate goals could be devised by basing them on the performance of past, similar restorations.

Chang et al. (2016) looked at factors that determined the success of saltmarsh restoration following de-embankment works at a site in the Netherlands. The study used criteria focusing on a combination of compositional, structural and functional measures (Hobbs and Norton, 1996); with target plant species based on published country-wide saltmarsh surveys. Permanent transects were surveyed over a 10-year period and documented vegetation composition. Ten years after de-embankment, the majority of the target species (between 78-96%) had been recorded from the transects; however, diversity of saltmarsh communities was generally low, with 50% of the site supporting secondary pioneer marsh. If success criteria had only considered presence of the target species, then success could have been claimed after the 10 years. However, by including the diversity and composition of the vegetation communities it was clear that the restored vegetation was dissimilar to natural marsh. The key factors determining success was the interaction between proximity to a creek, distance from the breach and grazing.

In a recent study (Laughlin et al., 2017), put forward a hierarchy system of the predictability of measures used in determining ecological restoration. The study analysed herbaceous species data (collected for 23 years) from pine forest in western USA following restoration. They found that the biomass and species-richness were the two most predictable and least variable measures, while community composition was the least predictable and most variable. They also found that trait-based measures of functional diversity tended to be more predictable and less variable than community-weighted-mean trait values (and both of these were again more predictable than community composition). They note that "*given the dynamic nature of taxonomic composition in many restoration experiments, strict targets based on composition may rarely be met*". Therefore, the use of functional trait-based metrics can provide meaningful information on restoration trajectories, combining composition with functional traits. However, (Laughlin et al., 2017) notes that monitoring dominant and invasive species will always be important.

There are obvious benefits (*e.g.* cost and time saving for monitoring) in recognising which measures of ecological success are likely to predict restoration success. But care needs to be taken, if for example excluding measures of community composition (as this requires more time in the field and a higher level of knowledge) over species-richness. This is especially true in less diverse habitats such as saltmarsh where species-richness measures between desirable and non-desirable community types can be very similar (Laughlin et al. (2017) acknowledges that their study only focuses on one habitat). For example, pioneer or low marsh species establishing at higher elevations of the tidal frame may support low numbers of species, but so too can species-poor examples of upper marsh vegetation types which would be preferable in this context. In addition, greater value of success may be attributed to scarce or rare plants which are only likely to be recorded if a more detailed assessment of species composition is recorded.

In the end it depends on what the original restoration objectives are; whether the focus is to achieve functional restoration where perhaps a habitat has a different set of species from the reference model (but within acceptable limits), or if the goal is to achieve a species assemblage which is close to the reference model.

1.6.3 Restoration Failures

Bellmer (2001) reviewed the reasons for restoration failures and identified three main causes:

- implementation failure, whereby the contractor disregards, or fails to achieve the required standard for restoration;
- functional failure, where the project designer has inadequate knowledge to produce the desired functional outcome; and
- failure to set quantifiable restoration objectives and criteria at the project onset, so that early warning systems are not in place to determine when restoration is not on track.

Mitsch and Wilson (1996) notes that the variable success of restoration projects is often down to a lack of understanding of the habitat function and that insufficient time is left for projects to mature. Even the oldest of restoration projects are ecological young and a final verdict on whether a site reaches functional equivalency is often premature. They state "*mitigation projects involving freshwater marshes should require enough time, closer to 15-20yr than 5yr, to judge the success or lack thereof. Restoration and creation of forested wetlands, coastal wetlands, or peatlands may require even more time*".

A similar conclusion was given by Mossman et al. (2013), (2012b) with regard to managed realignment sites. In the UK, most managed realignment sites were restored less than ten years ago, and the communities indicate an early-successional state with pioneer and low-marsh species. Therefore, this highlights the need for long-term monitoring studies.

1.6.4 Reference Model

The SER refers to the use of reference models or reference ecosystems (McDonald et al., 2016). The reference model is the target for the local native ecosystem being restored. It should include capacity for that system to adapt to existing and future environmental change. The reference ecosystem is derived from multiple sources of information, and should consider biotic, abiotic conditions in terms of composition, structure and functionality. It should also consider the successional processes that drive ecosystem development. The reference model should aim to characterise the condition of the ecosystem as if it had not been degraded and therefore can reference the actual site or can be based on numerous reference sites, field indicators or historical records. This approach of setting restoration targets using several reference sites to establish a mean of metrics as a basis from which to judge equivalency was set out by Bellmer (2001). The author gave the example that an objective may be to establish a saltmarsh with metrics that are 60-80% within the 'bound of expectation' of several nearby reference saltmarshes with similar elevations.

Similarly, Weinstein et al. (1996) when considering restoration success of a large-scale wetland project used ecological criteria based on the project itself, noting that the upper limit of the anticipated parameters for restoration would be represented by a relatively undisturbed reference marsh; and the lower limits would be determined by other restoration sites.

Kentula (2000) also highlights the value of comparing characteristics of new restoration projects with those of old projects undertaken with similar objectives. This valuable information resource can help determine the trajectory and rate of recovery and can give a useful insight into the value of specific restoration methods. Kentula notes that "*such comparisons can be used to determine whether new projects are developing as expected based on quantitative descriptions of old projects as they developed*" (Kentula et al., 1992a). The other benefit of reviewing old projects, even where they had limited restoration success, is that even failures can provide important information so that future restoration projects can learn and modify approaches. This ultimately should result in an increased number of positive restoration outcomes.

Specific information regarding the options for saltmarsh and sand dune restoration following pipeline and cable installation is set out in *Chapter 5*.

1.7 Aims and Objectives of this Thesis

The aim of this thesis is to answer questions regarding the success of vegetation restoration in saltmarsh and sand dunes affected by pipeline, cable or causeway construction. The question of restoration success is a long-standing one and has been widely studied, but specifically there is a lack of scientific evidence regarding post-construction vegetation recovery in coastal habitats. The need for this information is both practical and commercial with the continuing resource pressures on our coastline. Fundamental to this research is the unresolved question relating to the lack of an accepted definition of recovery. From this arise questions about which attributes of restored vegetation might best reflect recovery. With this information, more specific questions are considered such as what needs to be measured to detect recovery, how long does recovery take in different situations, and therefore how long does monitoring need to be continued. This leads on to questions regarding the trajectory of recovery if left to naturally regenerate; and what mitigation measures should be used to minimise impact and speed up recovery. Finally, questions regarding the need for habitat restoration are considered, when or if post-construction restoration is required and what are the triggers for requiring additional habitat creation and biodiversity offsetting.

The research questions introduced in the previous paragraph seem best addressed under five theme headings as summarised below:

- Theme 1 centres on defining attributes of vegetation recovery in terms of vegetation structure and function for both saltmarsh and sand dune habitats.
- Theme 2 focuses on the likely time frame for recovery.
- Theme 3 focuses on the likely outcomes of recovery.
- Theme 4 focuses on the methods required to minimise impacts during construction, and reviews the methods used for post-construction habitat restoration and enhancement.
- Theme 5 focuses on the methods used to detect and describe vegetation recovery. It considers whether the botanical survey methods in general use, can record vegetation change sufficiently well for the detection of recovery; and identifies those attributes that are best used to show vegetation change.

Details on the five themes are set out below, these (along with the hypotheses) have been developed from the literature review, available EIAs and observations during my consultancy experience.

1.7.1 Theme 1 - Defining Vegetation Recovery

Theme 1 centres on defining attributes of vegetation recovery in terms of vegetation structure and function for both saltmarsh and sand dune habitats. It considers which of these attributes best reflect vegetation change towards recovery.

The following characteristics or attributes of vegetation development are used to define and evaluate vegetation change, condition and recovery. These are based on commonly used attributes for monitoring vegetation condition such as those given in the Common Monitoring Standards (JNCC, 2004a, JNCC, 2004b) and widely recognised approaches in defining vegetation characters and strategies (Hill et al., 1999, Grime et al., 1988, Smith, 1913). Further details on the attributes and how they were used in subsequent analysis are given in *Chapter 2, Section 2.3*.

Attributes

- species frequency;
- vegetation composition *i.e.* percentage cover of individual species;
- combined cover of characteristic species defining vegetation zones or phytosociological groups *i.e.* NVC types;
- total cover of bare ground (either as a temporary or permanent feature) and conversely the total vegetation cover;
- mean sward height (in each quadrat);
- total cover of graminoids, herbs, algae or moss;

- the community weighted means of C-S-R plant strategies values (Grime et al., 1988), of Ellenberg values (*i.e.* light, moisture, pH, nitrogen and salinity) (Hill et al., 1999) and plant life cycle (*i.e.* perennial, annual, biennial) for each quadrat;
- presence of key desirable plant species (*i.e.* nationally rare or scarce plants, and species listed on the Vascular Plant England Red List);
- presence of undesirable plant species (*i.e.* invasive/ non-native);
- species diversity *i.e.* species-richness, evenness and dominance indices;
- extent and width of the total habitat resource *i.e.* saltmarsh or sand dunes and of the main constituent vegetation communities or vegetation zones;
- successional sequence *i.e.* following a unidirectional path *e.g.* embryo dunes through to fixed dunes or dune grasslands *etc.*; or a multidirectional path (where successional stages are skipped, arrested or reverted because of the impact) creating vegetation in local mosaics at various successional stages. An example of this is where secondary pioneer or lower marsh develops and is maintained in areas where mid-upper marsh would naturally occur; and
- presence of atypical vegetation communities.

The hypotheses for Theme 1 relating to saltmarsh habitats are set out in *Chapter 3*; and for sand dune habitats in *Chapter 4*.

1.7.2 Theme 2 – Time Frames for Vegetation Recovery

The second theme focuses on the time frames for vegetation recovery following construction. The installation of pipelines or cables across both saltmarsh and sand dune habitats is generally accepted as a temporary and reversible impact. However, the question of how long recovery takes following installation is currently not based on scientific evidence but from observations from EIA practitioners and statutory bodies from sites previously impacted. Therefore, continuing from Theme 1 and the attributes that best reflect recovery, the data from each site is divided into three arbitrary age classes (Short, Medium and Long-term[10]) depending on the time since impact. In addition, areas of vegetation expected to have remained undisturbed (*i.e.* beyond the construction area) are classified as Unaffected. It is expected that the greatest differences in the vegetation structure and function between On, Adjacent and Off sample areas will be identified during the Short-term, with these differences becoming less apparent by the Medium-term and eventually disappearing in the Long-term. It is also expected that the rate of recovery will also differ between vegetation zones.

[10] Short-term is defined here as 1-10 years, medium-term as 11-25 years and long-term 26-46 years.

The hypotheses for Theme 2 relate to saltmarsh habitats and are set out in *Chapter 3*; and for sand dune habitats in *Chapter 4*.

1.7.3 Theme 3 – Outcomes of Recovery

Following construction work on sensitive habitats such as saltmarshes or sand dunes there is a requirement under UK legislation (enforced by statutory nature conservation bodies) to return vegetation to its original condition as quickly as possible. The recovery of such sites is often difficult to predict due to a range of factors associated with both the existing site conditions and the level of impacts associated with the works. In addition, predicting successional trajectories in an environment which is subject to intrinsic dynamic disturbance events (such as storms) means there is some uncertainty in determining the outcome and time frames for vegetation recovery. Due to this complexity, there are likely to be multiple possible outcomes at each site and successional pathways may be multi-directional.

For this study four main vegetation recovery outcomes following construction are predicted in the On and possibly the Adjacent vegetation zones. This is described below:

1. recovery of vegetation in terms of species composition and vegetation condition results in vegetation being like the undisturbed vegetation. This is the minimum preferred outcome and is here called the “No Net Loss” scenario;
2. recovery of vegetation in terms of species composition and vegetation condition resulting in the recovering vegetation being different from the undisturbed vegetation despite which it is considered acceptable (*e.g.* vegetation recovery within the natural limits of the site such as a change in sub-community or community type). This is the “Acceptable Net Loss” scenario;
3. a change in species composition and vegetation condition resulting in the recovering vegetation being different from the undisturbed vegetation but more desirable (*e.g.* the development of species-rich dune slacks, or open bare ground habitat in dune systems). This benefit is referred to as a “Net Positive Impact” scenario; and
4. a change in species composition and vegetation condition results in vegetation developing into something different from the undisturbed vegetation which is considered an unacceptable outcome (*e.g.* following disturbance non-native or invasive species are established; or the creation of permanent areas of bare ground and pools because of changes to local topography). This is the “Unacceptable Net Loss” scenario.

The hypotheses for Theme 3 relate to saltmarsh habitats and are set out in *Chapter 3*; and for sand dune habitats in *Chapter 4*.

1.7.4 Theme 4 – Construction and Restoration

The fourth theme focuses on construction and restoration methods. Much of this centres on the mitigation hierarchy, a sequential process adopted to avoid, mitigate and compensate ecological impacts as set out in CIEEM (2016a). The mitigation hierarchy is a key principle for all pipeline/ cable installation projects aiming for No Net Loss or a Net Positive Impact scenario. The theme considers the methods needed to minimise impacts and where residual impacts remain, looks at options for habitat restoration. Decision triggers for intervention are also considered.

Much of this theme will be a review of published and grey literature determining pipeline/ cable installation methods as well as observations made at each site during my site visits. It will also draw on the information identified in Themes 1 to 3. The following research questions are considered.

- have the installation methods used at each site, influenced vegetation recovery?
- for historical sites, what was the original aim of site restoration *i.e.* landscape, biodiversity or flood protection *etc.*?
- if mitigation works (to minimise impacts) and habitat restoration, were taken what did these include and how were they complete?
- is vegetation recovery in sand dune habitats generally quicker and more successful than in saltmarsh habitats or vice versa? Are there any factors that influence the speed of recovery?
- can disturbance on saltmarsh or sand dune sites have a beneficial effect on vegetation composition and structure by mimicking natural disturbance events?
- what opportunities/ options are there for enhancement or habitat creation either on site or in the wider area?

Theme 4 is principally dealt with in *Chapter 5*, but also draws on information in *Chapters 3-4*.

1.7.5 Theme 5 - Methods to Detect and Describe Vegetation Recovery

Theme five focuses on future projects in coastal habitats and considers the assessment process. It identifies what attributes are best used prior to construction as part of the baseline assessment, and in subsequent years to detect, monitor and record vegetation recovery. This will draw on the information identified in the previous themes.

The following research questions are considered.

- what are the current survey methods used by consultants to describe the baseline vegetation prior to construction?
- are these survey methods sufficient to enable the detection of vegetation change from the baseline? And should a combination of survey methods be used?
- are there species or vegetation attributes identified in Theme 1 and 2 that can help define vegetation change in a more efficient way allowing for a focused survey effort?
- how long should post-construction monitoring be undertaken and how frequently?

Guidelines based on this theme are proposed in *Chapter 6* as a minimum standard for future botanical monitoring such as extent, duration and frequency.

SITES & METHODS

Chapter 2 Sites and Methods

2.1 Site Selection

2.1.1 Introduction

The focus of my PhD is coastal habitats, this is partially due to my experiences gained through my consultancy work as well as a personal interest. The final decision on which habitat types to include was based on my literature research, consultation exercise, and an understanding of the distribution of UK habitats.

From the outset, I decided to restrict my study to linear developments such as pipelines and cable installations. This was for two reasons; most linear developments only require temporary land take which allows subsequent habitat restoration; and secondly the effect on habitat condition following development can be analysed comparing affected areas with adjacent undisturbed areas within the same vegetation zone.

I also had to decide which coastal habitats to include. Initially I considered including coastal cliff and shingle however I found that there were few projects where landfall crossed these habitats. Coastal cliff provides significant engineering challenges, and so it is generally avoided, or where it is necessary, direct drilling methods are employed (*e.g.* the Langeled Pipe, Easington (Vercruysse and Fitzsimons, 2006)). In addition, there were also practical health and safety implications surveying cliff habitats. For shingle habitat, there were few suitable study locations, and where these were present *e.g.* at Sizewell Power Station restoration had been already been reported by Walmsley and Davy (1997); in addition a detailed description of shingle management and restoration has been documented by Doody and Randell (2003). Other cable projects identified *e.g.* Sheringham Shoal or London Array Offshore Wind Farms were routed to avoid shingle habitat or would only effect limited areas of vegetation.

In conclusion, I felt including only a very small number of coastal cliff or shingle sites would detract from the focus of my study and would provide limited information to add to the evidence base. In comparison saltmarsh and sand dune habitat are well distributed around the UK; and where they occur can form significant areas of natural and semi-natural habitats making their avoidance difficult.

2.1.2 *Desk-based Assessment*

The initial phase of the study focused on identifying potential sand dune and saltmarsh sites in the UK. This involved contacting a variety of organisations and individuals. Initially my approach was to contact the coastal habitat teams through the three main UK government nature conservation bodies *i.e.* Natural England, Natural Resources Wales and Scottish Natural Heritage. Through this initial contact, I approached regional teams and site managers to help identify potential sites. I also contacted environmental consultants through the CIEEM[11] and coastal groups on LinkedIn for their assistance. Through research on the internet I contacted environmental managers at oil, gas and renewables companies actively involved in installing and managing pipeline and cables. In total, I approached approximately 100 people for information, with contact data and an outline of responses compiled in a Microsoft Excel spreadsheet for future reference.

The list of suggested oil and gas pipeline or cable projects was then reviewed considering the available data. For each site, a data retrieval exercise was undertaken to obtain suitable baseline information, which could be used to evaluate vegetation change and recovery and to determine methods for construction and restoration. Much of this data is held as unpublished hard-copy reports (now in storage) and therefore data retrieval included visits to local offices and meetings to track down the relevant information. The availability of these archived reports became a key selection criterion for my potential study sites, and where information was not forthcoming the site was then excluded from my main study.

The following key documents and information was obtained to inform the site evaluation:

- The Ecology Chapter produced as part of the EIA, summarising baseline information on pre-construction habitats, vegetation condition and species diversity. It should provide information on the likely impacts (time and severity), mitigation strategy, and residual impacts (*i.e.* those which remain after mitigation).
- Pre- or post-construction botanical survey reports. The pre-construction report details survey methods, and provides a description of the baseline habitats and vegetation condition. The post-construction botanical report (required to satisfy planning) repeats the original survey and is undertaken on a regular basis for a specified time after the development.
- Construction documents produced by the developer detailing technical instructions regarding installation methods and potentially details of the post-construction vegetation

[11] Chartered Institute of Ecology and Environmental Management

reinstatement. Some of this information is included in the Ecology Chapter or in stand-alone Method Statements/construction plans.

I also contacted the local biological record centre covering each study site for plant species and for archived botanical reports. Vegetation surveys from before construction were sought along with surveys completed in intermediate years so that vegetation change could be assessed against the current study.

Other sources of site information included newspaper articles, published reports produced by nature conservation organisations and relevant databases such as the Marine Data Exchange[12], The Marine Case Management System[13] and the Online Marine Registry[14].

2.1.3 Sites

After reviewing the available data and completing a preliminary site visit (in 2014), thirteen construction projects were identified as the focus of my survey effort. These projects are in England and Wales and include eight saltmarsh projects, four sand dune projects and one project which crossed both habitat types.

The saltmarsh projects can be broadly grouped by location. The west coast sites at Walney Island *i.e.* South Morecambe, North Morecambe and River Fields were installed over a twenty-year period (1982, 1993 and 2003) and are situated in close proximity to each other (less than 1.5km distance between the sites). These pipelines provide a useful comparison of vegetation recovery over time as they all supported similar pre-construction vegetation, were surveyed by the same team of surveyors, and the pipelines were installed using a similar method (*i.e.* open-cut). The pipelines were subject to varying levels of post-construction restoration. The three south coast pipelines (at Poole Harbour in Dorset) were all installed in 1986 using open-cut construction methods but crossed different vegetation types with examples of upper, mid, lower and pioneer marsh. In contrast, the projects on the east coast all crossed species-poor saltmarshes with a limited upper and mid-marsh. These projects were subject to a range of construction methods (*i.e.* cable plough, open-cut and causeways), but were similar in that the vegetation was left to naturally regenerate.

The sand dune projects at Coatham Common, Redcar allow comparison over time, with two of the pipelines running adjacent to each other (installed in 1991 and 2011). The pipelines crossed similar vegetation encompassing a range of dune types. The construction and restoration methods used for these projects was similar. The pipeline installed at Talacre Warren in North

[12] http://www.marinedataexchange.co.uk/ (hosted by The Crown Estate)
[13] https://marinelicensing.marinemanagement.org.uk/mmofox5/fox/live/MMO_LOGIN/login (hosted by the Marine Management Organisation)
[14] http://www.omreg.net/ (hosted by ABPmer Ltd)

Wales, was installed in 1994, and followed the same construction and restoration methods as those at Coatham Common. A further benefit was that these three sand dune pipelines were surveyed by the same botanist.

A summary of the projects (case studies) used in this study are given in Table 1 below; with a full description provided in Appendix 2 Tables 4-14). A map showing the project locations is given in Figure 2.

Table 1 – Case study project details.

Project Name	Location	Habitat	Year of Installation	Survey Date	No. of Quadrats	
					Current	Historical[15]
Thanet Offshore Wind Farm (OWF)	Pegwell Bay, Kent	Saltmarsh	2010	Sept 2015	60	8
Rivers Fields pipeline	Walney Island, Barrow-in-Furness	Saltmarsh	2003	July 2016	63	64
North Morecambe pipeline	Walney Island, Barrow-in-Furness	Saltmarsh	1993	July 2016	76	50
South Morecambe pipeline	Walney Island, Barrow-in-Furness	Saltmarsh	1982	July 2016	71	0
Wytch Moor pipeline	Poole Harbour	Saltmarsh	1986	June 2015	40	0
Shotover Moor pipeline	Poole Harbour	Saltmarsh	1986	June 2015	25	0
Cleavel Point pipeline	Poole Harbour	Saltmarsh	1986	June 2015	35	0
Inner Trail Bank	The Wash, Norfolk	Saltmarsh	1972	Sept 2016	100	0
Tetney Sealine Pipe	Grimsby, Lincolnshire	Saltmarsh and sand dunes	1969	Aug–Sept 2016	111	0
Amoco CATS pipeline	Coatham Sands, Redcar	Sand dunes	1991	June 2016	66	0
Project Breagh pipeline	Coatham Sands, Redcar	Sand dunes	2011-2012	June 2016	60	124
Teesside OWF	Coatham Sands, Redcar	Sand dunes	2013	June 2016	20	0
Point of Ayr pipeline	Talacre Warren, Flintshire	Sand dunes	1994	June, Aug 2015; July 2016	137	151

Other Sites

The project also draws on the findings of other similar studies from the UK. For sand dunes this includes restoration work undertaken in north-east Scotland following oil pipeline installation between 1970 and 1990 at Morrich More (Dargie, 2001a) and at Cruden Bay, Shandwick and St. Fergus (Ritchie and Gimingham, 1989). For saltmarsh it includes reinstatement work following the installation of the Corrib Gas Onshore Pipe in County Mayo, Eire in 2013 (Neff, 2014); and the ongoing reinstatement work associated with offshore cable installation in The Wash at Lincs

[15] From various sources

Offshore Wind Farm (OWF) and Race Bank OWF undertaken between 2011 and 2016 which I have been directly involved with.

Information on restoration and habitat creation draws on dune work in Wales (*e.g.* at Kenfig, Newborough and Merthyr Mawr National Nature Reserves (Ludlow, 2015)); and in The Netherlands (*e.g.* Zuid-Kennemerland National Park/Natura 2000 site (Natuurmonumenten, 2015a), Voornes Duin, Duinen Goeree and Kwade Hoek (Natuurmonumenten, 2015b)) where large-scale dune restoration work has been undertaken to rejuvenate dune systems. For saltmarsh restoration and habitat creation examples will include the results and lessons learned from managed realignment/sediment recharge projects for example at Steart Marshes (McGrath and Jenkins, 2014), Nigg Bay (Elliott, 2015), Lymington Harbour (Lowe, 2013, Lowe, 2012) and Wallasea Island Wild Coast Project led by the RSPB.

Further information was obtained through the attendance of conferences on the creation and restoration of saltmarsh and sand dunes; including Native Seed Science, Technology and Conservation Initial Training Network (Kew, 2017), Littoral2017 (Liverpool, 2017), Using Dredge Sediments for Habitat Creation and Restoration (Southampton, 2016), Dynamic Dunes (Netherlands, 2015), and the CIEEM conferences on Linear Infrastructure and Biodiversity (Birmingham, 2016), Managing Change in Coastal Habitats (Bristol, 2015), and Progress in Effective Habitat Restoration, Translocation and Creation (Edinburgh, 2014).

Figure 2 – Map showing the project locations used as case studies for this thesis. The sites at Walney Island, The Wash, Thanet and Poole Harbour were saltmarsh sites; while those at Coatham Common and Talacre were sand dunes. Tetney Marshes supported both saltmarsh and sand dune habitats.

2.1.4 Survey Strategy

On completion of the desk-based exercise and preliminary site visits the survey strategy was reviewed. Initially, I proposed to repeat the original survey methods at each site to allow direct comparison between pre- and post-construction vegetation thus allowing a Before, After, Impact, Control analysis to be undertaken. However, after reviewing the available information it was clear that the survey methods and quality of the historical data varied significantly between sites. There were also differences in the survey method used between the pre- and post-construction stages. I therefore concluded that this approach would not allow comparison between sites or even comparison of an individual site over time. The main data issues are outlined below:

- no baseline assessment was taken of the actual pipeline/ cable route. This often came about after a late change in installation methods or a reroute was adopted after the baseline surveys had been completed;
- qualitative vegetation descriptions were frequently used to describe baseline conditions, and where species-lists were include, most gave no indication as to species abundance;
- quadrat sampling (when used) followed a variety of survey methods with some sites using quadrats along transects, others sampling vegetation across grids, while at others a random sampling strategy was used;
- the method of recording species abundance was inconsistent, with percentage cover, Domin-scale, frequency counts using sub-divided quadrats, or presence or absence;
- relocating the original vegetation samples was difficult or impossible as accurate grid references had not been recorded. Often there were references to features on the ground which had since been lost, or the information was not specific enough to determine the correct feature; and
- comparison between sites was difficult due to differences in the quadrat size used, density and number of quadrats, survey extent, survey season and surveyor capability in terms of species identification skills.

To overcome the disparity of the quality and level of detail of the historical surveys I amended my sampling strategy so that the study would focus on my survey data and only use the historical information as a reference where it was possible to do so. I therefore developed a single survey approach that could be replicated at either the saltmarsh or sand dune sites. Further details are given in *Section 2.2.3* but in summary it focused on undertaking random stratified quadrat sampling within vegetation compartments in three sample areas, On, Adjacent, and Off the impacted area.

2.2 *Survey Methods*

2.2.1 Introduction

Between 2015 and 2016 I undertook botanical surveys at thirteen study sites. In 2015 surveys were completed at Poole Harbour, Pegwell Bay and Talacre Warren, with the remaining sites at Redcar, Walney Island, Tetney Marshes and on The Wash surveyed in 2016.

2.2.2 Historical Surveys

To increase the quadrat data available for each vegetation type, historical quadrats were incorporated into the data set from available pre- and post-construction monitoring data. The post-construction monitoring data typically had been collected for up to five years documenting the initial vegetation recovery following construction. This data was initially reviewed for accuracy and relevance. Where sufficient geographic information was available to pin-point its location, it was entered into Microsoft Excel to allow a comparison with the current surveys.

Much of the historical data (especially for the sand dunes) had been collected as presence/ absence data and was therefore only suitable as a secondary binary dataset (*Section 2.4.3*). Plant names were standardised using Stace (2010) and the use of the V-Lookup tool allowed comparison between species-lists. Plant species lists were cross-referenced against the JNCC Excel spreadsheet - *Conservation Designations for UK Taxa.*

In addition, any available baseline mapping *e.g.* NVC habitat areas and locations of species-lists or quadrat data was entered into a GIS package known as QGIS (*Section 2.5.1*). Historical aerial photography and Ordnance Survey mapping was used to compare the spatial distribution of the vegetation communities, as well as changes in key features such as creeks or sea defences.

2.2.3 Quadrat Sampling

A random stratified sampling approach was used for the quadrat sampling. The pipeline/cable route was mapped using QGIS and three buffer zones created representing the sample areas of On, Adjacent and Off. Details regarding the three sample areas are given below:

- On sample area included the pipeline or cable trench and the working width. This was usually between 20-35m and was identified from historical survey reports or aerial photographs taken shortly after installation. This sample area is most affected by the construction with the complete loss of vegetation, vegetation damage, reworking of sediments, sediment compaction and changes to topography expected.
- Adjacent sample area was measured as a 25m wide buffer either side of the working width (*i.e.* On sample area). The vegetation here was expected to generally remain undisturbed

although some localised impacts may occur such as trampling caused by unauthorised access (these impacts are not regularly documented). Other changes in vegetation may come about as a result of damage in the On sample area.

- Off sample area was measured as a 25m wide buffer either side of the Adjacent sample area. This area is assumed to have been undisturbed by construction works and is therefore used as a control.

Initially, prior to field work the vegetation was mapped into broad habitat types using aerial photography and historical surveys in QGIS. These mapped vegetation areas were used to generate random points (using a random point generator), which were loaded on to a hand-held GPS unit[16]. Sufficient points were created so that those falling on boundaries or in atypical vegetation could be avoided. In the field, the vegetation boundaries were checked and refined following the NVC survey approach, *i.e.* with the vegetation mapped into homogenous stands. Each stand representing an NVC community or sub-community. Vegetation sampling was then taken within these boundaries at the pre-generated sampling points. Where additional quadrat sample points were taken in the field, for example in areas of habitat not identified in the desk-based exercise, these were selected as randomly as possible within the sample area.

The benefits of using a random sampling approach ensures all the main habitat types were sampled and characteristics of each stratum were measured allowing a comparison between them (Hill et al., 2005).

In addition to the three main sample areas (On, Adjacent and Off) quadrats were classified into the main vegetation zone as it was expected that zonation would be a key influencing factor on species composition (later supported by the ordination analysis *Section 2.4.3*).

An illustration showing the survey sample strategy used for the saltmarsh and sand dune survey areas is given in Figure 3.

For saltmarshes, samples were taken in driftline vegetation, mid-upper marsh, low-mid marsh, and pioneer marsh. These vegetation zones were defined using the terminology used in Common Standards Monitoring (CSM) guidance for saltmarsh (JNCC, 2004a). A table summarising the saltmarsh vegetation zones with their equivalent National Vegetation Classification types (found within the study sites) and European Union Habitat Directive types is given in Table 2.

---

[16] Garmin eTrex®10

Table 2 - Saltmarsh vegetation types with zone, equivalent National Vegetation Classification (NVC) type and European Union Habitats Directive Annex I habitat.

Zone (as defined by CSM) and used in this thesis	Equivalent NVC type (recorded in study sites)	Habitats Directive Annex I habitat (and code)
Driftline	SM24 *Elymus pycnanthus* salt-marsh community; SM28 *Elymus repens* salt-marsh community	Annex I types: Atlantic salt meadows (1330)
Mid-upper marsh	SM13 *Puccinellia maritima* salt-marsh community (sub-communities b,c,d); SM15 *Juncus maritimus-Triglochin maritimum* salt-marsh community; SM16 *Festuca rubra* salt-marsh community; SM18 *Juncus maritimus* salt-marsh community;	Annex I types: Atlantic salt meadows (1330) pp, Mediterranean and thermo-Atlantic halophilous scrubs (1420)
Low-mid marsh	SM10 Transitional low-marsh vegetation with *Puccinellia maritima*, annual *Salicornia* species and *Suaeda maritima;* SM13a *Puccinellia maritima* salt-marsh community, sub-community with *Puccinellia maritima* dominant; SM14 *Halimione portulacoides* salt-marsh community	Annex I types: Atlantic salt meadows (1330)
Pioneer marsh	SM6 *Spartina anglica* salt-marsh community; SM8 Annual *Salicornia* salt-marsh community; SM9 *Suaeda maritima* salt-marsh community; SM11 *Aster tripolium* var. *discoideus* salt-marsh community; SM12 Rayed *Aster tripolium* on salt-marshes	Annex I types: Salicornia and other annuals colonising mud and sand (1310), Spartina swards (1320)

For sand dunes, samples were taken in embryo dunes, mobile dunes, fixed dunes, dune slacks and dune grassland. These vegetation zones were defined using the terminology used in Common Standards Monitoring guidance for sand dunes (JNCC, 2004b). A table summarising the sand dune vegetation zones with their equivalent NVC types (found within the study sites) and EU Habitat Directive types is given in Table 3. Quadrat data for the embryo and mobile dunes were combined for analysis here as there was insufficient quadrats when considered individually.

Table 3 - Sand dune vegetation types with zone, equivalent National Vegetation Classification (NVC) type and European Union Habitats Directive Annex I habitat.

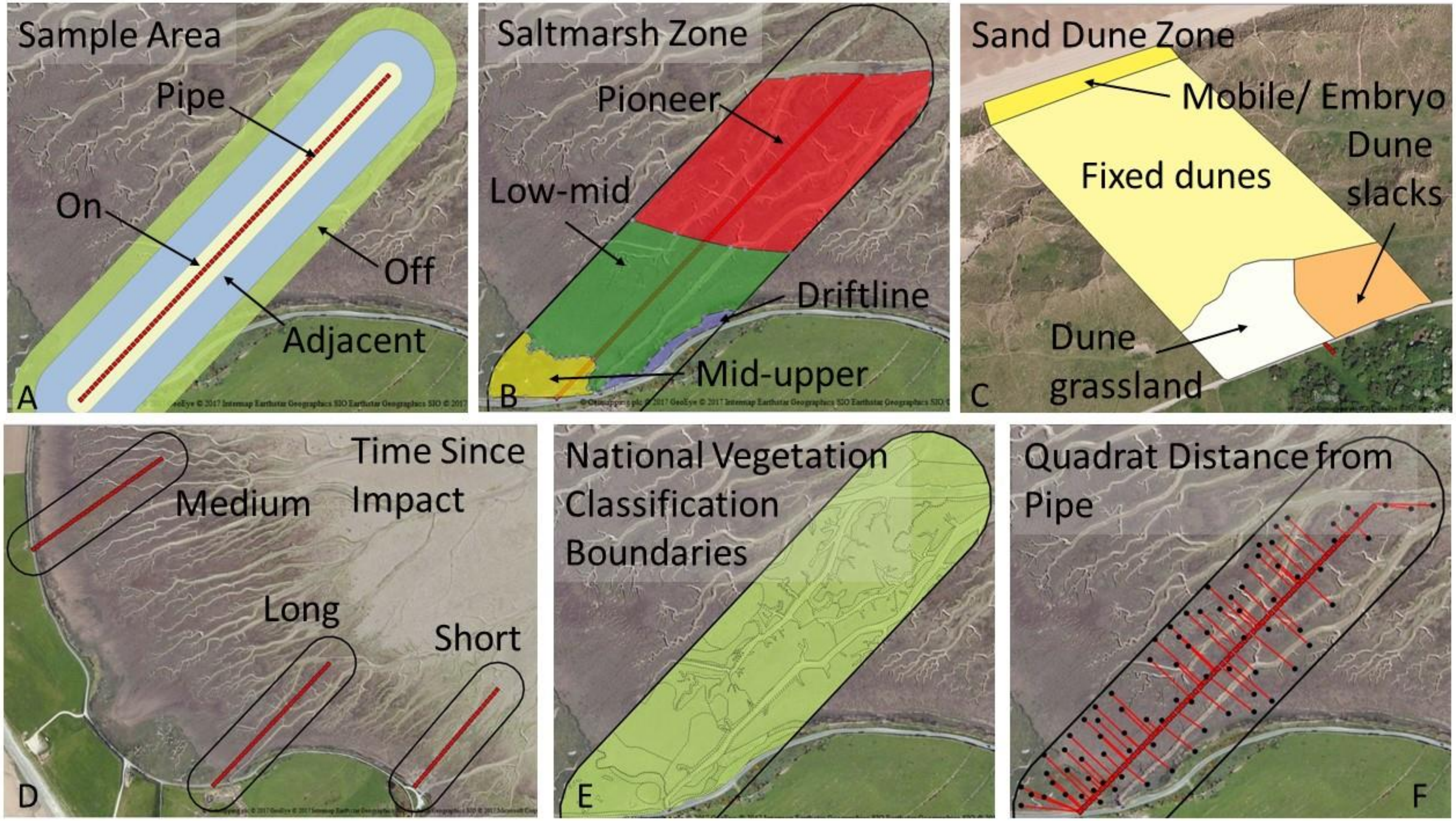
Zone (as defined by CSM) and used in this thesis	Equivalent NVC type (recorded in study sites)	Habitats Directive Annex I habitat (and code)
Embryo/ mobile dunes	SD4 *Elymus farctus* ssp. *boreali-atlanticus* foredune community; SD5 *Leymus arenarius* mobile dune community; SD6 *Ammophila arenaria* mobile dune community	Embryonic shifting dunes (H2110); Shifting dunes along the shoreline with *Ammophila arenaria* (H2120)
Fixed dune grassland	SD7 *Ammophila arenaria - Festuca rubra* semi-fixed dune community; SD8 *Festuca rubra - Galium verum* fixed dune grassland	Fixed dunes with herbaceous vegetation ('grey dunes') (H2130)
Dune grassland	SD9 *Ammophila arenaria-Arrhenatherum elatius* dune grassland; MG1 *Arrhenatherum elatius* grassland	Fixed dunes with herbaceous vegetation ('grey dunes') (H2130)
Dune slacks	SD13 *Sagina nodosa-Bryum pseudotriquetrum* dune-slack community, SD14 *Salix repens-Campylium stellatum* dune-slack community, SD15 *Salix repens-Calliergon cuspidatum* dune-slack community, SD16 *Salix repens-Holcus lanatus* dune-slack community, SD17 *Potentilla anserina-Carex nigra* dune-slack community, and the saltmarsh community SM20 *Eleocharis uniglumis* salt-marsh community	Humid dune slacks (H2190)

On site, a combination of survey methods was used. The first task completed at each site was a detailed habitat survey defining the vegetation into compartments based on the communities and sub-communities using the NVC survey approach (Rodwell, 2006). Habitat areas were identified by eye and mapped onto freely available aerial photographs. To aid this a hand-held GPS[17] was used. In each habitat area, a target-note and species-list (with Dafor[18]) was made detailing the vegetation structure and composition, and a reference photograph taken. The NVC survey covered both the affected pipeline/cable working width and a wider area which included undisturbed vegetation, generally extending for *c.*100m either side of the pipeline/cable. For saltmarsh sites, the survey included vegetation from the shore-line or sea defence to the limit of vegetation growth (unless health and safety reasons prevented access). For sand dune sites, surveys encompassed embryo dunes to dune grassland. For both saltmarsh and sand dune sites transitional or atypical habitats at the edge of the survey areas were recorded as part of the NVC survey but were generally not sampled using quadrats.

A standard 2m×2m quadrat was used for both saltmarsh and sand dune habitats. The number of quadrats used in each compartment depended on the complexity of the habitat and its area; although as a minimum five quadrats were taken so that data could be analysed into NVC types as required. The percentage cover of each species was recorded in the quadrat (estimated by eye) to provide an overall species frequency. By stratifying the sampling, separate estimates of frequency were made in each stratum. In addition to recording plant species the following additional attributes were recorded in each quadrat *i.e.* cover of vegetation, bare ground, plant litter, algae and moss. Average sward height was measured in nearest centimetres (excluding the flower head) taken from three points, (the bottom left-hand corner, centre and top right-hand corner). In addition, the maximum and minimum vegetation heights were recorded to provide the range. For reference a photograph of the quadrat was taken.

[17] Garmin eTrex®10
[18] DAFOR-scale – measure of abundance (Dominant, Abundant, Frequent, Occasional and Rare). In addition, I used the pre-fixes L for local and V for very

Figure 3 - Survey sample strategy used for quadrat analysis explaining: sample area - On, Adjacent, Off (A); vegetation zones for both the saltmarsh (B); and sand dunes (C); time since impact – Short-term (0-10 years); Medium-term (11-26 years) and Long-term (>26yrs) (D); vegetation boundaries using the National Vegetation Classification (E); quadrat distance from pipe (F)



I completed all the field work myself; but it is recognised that this can lead to observer bias (Hill et al., 2005, Morrison, 2016) in particular in assessing species abundances and in species identification errors. My previous survey experience in undertaking quadrat surveys in these habitats helped to minimise observer bias. In addition, to provide comparable assessments across the 13 project sites the following approach was followed;

- sufficient time was allocated for the quadrat sampling and where necessary *i.e.* at Talacre Warren, Pegwell Bay and Poole Harbour additional time was used to complete the surveys. On average 30 minutes per quadrat was allocated for sand dune quadrats and 20 minutes per quadrat for saltmarsh;
- surveys avoided poor weather *i.e.* heavy rain, cold, windy weather (which can affect concentration time and hinder species identification). In addition, survey days were limited to a maximum of 8 hours to reduce the effects of fatigue;
- surveys were taken at optimal survey periods for the likely species encountered *e.g.* sand dune sites were surveyed in early summer (May-July) and saltmarshes surveyed in late summer (July-September);
- cover was estimated based on experience and by reference to the visual interpretation threshold drawings given in Rodwell (2006);
- plant identification was completed in the field during the survey using field keys, both vegetative and non-vegetative material was identified. Where necessary a specimen, identification notes, quadrat details and photographs were taken to identify the species later. Most species identification was undertaken in the evening following collection, so that material was in optimal condition, and if required the species could be revisited in the field before leaving the site. Moss specimens were stored in labelled paper envelopes so that they could be identified at a later date with the use of a microscope. Uncertain species identifications were checked with an expert; and
- quadrat sample points were generated randomly prior to starting fieldwork (using the historical surveys and aerial photographs) and where extra quadrats were necessary these were plotted into QGIS each evening to ensure full coverage of the site.

2.2.4 Defining NVC communities

Quadrat data were collected from homogeneous stands with at least five quadrats recorded in each sampled vegetation type. This provides not only details of vegetation cover in each quadrat, but also enables frequency estimates for each species to be calculated (*e.g.* a species recorded in 3 quadrats out of 5 has a frequency of 60%). To aid the vegetation diagnosis the quadrat data was analysed using computer matching software MATCH v4 (Thomson, 2004). MATCH uses both the frequency and the maximum cover abundance of each species to generate a constancy value. This constancy value is compared with the constancy profile of communities published in the British Plant Communities (Rodwell, 2000, 1992, 1991) using the Czekanowski coefficient. MATCH provides a list of the ten most similar communities (and sub-communities). It should be noted that MATCH provides only an indication of the NVC type, and the highest coefficient does not necessarily indicate a correct NVC diagnosis especially when the coefficient values are very similar. It is always necessary to therefore refer to the full NVC descriptions given in the British Plant Communities.

2.2.5 Nomenclature and Species Standards

Throughout this report the following conventions have been used to ensure a consistent approach in naming species and referring to habitat types. Scientific names of vascular plants follow Stace (2010). Where the original report or case study refers to a binominal which has subsequently been replaced, the currently accepted name, has been used. For mosses and liverworts these follow Atherton et al. (2010). Although care was taken to record mosses and liverworts during quadrats surveys, it is unlikely that species-lists are comprehensive. Algae species were not routinely identified or differentiated as part of the study but included the macroalgae species *Enteromorpha* spp. *Fucus spiralis*, *Pelvetia canaliculate,* and *Ulva lactuca.* No attempt was made to identify the microalgae species.

For vegetation types, names of NVC communities and sub-communities follow Rodwell (2000). For these the full NVC name is give in the first instance and then abbreviated to the standard letter and numerical code for example SM13c *Puccinellia maritima* salt-marsh community, *Limonium vulgare-Armeria maritima* sub-community is given simply as SM13c. It should be noted that the community names used in the NVC volumes were based on plant authorities given in Flora Europaea (Tutin et al., 1964 et seq.) and therefore there are some discrepancies between the current accepted name and the NVC *e.g. Atriplex portulacoides* is given as *Halimione portulacoides*.

Plant designations are based on the JNCC Excel spreadsheet - *Conservation Designations for UK Taxa* (JNCC, 2016) which compiles species data associated with international and national conventions and directives. The list of invasive non-native plant species was obtained from the GB Non-native Species Secretariat.

A survey form for saltmarsh and sand dune sites was developed prior to the commencement of fieldwork, the form was designed for ease of use, to ensure data collection was standardised and for speed/ accuracy of subsequent data entry.

2.2.6 Access and Health and Safety

Prior to undertaking the surveys, much work was taken in obtaining site access from landowners and tenants unless the site had public access.

Due to the potential health and safety risks especially when working in saltmarsh environments, a detailed risk assessment was completed for each site. This document provided details on the site (including grid reference, a description of the site character, details of landowners, survey methods *etc*.), identified possible health, safety and environmental risks, provided details in case of an emergency and details of welfare arrangements.

Survey windows for each site were planned against the tide times. At some sites *e.g.* those with important breeding bird populations, surveys had to fall outside the breeding bird period, (1st March until 31st July) to minimise disturbance.

For the survey work on Walney Island, I was assisted by three members of Cumbria Wildlife Trust Marine Trainee scheme, their assistance was greatly appreciated, as parts of the Walney Island sites would have been otherwise inaccessible.

2.3 Data Entry and Descriptive Analysis

Following the completion of each survey, the data were entered into Microsoft Excel using a standardised worksheet. Quadrat data from each site was initially entered separately but was then subsequently combined to produce a saltmarsh dataset and a sand dune dataset. Along with species cover data the following information was compiled for each quadrat and site;

- distance from pipe/cable (*Section 2.5.2*);
- quadrats were allocated to the appropriate sample area depending on their distance from the pipeline/ cable (*i.e.* On, Adjacent or Off);
- quadrats were allocated to the appropriate vegetation zone (*i.e.* pioneer, low-mid marsh, mid-upper marsh and driftline for saltmarsh and embryo and mobile dunes, fixed dunes, dune grassland and dune slacks, for sand dunes);
- average sward height (based on the three swards heights in the quadrat);
- total number of species per quadrat;
- measures of biodiversity *i.e.* Simpsons Diversity Index, Shannon Diversity Index, Shannon Evenness Index, Margalef Diversity Index, and Berger-Parker Dominance Index (Magurran and McGill, 2011);

- counts of the number of plant species listed as Nationally Rare[19] (Wiggington, 1999) or Nationally Scarce[20] (Stewart et al., 1994) complied in the JNCC Conservation Designations Spreadsheet (JNCC, 2016) and plant species listed on the Vascular Plant England Red List (as Critically Endangered, Vulnerable, Endangered and Near Threatened) (Stroh et al., 2014);
- Ellenberg values for light, moisture, pH, nitrogen and salinity were calculated for each quadrat using the published reference data for UK species (Hill et al., 1999). Weighted cover values for each quadrat were computed using an open source tool designed to work in Microsoft Excel known as Vegetation Trend Analysis (VTA) (Hancock, 2016);
- C-S-R plant strategies values were determined for each species using a dichotomous key (Figure 3.2 Page 28 Grime et al. (1988)), and Frank and Klotz (1990). Weighted cover values for each quadrat were calculated using VTA (Hancock, 2016); and
- a community weighted mean using the plant life cycle (*i.e.* perennial, annual, biennial) was calculated for each quadrat.

On completion of the data entry, pivot tables and descriptive statistics were used to summarise the attribute data. Simple box plots showing quantitative values for the range (minimum and maximum), first and third quartiles, median, and outliers were produced for key species. Where appropriate the box plots were produced for the entire saltmarsh/ sand dune dataset *i.e.* to show differences in the species numbers across the vegetation zones, amount of bare ground, mean sward height, biodiversity indices and the community weighted means for Ellenberg, C-S-R plant strategies and plant life cycle. In addition, key individual species typical of each vegetation zone were plotted using the categorical groups for sample area - On, Adjacent and Off; and time since impact categories– Short, Medium and Long-term with undisturbed areas classified as Unaffected.

Data analysis regarding rare and scarce species and non-native or invasive species was limited due to the scarcity of records in the dataset and therefore they could only be described for each vegetation zone.

[19] Rare – found in not more than 15 different 10×10km grid-squares in the British Isles since 1987
[20] Scarce - found in not more than 100 different 10×10km grid-squares in the British Isles since 1987

2.4 Data Analysis

2.4.1 Data Transformation

Prior to analysis, the species percentage cover data needed to be transformed to allow parametric testing, to achieve a "normalised distribution", reduce skew and to stabilise variance.

I reviewed the most appropriate transformation method for percentage cover data. This included using an arcsine square root transformation, which would take account for the constrained, asymmetrical nature of the percentage values (*i.e.* cover values are constrained to between 0-100%, with many species having a zero value) (Grafen and Halls, 2002). This transformation is given by the formula:

$$= \frac{180}{\pi} \sin^{-1}\left(\sqrt{\frac{y}{100}}\right)$$

Where y is the attribute *i.e.* percentage cover.

However, the arcsine transformation makes comprehending the resulting data more complicated and therefore requires back transformation.

After, consultation with a statistical advisor from the University of Reading Statistical Services Centre the use of an empirical logit transformation was suggested. This transformation is given by the formula:

$$\log\left(\frac{(y+1)}{100-(y-1)}\right)$$

Where y is the attribute *i.e.* percentage cover.

Warton and Hui (2011) set out the argument regarding the benefits of using a logit transformation over arcsine square root transformation. However, for my data this transformation model was not used as many of the transformed values became negative; and where cover was over 100% *i.e.* for total vegetation cover the empirical logit transformation returned an error.

The use of log base transformations for species abundance data is set out in Magurran (2004). It suggests the use of $\log_2$, $\log_3$ or $\log_{10}$ depending on the scale of the abundance of the species recorded. However, a log base transformation of zero (which is frequently recorded in vegetation quadrat data) returns an error.

To overcome these problems, a simple transformation of all percentage data was possible using log(y+1). The benefit of using this transformation for the statistical analysis is that CANOCO 5 (the software used for the multivariate analysis) automatically transforms percentage cover data using this formula, and therefore both the analysis completed in Minitab and CANOCO used the same approach.

2.4.2 Minitab

The statistic programme Minitab® version 17.2.1 was used for analysis. Initially basic descriptive statistics were used for each attribute or species to summarise the data in each zone. Where the means appeared to differ, One-way Analysis of Variance, was completed. In addition, a simple linear regression was undertaken using the distance of the quadrat from the pipeline/ cable with the attribute or species.

Further analysis was completed using a General Linear Model which considered the response *i.e.* attribute or species, with the sample area as a factor and distance of the quadrat from the cable/ pipe as a covariate. This was followed by undertaking a Tukey Pairwise Comparison test to determine the 95% Confidence Intervals of the means between factors. A further GLM was used combining the above with the addition of age class as a further factor. For the GLM, I analysed 679 saltmarsh quadrats and 758 sand dune quadrats.

2.4.3 Multivariate Analysis

CANOCO 5 (Smilauer and Leps, 2014) was used to undertake multivariate analysis. The software is specifically designed for analysing complex community data and combines unconstrained and constrained ordination methods with variation partitioning and the use of permutation tests to allow testing of statistical hypothesises. One of the main uses of the software is in identifying community pattern and correlating this to environmental variables or species traits.

The saltmarsh data comprised 679 quadrats with 43 species and species abundances given as percentages. For the sand dune data, two datasets were used; one based on data collected during my surveys (comprising 758 quadrats with 217 species and species abundances given as percentages); while the other, included past quadrat data (collected for around five years after construction). Species cover collected in the past surveys typically used presence/ absence data, or Domin values[21] rather than percentage covers. This larger dataset contained 1175 quadrats and 264 species. The use of the larger dataset was necessary to increase the quadrat data available for each vegetation zone, particularly for the Short-term. For the sand dune analysis, both the larger binomial dataset and the smaller percentage cover datasets were analysed in CANOCO, although only the results of the larger dataset are presented in *Chapter 4*.

After the data was imported into the software from Excel, an initial unconstrained analysis was taken. This analysis summarises patterns of species composition variation across quadrats.

[21] Measure of species abundance widely used in the NVC survey methods

Species are shown as a triangle labelled using six letter codes. Those species shown in close proximity in the plot correspond to species often occurring together. The resulting output provides the total variation explained by the data, an adjusted percentage (a more conservative percentage based on the sample size), the contribution of each of the ordination axes and the axis gradient length.

To determine whether a linear or unimodal ordination model is used, CANOCO 5 measures the length of the ordination axes. Where the length of the longest (gradient) axis is over 3.7SD units a unimodal method is recommended. For both the sand dune and saltmarsh datasets the length of axis 1 was greater than 3.7SD so a unimodal ordination was appropriate. Detrended Correspondence Analysis (DCA) was used for the unconstrained ordination and Canonical Correspondence Analysis (CCA) for constrained ordination.

The unconstrained analysis was repeated to include supplementary environmental variables. The resulting plot shows species; numerical environmental variables as an arrow (with the arrow pointing in the approximate direction of its steepest increase in value); and symbols to show the classes of the factorial variables (with those species in close proximity a symbol showing a relative preference towards that individual environmental variable class).

Constrained ordination (CCA) of all data, tested the significance of environmental explanatory variables, in explaining the variation in the sand dune and saltmarsh vegetation community compositions respectively. The interactive forward selection procedure was used, to choose the subset of explanatory variables that had significant conditional effects. To limit the frequency of false discoveries in terms of identifying non-significant explanatory variables, the False Discovery Rate feature was used.

The constrained ordination axis corresponds to the directions of the greatest data set variability that can be explained by the environmental variables. The result of the constrained ordination is a percentage of variation explained by the model, an adjusted percentage (based on the sample size) and the contribution of each of the ordination axes. The significance of the model was based on 4999 unrestricted Monte-Carlo permutations.

For the unimodal ordinations, rare species (with a low total abundance) were down-weighted within the CANOCO programme.

The interactive effect of two explanatory variables (sample area and duration since the impact) was also considered, using a constrained ordination model.

In both sand dune and saltmarsh habitats, vegetation zonation was expected to explain a significant amount of the variation in species composition. To test this, an initial analysis of the whole saltmarsh and sand dune datasets using CCA and interactive forward selection was used.

It showed that vegetation zonation had the greatest explanatory effect of the environmental variables tested. Zonation was therefore used as a group, in the subsequent analysis, allowing quadrats from each zone to be tested independently.

The use of published Ellenberg values for Light, Moisture, pH, Nitrogen requirement, and salinity (as cumulative weighted means) was also used to further explain the variation in the CCA analysis.

The number of species shown in the graphical outputs in CANOCO were generally limited to between 30 and 40 species, to aid interpretation. CANOCO selects plant species for inclusion based on best predicted fit.

Species Response Curves, showing key species within each vegetation zone against Years and Log Distance from Pipe, were also produced.

Species diversity diagrams using CCA were also produced, these show species number, with environmental variable axis and classes of the factorial variables. For the low-mid marsh, initially the species diversity diagram was based on a CCA plot but the resulting graph showed characters of the 'arch effect' (ter Braak and Smilauer, 2012, Smilauer and Leps, 2014). The arch effect indicates that two or more explanatory variables are strongly correlated with each other. Attempts to minimise the arch effect by removing the correlated explanatory variable (based on forward selection) did not produce satisfactory results, so the CCA process was repeated using a detrending procedure and a 2nd order polynomial (DCCA).

2.5 Geographical Information System

2.5.1 Historical Data

QGIS[22], a free, open source Geographical Information System, was used to display and analyse the historical pre-construction baseline data as well as any intermediate data sets available. For each site, the historical reports were reviewed for suitable information for inclusion in the GIS. This included quadrat data where accurate Ordnance Survey grid references were given or reports where habitat features were mapped with sufficient clarity that these could be located and digitised. For each site, the following was compiled:

- base mapping (MasterMap) and historical 1st Edition OS maps were obtained through the Edina Digimap service. Recent aerial photographs were obtained from Bing Maps or Google Maps through the QGIS Open Layers Plugin, depending on the age, coverage and quality of the image;

[22] version 2.12.2

- digital boundary datasets showing statutory designated sites were downloaded from Natural England, Natural Resources Wales and the Joint Nature Conservation Committee through the Ordnance Survey Open Government Licence and Open Government Licence;
- the pipeline/cable route was identified from the Environmental Statement or baseline reports. This was digitised as a line shapefile. Associated work areas were digitised as polygon shapefiles;
- the pipeline/cable route was used to generate a buffer zone of equivalent width to the work corridor (*i.e.* working width). This therefore generated the On sample area. In some cases, (*e.g.* Project Breagh and Rivers Fields) freely-available aerial photographs clearly showed the actual working area and therefore this was used as the On sample area. Two further buffers were created from the working width to create the Adjacent and Off sample areas;
- where the historical reports included paper copy maps, these were scanned, and the resulting raster image was calibrated against known fixed locations shown on recent mapping/aerial images producing a rectified image. The calibration of the image depended on the original image resolution, extent, and orientation. Information shown in the rectified image was then digitised, and associated attribute tables populated;
- data with grid references or latitude/longitude information were standardised to use the British National Grid using a Batch Convertor Tool[23], these points were plotted, and associated attribute tables populated;
- NVC survey data or other historical surveys showing habitat boundaries were digitised. Associated data tables with information on NVC code, surveyor, survey date and habitat extent were populated; and
- in some cases, *e.g.* Tetney Marshes, the recent NVC habitat survey was provided by Natural England as a GIS dataset and this was directly inputted into the work package for subsequent analysis.

2.5.2 Current Surveys

Prior to starting field work the most recent aerial photographs and base mapping were obtained and reviewed. The pipeline/ cable route shapefiles and the associated buffers were used to define the survey area. In both saltmarsh and sand dune systems, the main habitat areas were digitised using differences in texture and colour of the vegetation to create polygons. These habitat polygons were used to generate random quadrats (*Vector – Research Tools – Random Points*). The quadrat locations were uploaded onto a handheld GPS unit, and it was used to relocate quadrats in the field. Where additional quadrats were required, or the location of pre-populated quadrats

[23] http://gridreferencefinder.com/batchConvert/batchConvert.php

were altered due to features on the ground, these were plotted, each evening, to ensure an even spread of quadrats across each vegetation zone and sample area.

To calculate the distance from each quadrat to the pipeline/ cable route (*i.e.* the distance from the impact) the pipeline/ cable line was converted to a series of points using a GIS Plugin tool (*Locate Points Along Lines*). Using the MMQGIS tool (*Create - Hub Distance*) the shortest distance between the quadrat point and the pipeline/cable points was generated as a line. By updating the attribute table (*Field Calculator – Update Existing Column Distance – Geometry- $Length*) the length of the line could be calculated in metres.

Buffers were used to assign the quadrats to the three sample areas, On, Adjacent and Off.

Following completion of the fieldwork, habitat areas (using NVC codes) were mapped, along the pipeline/ cable and associated tables populated with habitat type, surveyor and survey date. Habitat areas were calculated within a 100m wide buffer using a geoprocessing tool to clip the habitat area to the extent of the buffer. The field calculator tool within the attribute table (*Field Calculator – Geometry - $Area*) could be used to calculate the area as square metres.

Other features were also digitised as appropriate, for example areas of bare sand or mud, standing water and creeks.

The spatial data allows changes over time to be visually assessed.

SALTMARSH

Chapter 3 Saltmarsh Vegetation Recovery

3.1 Introduction

As discussed in *Section 1.6* the concept of post-construction ecological restoration following the degradation of habitats has been around since the 1980s (Bradshaw, 1983, Bradshaw and Chadwick, 1980); although it has arguably been in practice for centuries (Martin, 2017). The term 'ecological restoration' first appeared in print[24] in a 1984 article in *Restoration and Management Notes* ((Martin, 2017). However, it was not commonly used until the Society of Ecological Restoration was formed in 1988.

Specifically, with regard to saltmarsh, many of the concepts behind recovery and success criteria, have come about from the restoration of damaged sites and the creation of new saltmarsh as part of managed realignment schemes (Bakker et al., 2002, Boorman, 2003, Brooks et al., 2015, Crooks et al., 2002, French, 2006, Garbutt and Wolters, 2008, Mossman et al., 2012b, Van Loon-Steensma et al., 2015). They particularly focus on the likely direction of succession, factors influencing vegetation establishment and time frames for recovery.

There are also studies on disturbance episodes on saltmarsh (whether anthropogenic or natural) which help build up a picture of post-disturbance recovery (Adnitt et al., 2007, Allison, 1995, Álvarez-Rogel et al., 2007, Beeftink, 1977, De Leeuw et al., 1992).

However, there are few examples directly applicable to pipeline or cable installation and its effect on saltmarsh habitat, although it is widely recognised as having a damaging effect causing physical disturbance (BERR, 2008, Boorman, 2003, Brooke et al., 1999, Dargie, 2001a, Dargie, 1988, Gray, 1986, Knott et al., 1997, John et al., 2015, Zedler and Adam, 2002). Interestingly, saltmarshes are perceived to be easily restored. Doody (2007) notes that saltmarshes provide added-value in "providing pipeline landfall sites; the close proximity to the sea, ease of digging and relative remoteness makes them ideal for burying pipes. Restoration is also relatively easy". The following sections aim to provide evidence regarding this statement so that informed decision-making by practitioners can be applied to future projects.

---

[24] Although it may have been used earlier

3.2 *Hypotheses*

3.2.1 *Introduction*

This chapter focuses on vegetation recovery of saltmarsh habitats following temporary development (*i.e.* pipeline, cable or causeway installation). The use of the term pipeline in this chapter and subsequently, refers to all temporary developments, unless specifically stated. The hypotheses all relate to the period following construction, and to effects that will become less marked or disappear over time. It provides evidence with regards to Themes 1-3 identified in *Sections 1.6-1.9.* These are:

- Theme 1 centres on defining attributes of vegetation recovery in terms of vegetation structure and function for saltmarsh habitats.
- Theme 2 focuses on the likely time frame for recovery.
- Theme 3 focuses on the likely outcomes of recovery.

The hypotheses are sub-divided by pre-construction vegetation zone *i.e.* driftline, mid-upper marsh, low-mid marsh and pioneer marsh (as shown in Figure 4 and Photo Plate 1). Photos of some the characteristic species are shown in Photo Plate 2. These zones are based on the definitions set out in the Common Standard Monitoring Guidelines for Saltmarsh (JNCC, 2004a). Details on the statistical analysis methods used are provided in *Section 2.4*.

3.2.2 *General Hypotheses*

In saltmarsh disturbance caused by the installation of cables and pipelines is likely to result in the following outcomes:

- A loss of species diversity resulting in the disturbed areas supporting fewer species;
- A loss in specific plant species that are intolerant to disturbance/ physical damage, and inversely an increase in those that are more competitive/ or ruderal in nature;
- A change in vegetation composition. In saltmarsh it is expected that there will be increase in early successional communities *i.e.* pioneer or lower marsh which develops as a secondary habitat, and inversely a loss in mid to upper marsh and driftline vegetation;
- An increase in bare ground and open habitats; and
- Time frames for recovery will be dependent on the vegetation zone, the main vegetation communities and the degree of damage from construction, but it is likely to be in the Medium to Long-term before the species composition and structure is similar to the Unaffected vegetation.

3.2.3 Driftline

1. Following construction, the cover of *Elytrigia atherica* in the On sample area will be less than in the Off sample area. Its cover will increase rapidly therefore, the greatest difference in cover of this species will be between areas impacted in the Short-term (where there will be less) compared to Unaffected areas.
2. Following construction, as a result of disturbance the cover of annual or ruderal species such as *Atriplex littoralis, Atriplex prostrata* and *Cochlearia officinalis* will be higher in the On sample area compared to the Off sample area. Also, the greatest difference in cover will be between areas impacted in the Short-term compared to Unaffected areas.
3. Cover of typical lower-marsh species such as *Aster tripolium* and *Puccinellia maritima* will increase On the pipeline in the Short-term. In Medium-Long-term cover of these species will return to pre-construction levels.
4. Following pipeline installation, the invasive grass *Spartina anglica* (not typically found in the driftline zone) will increase in cover in the On sample area.
5. Following pipeline installation there will be an increase in cover of bare ground (and inversely a decrease in vegetation cover) in the On sample area compared to the Off area.
6. It is expected that there will be an increase in species-richness On the pipeline compared to Off, at least in the Short-term, compared to Unaffected areas where *Elytrigia atherica* is dominant.
7. The extent (ha) of driftline habitats following construction, will fall in the Short-term, but in the Long-term will reach pre-construction extents. Where local elevation is increased *i.e.* along the pipe or causeway the extent of this vegetation type may expand.
8. In the driftline zone, where impacts are minor (*i.e.* no change in topography or severe compaction) the vegetation could recover quickly *i.e.* in the Short-term (*i.e.* 1-10 years). Areas subject to heavy disturbance are likely however to support pioneer vegetation in the Short-term. In the Long-term driftline vegetation will fully recover.

3.2.4 Mid-upper Marsh

9. In the mid-upper marsh following construction rapid growth by grasses *e.g. Agrostis stolonifera*, *Festuca rubra* and *Puccinellia maritima* will result in higher cover in the On sample area compared to the Off area and over time between the Short-term and Unaffected vegetation.
10. In contrast, it is expected that slower growing graminoids such as *Bolboschoenus maritimus, Juncus gerardii* and *Juncus maritimus* will have a lower cover in the On sample area compared to the Off sample area, and that over time these species will increase in cover.

11. Characteristic herb species of the mid-upper marsh such as *Armeria maritima, Glaux maritima*, *Limonium vulgare*, *Plantago maritima* and *Triglochin maritimum* will have lower cover in the On sample area compared to the Off sample area. As perennials, they are likely to take longer to re-establish in the disturbed area and may not be recorded until the Medium or Long-term.
12. Cover of early successional species such as *Aster tripolium* and *Salicornia* agg. will be higher On the pipeline compared to Off, and in the Short-term compared to Unaffected vegetation.
13. Following pipeline installation, the invasive grass *Spartina anglica* (not typically found in the mid-upper marsh) will occur at higher abundance in the On sample area.
14. Following pipeline installation there will be an increase in cover of bare ground (and inversely a decrease in vegetation cover) in the On sample area compared to the Off area, at least in the Short-term.
15. Where the mid-upper marsh is impacted by pipeline construction, species-richness will be lower than in the Unaffected or Long-term vegetation.
16. The extent (ha) of mid-upper marsh habitats following construction, will fall in the Short-term but in the Medium-term will show recovery to pre-construction extents.
17. In the mid-upper marsh, in the Short-term there will be an increase in early successional communities *i.e.* pioneer marsh or low-mid marsh. Vegetation recovery will occur in the Medium to Long-term (11-50 years).

3.2.5 Low-mid Marsh

18. As *Atriplex portulacoides* is intolerant of physical damage this species will have a lower cover in the On sample area compared to the Off sample area. It is expected that it will re-establish itself slowly, with lower cover in the Short-term. In the most disturbed areas, it may not recover until the Medium-term.
19. In the Short-term there will be higher cover of *Salicornia* agg. On the pipeline. Over time *Salicornia* agg. will show a reduction in cover and there will be a significant difference in cover between the Short-term and Unaffected areas.
20. Following construction, the cover of other characteristic species of this zone *i.e. Aster tripolium, Puccinellia maritima* and *Suaeda maritima* will quickly re-establish, although cover On the pipe is expected to be lower than the Off area at least in the Short-term.
21. Following pipeline installation, the invasive grass *Spartina anglica* will increase in cover in the On sample area compared to the Off area.
22. The cover of bare ground and Algae in the low-mid marsh will be higher On the pipeline compared to Off.

23. Where the low-mid marsh is impacted On the pipeline, species-richness will be lower than in the Unaffected or Long-term vegetation.
24. The extent (ha) of low-mid marsh habitats following construction, will fall in the Short-term but in the Medium-term will show recovery to pre-construction extents. In addition, locally there may be increases in low-mid marsh where it replaces other vegetation types.
25. In the low-mid marsh, in the Short-term there will be increase in secondary pioneer marsh with vegetation recovery expected in the Medium-term (11-25 years).

3.2.6 Pioneer Zone

26. In the pioneer zone following construction, bare ground will initially be colonised by Algae spp., and *Salicornia* agg. It is expected that the cover of *Salicornia* agg., will continue to increase over time from the Short to Long-term, whilst Algae cover will decrease.
27. Following pipeline installation, the invasive grass *Spartina anglica* will have higher cover in the On sample area compared to the Off area. Cover will increase over time, so that the Short-term is likely to have lower cover than the Unaffected vegetation.
28. Bare ground cover On the pipeline will be higher than Off of it.
29. Where the pioneer marsh is impacted On the pipeline, species-richness will be lower than the Unaffected or Long-term vegetation.
30. The extent (ha) of pioneer marsh habitats following construction, will increase in the Short-term, but over time (by the Long-term) it will be similar or less than the pre-construction area.
31. Pioneer marsh will increase following construction with the development of secondary pioneer marsh, at least in the Short-term. Pioneer marsh will be retained at the outer reaches of the saltmarsh (even if the overall vegetation cover is reduced); but will also likely to develop in other zones where disturbance creates areas of bare ground. Vegetation recovery is expected in the Medium-term (11-25 years).

3.2.7 Creeks, Bare Ground and Saltpans

32. Following pipeline installation there will be a Short-term loss of creeks, however over time (by the Medium- to Long-term) natural process will create new creek systems.
33. It is expected that new pools and areas of bare ground will develop along the pipeline in the Short-term due to vegetation loss, impeded drainage and low creek densities. Over time it is expected that these will become infilled with sediment and consequently vegetation will be able to establish.
34. In the mid-upper marsh, it is expected that new saltpans will develop (where sediments become hypersaline), limiting plant growth. These features may become permanent saltmarsh features.

Figure 4 – An illustration showing the key saltmarsh vegetation zones (JNCC, 2004a) and National Vegetation Classification communities (Rodwell, 2000) from the sea defence (top) to the mudflats (bottom) as recorded at my case study sites. Driftline vegetation types SM24 *Elymus pycnanthus* salt-marsh community. **Mid-upper marsh vegetation types** SM13c *Puccinellia maritima* salt-marsh, *Limonium vulgare*-*Armeria maritima* sub-community and SM13d *Plantago maritima*-*Armeria maritima* sub-community; SM16 *Festuca rubra* salt-marsh community; SM18 *Juncus maritimus* salt-marsh community. **Low-mid marsh vegetation types** SM13a *Puccinellia maritima* salt-marsh community, sub-community with *Puccinellia maritima* dominant, SM14a *Halimione portulacoides* salt-marsh community, sub-community with *Halimione portulacoides* dominant and SM14c *Puccinellia maritima* sub-community; SM10 Transitional low-marsh vegetation with *Puccinellia maritima*, annual *Salicornia* species and *Suaeda maritima*. **Pioneer marsh vegetation types** SM11 *Aster tripolium* var. *discoideus* salt-marsh community, SM9 *Suaeda maritima* salt-marsh community, SM8 Annual *Salicornia* salt-marsh community, and SM6 *Spartina anglica* salt-marsh community.

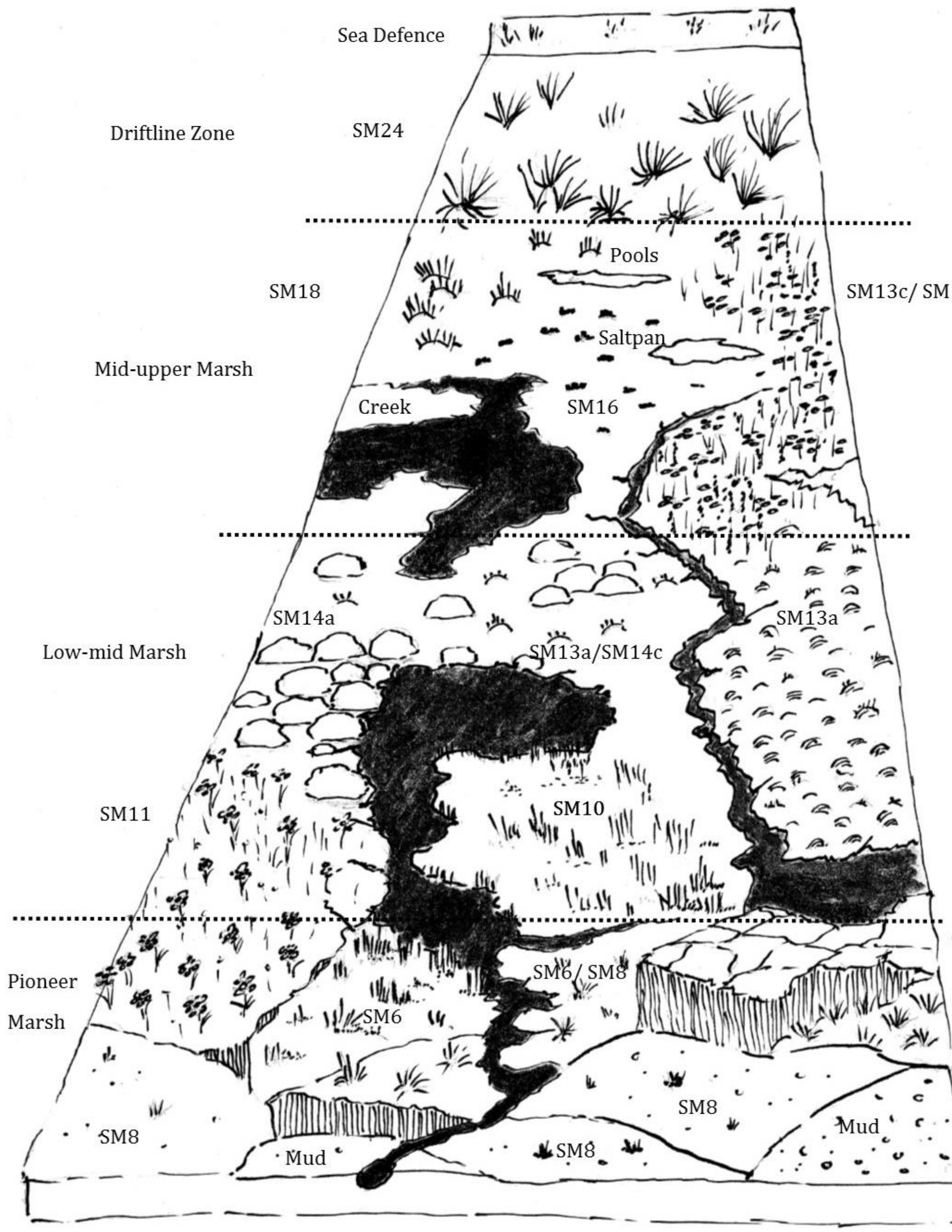


Photo Plate 1 – Examples of saltmarsh vegetation zones taken at case study sites

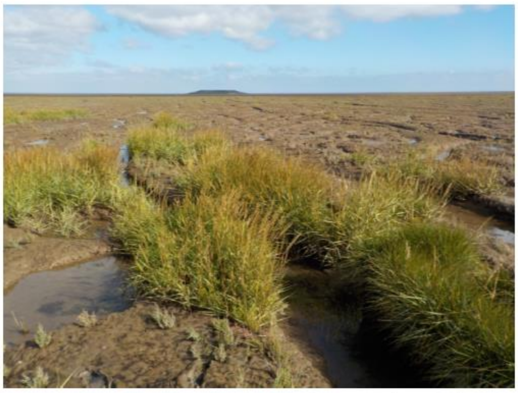
Photo taken at Inner Trial Bank showing the driftline and low-mid marsh.

Photo of driftline vegetation (dominated by *Elytrigia atherica*) with raised section of pipeline at Tetney Marshes.

Mid-upper marsh showing *Limonium vulgare* , at South Morecambe.

Low-mid marsh with *Atriplex portulacoides, Puccinellia maritima* at North Morecambe.

Low-mid marsh with *Aster tripolium* at Inner Trial Bank.



Pioneer marsh with *Spartina anglica* on The Wash.

Pioneer marsh with scattered *Salicornia* agg. on The Wash.

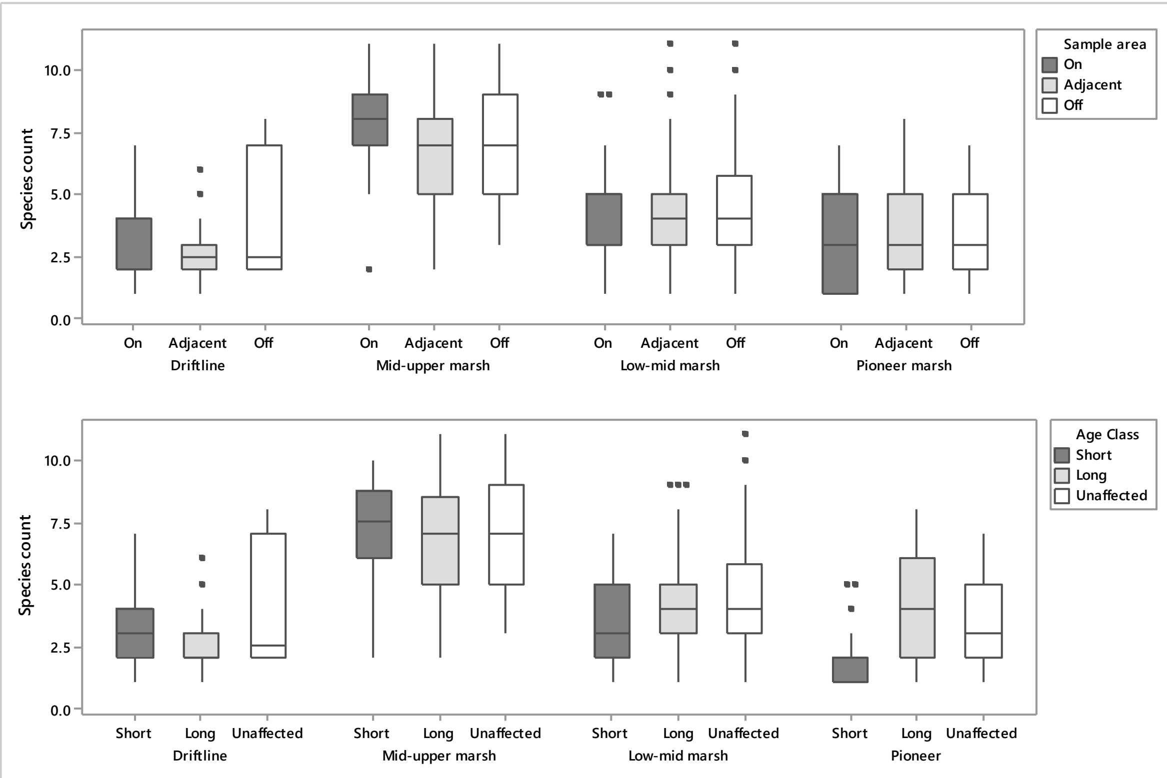
3.3 Results – All Vegetation Zones

3.3.1 Boxplots

The entire dataset for saltmarsh was initially reviewed using a series of boxplots and descriptive statistics. These focused on the differences between the vegetation zones with sample area and time since impact.

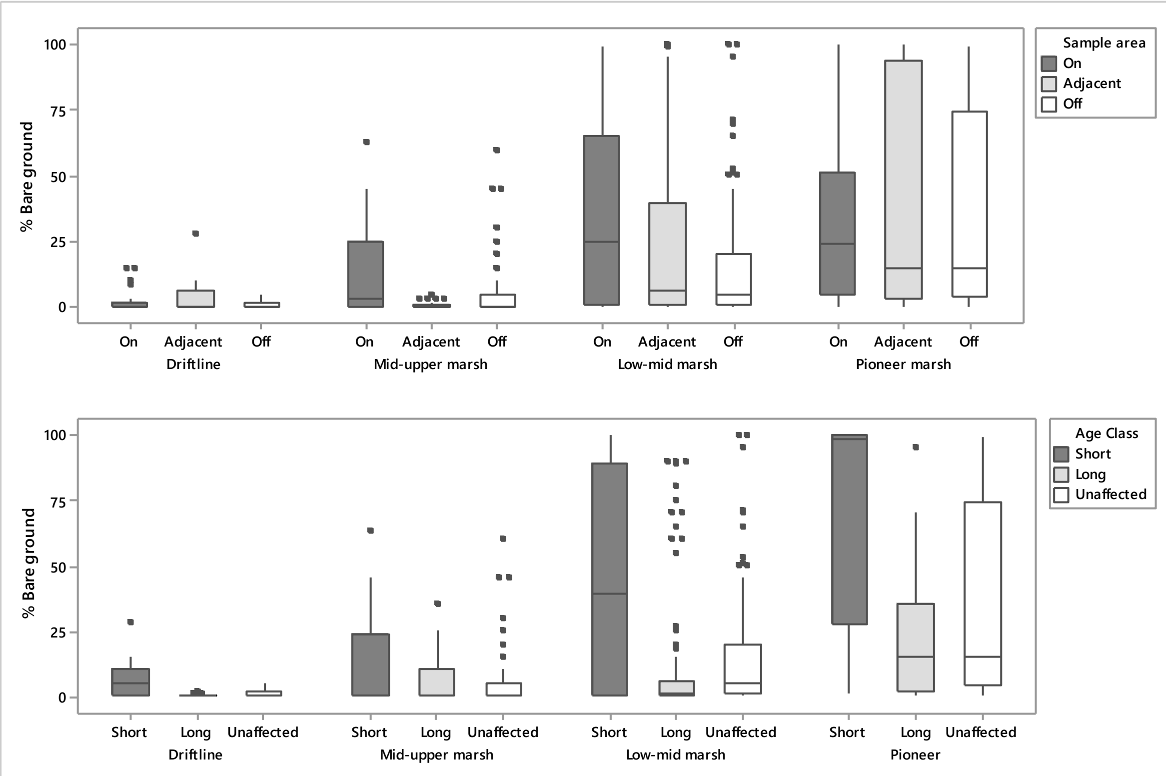
The number of species recorded in each vegetation zone showed that there was little difference between the sample areas or time since impact for the driftline, mid-upper marsh and low-mid marsh. There was a greater variation in species numbers for the pioneer marsh; which when analysed using a General Linear Model showed that both sample area and time since impact was statistically significant (Figure 5).

Figure 5 - Boxplots showing the number of species with vegetation zones (driftline, mid-upper marsh, low-mid marsh and pioneer marsh), and sample area (On, Adjacent and Off) [top] and time since impact (Short-term, Long-term and Unaffected) [bottom].



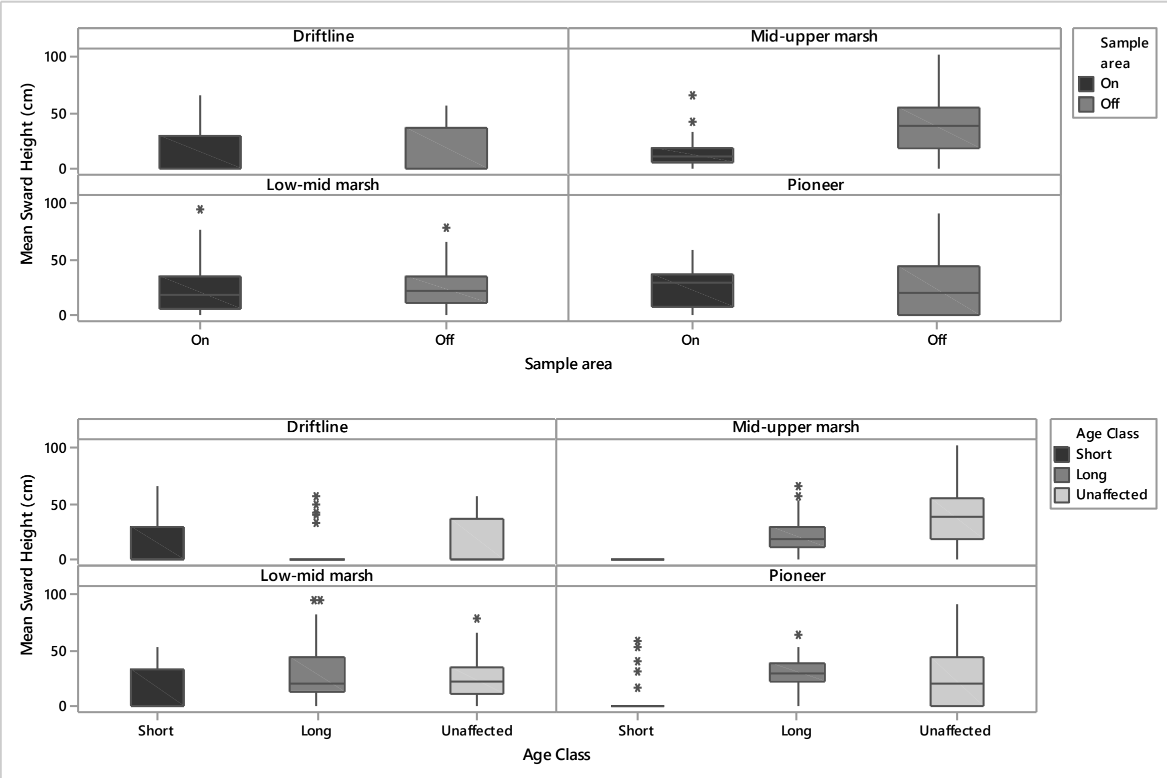
The extent of bare ground along the pipeline compared to unaffected areas was also analysed as typically existing vegetation is lost during construction. It was expected that vegetation recovery (and consequently the amount of bare ground) in the different zones would take differing amounts of time to return to a similar structure as the Unaffected vegetation. The cover of bare ground with vegetation zone, sample area and time since impact is shown in Figure 6. The figure shows that there was little difference with sample area in the driftline zone, but the On sample area had a higher cover of bare ground in the mid-upper and low-mid marsh, although the data does show considerable variation between the samples. Across all of the vegetation zone bare ground was highest unsurprisingly in the Short-term compared to the Long-term or Unaffected areas.

Figure 6 - Boxplots showing cover of bare ground with vegetation zones (driftline, mid-upper marsh, low-mid marsh and pioneer marsh), and sample area (On, Adjacent and Off) [top] and time since impact (Short-term, Long-term and Unaffected) [bottom].



The average sward height of the vegetation showed little difference in the driftline, low-mid marsh and pioneer zones for sample area. Greater variation was recorded between the sward height with time since impact, particularly in the mid-upper marsh and the pioneer marsh, where typically in the Short-term the sward height was much shorter than in the Unaffected vegetation (Figure 7).

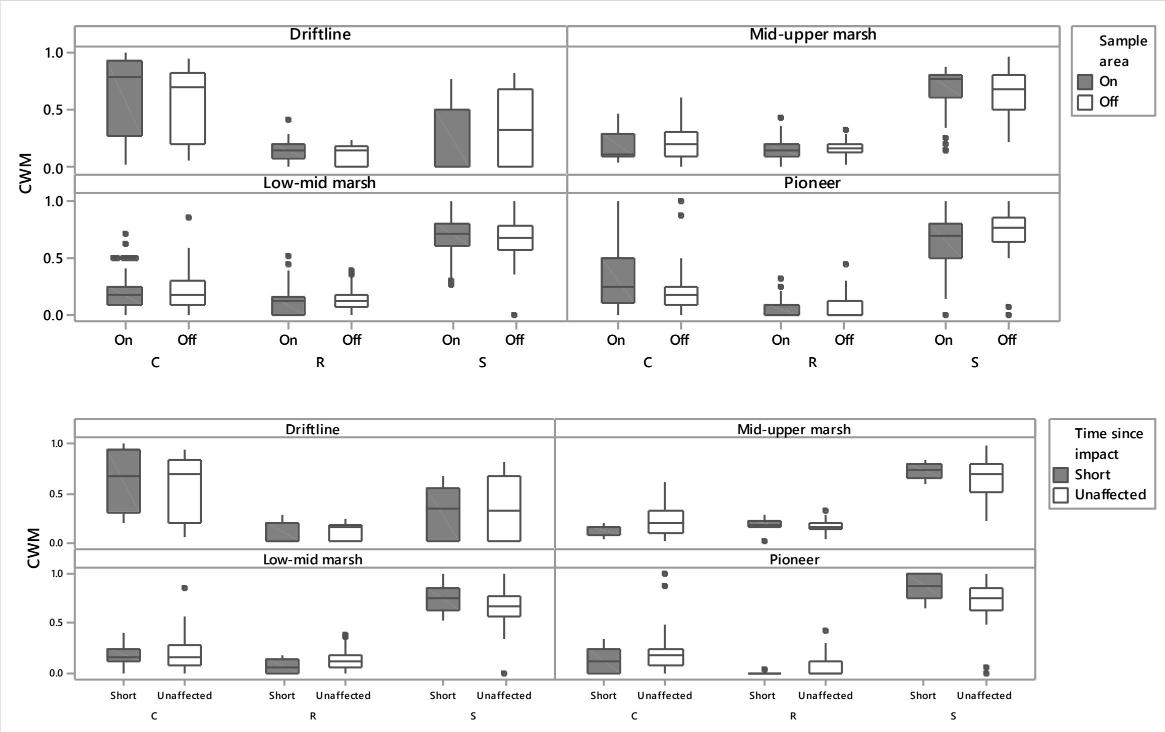
Figure 7 - Boxplots showing mean sward height with vegetation zones (driftline, mid-upper marsh, low-mid marsh and pioneer marsh), and sample area (On, Adjacent and Off) [top] and time since impact (Short-term, Long-term and Unaffected) [bottom].



The proportion of competitive, ruderal and stress-tolerant species (based on Grime's CSR strategy (Grime et al., 1988) showed little difference in the driftline and low-mid marsh zones. In the mid-upper marsh there was a greater proportion of stress-tolerant species in the Unaffected zone compared to the Short-term. In contrast, in the pioneer zone competitive species made up a larger proportion of the sward On the pipeline (Figure 8).

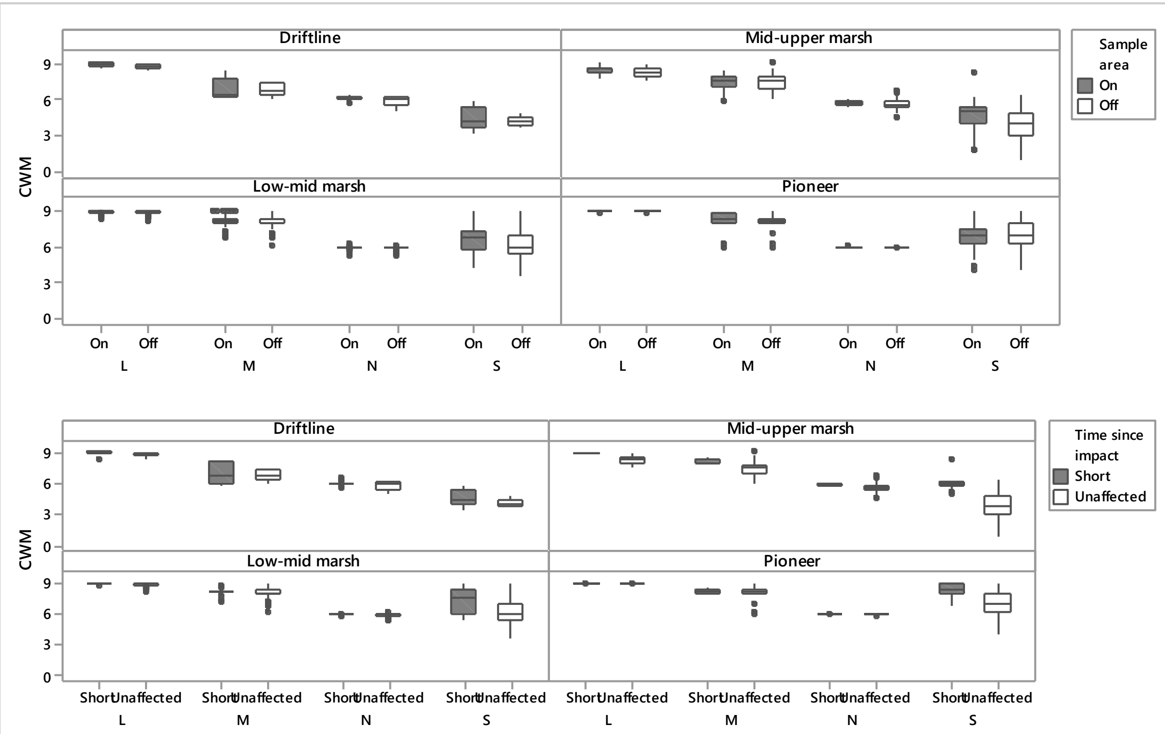
The differences in the community weighted means of quadrats with four key Ellenberg indicators (species requirement for light, moisture, nutrient and tolerance to salinity) (Hill et al., 1999) is shown in Figure 9. The difference in pH across the saltmarsh zones and individual species was very similar and consequently was not used in the analysis. The figure shows little difference between the vegetation zones with sample area or time since impact.

Figure 8 - Boxplots showing Community Weighed Means (CWM) of CSR strategies (Grime et al., 1988) with vegetation zones (driftline, mid-upper marsh, low-mid marsh and pioneer marsh), and sample area (On, Adjacent and Off) [top] and time since impact (Short-term and Unaffected) [bottom].



Community weighted means (CWM) (i.e. plot-level trait values weighted by species abundances) generated in CANOCO 5 for CSR Strategies
C=Competitor, R=Ruderal, S=Stress-tolerator (Grime et al., 1988)

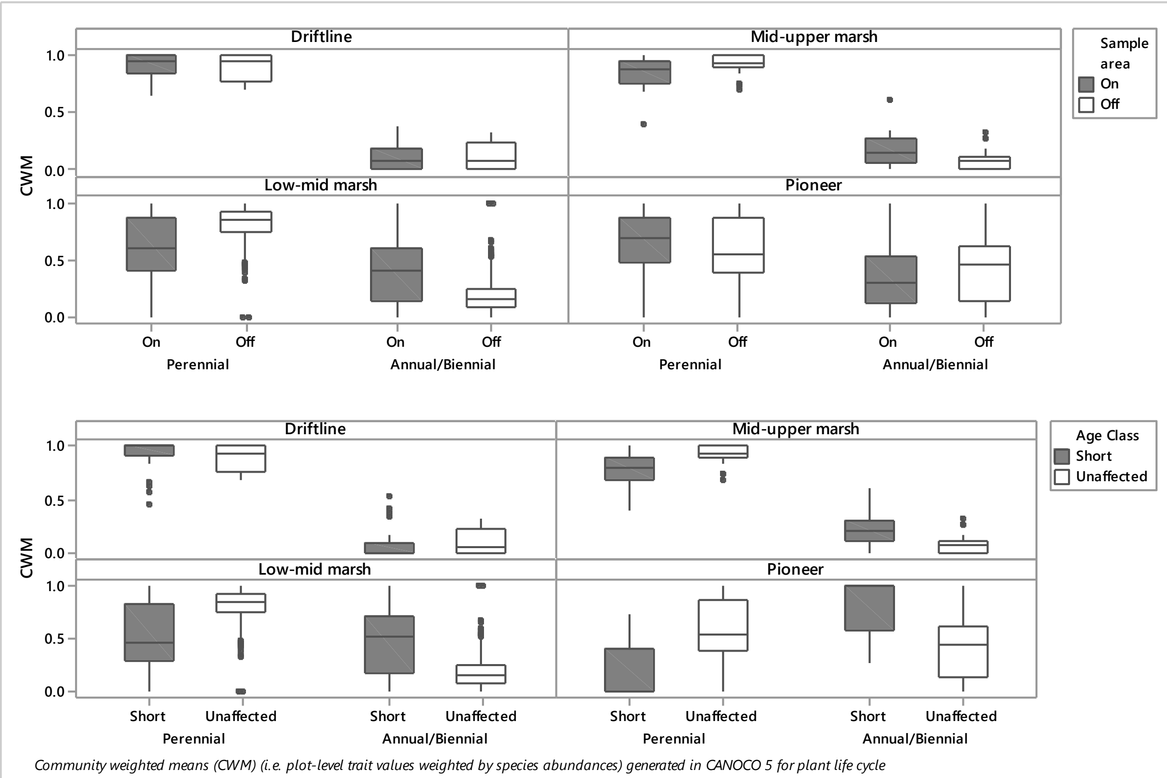
Figure 9 - Boxplots showing Community Weighed Means (CWM) of Ellenberg values – light, moisture, nitrogen and salinity (Hill et al., 1999) with vegetation zones (driftline, mid-upper marsh, low-mid marsh and pioneer marsh), and sample area (On, Adjacent and Off) [top] and time since impact (Short-term and Unaffected) [bottom].



Community weighted means (CWM) (i.e. plot-level trait values weighted by species abundances) generated in CANOCO 5 for Ellenberg values
L=Light, M=Moisture,N=Nitogen (in effect a general indicator of soil fertility), S=Salinity, note pH excluded (Hill et al., 1999)

The differences in the community weighted means of quadrats when considering plant life cycles *i.e.* perennial versus annual or biennial life cycles showed no differences in the driftline zone. In the mid-upper marsh, the proportions of perennials, annuals and biennials was similar with sample area; but in the Short-term there was a greater variation between quadrats. In the low-mid marsh there was a greater variation in the life cycle of quadrats On the pipe and in the Short-term. In the pioneer marsh in the Short-term there were fewer perennial species and more annual species compared to the Unaffected vegetation (Figure 10).

Figure 10 - Boxplots showing Community Weighed Means (CWM) of plant life cycle (perennial, annual, biennial) with vegetation zones (driftline, mid-upper marsh, low-mid marsh and pioneer marsh), and sample area (On, Adjacent and Off) [top] and time since impact (Short-term and Unaffected) [bottom].

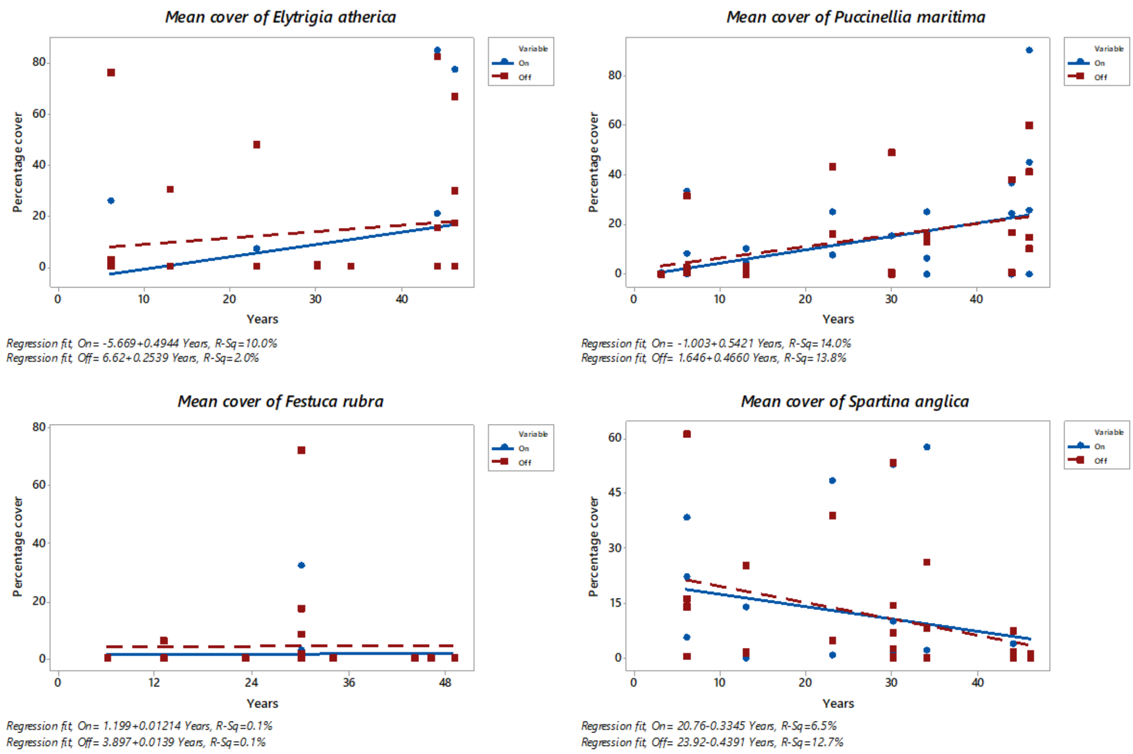


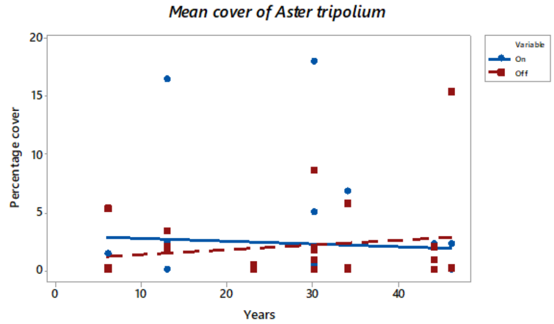
3.3.2 Scatterplot Recovery Trends

The mean cover for key individual species representative of each zone were analysed. This includes the graminoids *Elytrigia atherica*, *Puccinellia maritima*, *Spartina anglica* and the forbs *Aster tripolium*, *Atriplex portulacoides*, *Atriplex prostrata*, *Limonium vulgare*, *Plantago maritima*, *Salicornia* agg., *Suaeda maritima*, *Triglochin maritimum*, and Algae agg. The mean cover of each species from each site was calculated, with the On and Off values separated. These values were plotted as a scatterplot with years with a regression line of best fit applied. It was hoped that the scatterplots would give an indication of the direction and recovery times of each species. However, there was insufficient data points (once the values had been averaged by site) to further divide the data by vegetation zone. Therefore, the mean values include the values from zones where a species is only found a low-level of abundance. As an example, when considering *Elytrigia atherica* it has a high cover in the driftline vegetation zone (typically between 70-100%), but in other zones it is typically absent. This means there is large amount of variation in the cover values resulting in weak relationships, consequently the plots only provide a general trend of the direction of recovery. The graphs are shown in Figure 11.

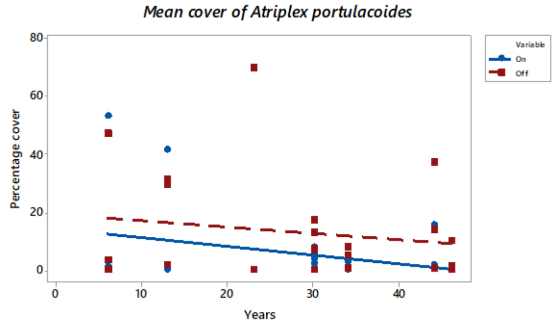
Elytrigia atherica shows that Off of the pipeline cover was fairly consistent over time, increasing slightly (R-Sq=2%), while for the On sample it showed an increase in cover (R-Sq=10%). However, the other grasses *Festuca rubra*, *Puccinellia maritima* and *Spartina anglica* showed little difference between the cover from On and Off the pipeline, with *Puccinellia maritima* increasing over time, *Festuca rubra* staying constant and *Spartina anglica* decreasing. The cover of *Aster tripolium*, *Atriplex prostrata*, *Limonium vulgare*, *Plantago maritima*, *Suaeda maritima* and Algae spp. Were constant over time with little difference between the On and Off sample area. Greater variation was noted with *Atriplex portulacoides* which showed a general reduction in cover for both On and Off the pipeline but had a higher cover overall Off the pipe. On the pipeline *Salicornia* agg. increased in cover over time (R-Sq=8.3%), but its cover decreased Off of it.

Figure 11 - Scatterplots with a regression line of best fit, showing the mean cover of key saltmarsh species for On (shown in blue) and Off (shown in red) the pipeline.

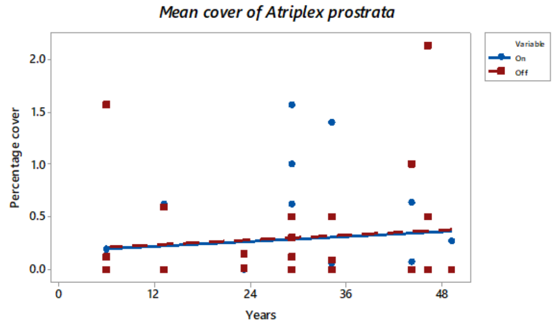




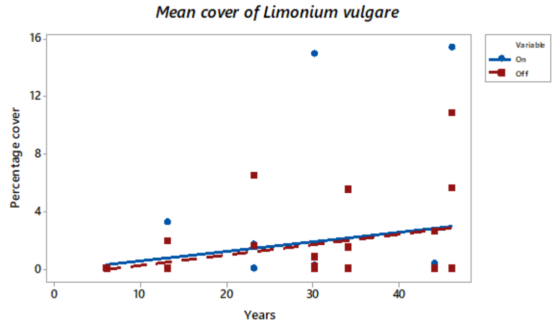
Regression fit On= 3.090-0.02742 Years, R-Sq=0.6%
Regression fit Off= 0.97+0.0407 Years, R-Sq=2.5%



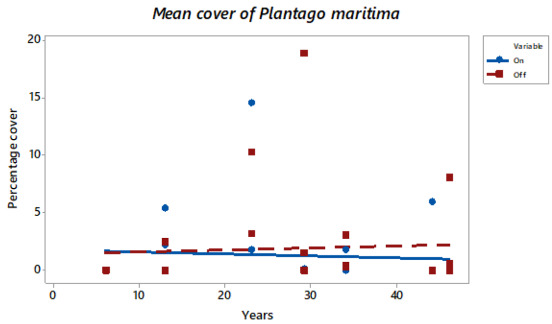
Regression fit On= 14.43-0.3083 Years, R-Sq=10.5%
Regression fit Off= 19.46-0.2259 Years, R-Sq=3.2%



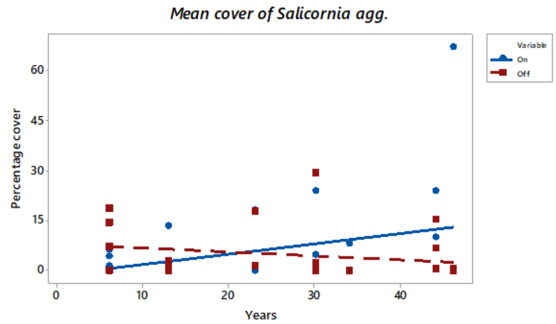
Regression fit On= 0.1732+0.003887 Years, R-Sq=1.5%
Regression fit Off= 0.1956+0.003776 Years, R-Sq=1.0%



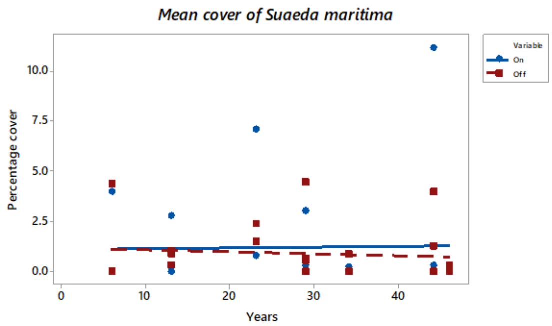
Regression fit On= -0.131 +0.06783 Years, R-Sq=4.8%
Regression fit Off= -0.471+0.07330 Years, R-Sq=13.4%



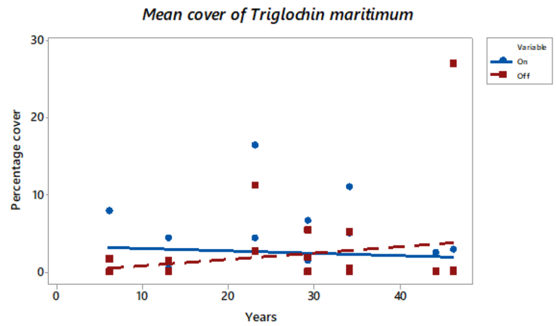
Regression fit On= 1.793-0.01801 Years, R-Sq=0.6%
Regression fit Off= 1.396+0.01947 Years, R-Sq=0.4%



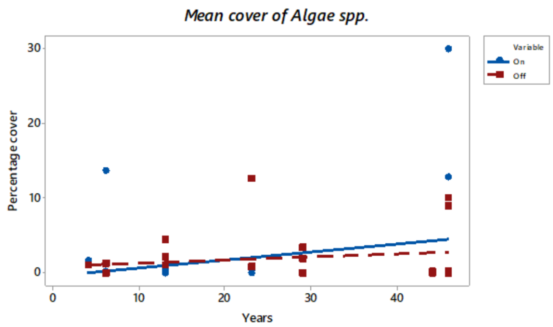
Regression fit On= -1.059+0.3040 Years, R-Sq=8.3%
Regression fit Off= 8.195-0.1276 Years, R-Sq=4.9%



Regression fit On= 1.109+0.00309 Years, R-Sq=0.0%
Regression fit Off= 1.168 +0.00945 Years, R-Sq=0.9%



Regression fit On= 3.426-0.03230 Years, R-Sq=1.2%
Regression fit Off= -0.017+0.08296 Years, R-Sq=4.2%

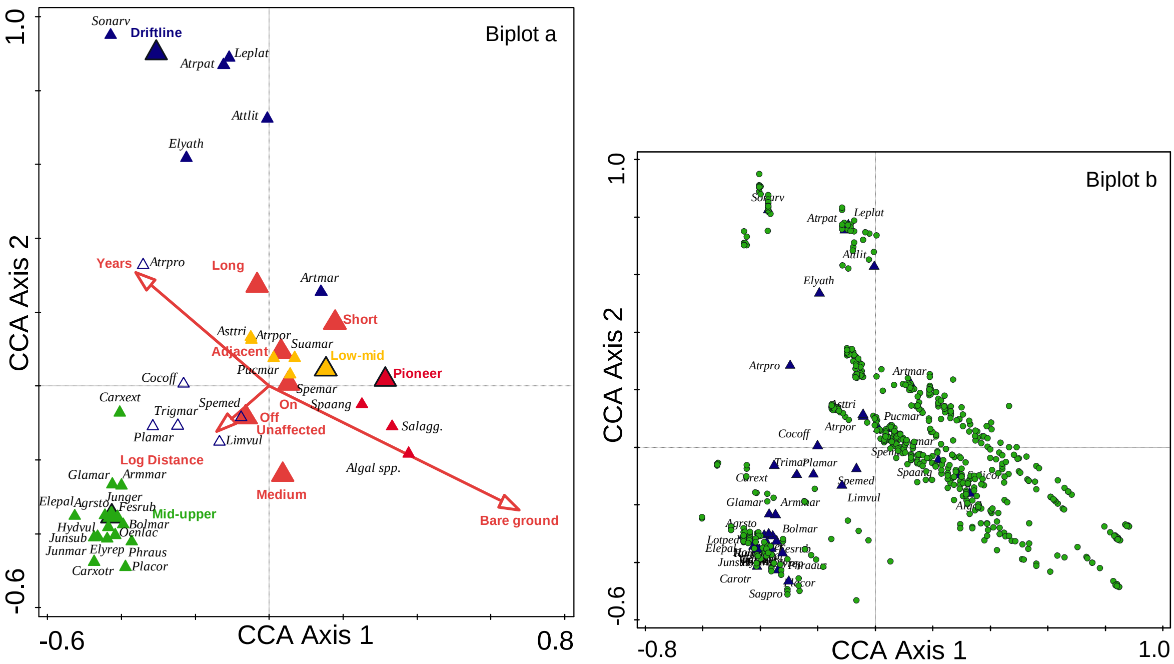


Regression fit On= -0.276+0.1024 Years, R-Sq=5%
Regression fit Off=0.894+0.04105 Years, R-Sq=3.1%

3.3.3 Canonical Correspondence Analysis

A constrained ordination (CCA) of all data was undertaken to test the significance of the environmental explanatory variables in explaining the variation in species composition. The distance of a species symbol and the symbols of environmental variable classes shows the relative preference of that species for individual environmental variable classes. The species is predicted to occur with the highest relative frequency (or with the highest probability) in classes with their symbols close to that species' point. In Figure 12, dummy variables for vegetation zone was included. As expected, there is a clear preference of the typical saltmarsh species to vegetation zone for example with the driftline supporting *Elytrigia atherica* with ruderals and tall-perennials such as *Atriplex patula*, *Atriplex littoralis*, *Lepidium latifolium* and *Sonchus arvensis*. The greatest number of species is associated with the mid-upper marsh. Here, species typical of this vegetation zone such as the graminoids *Agrostis stolonifera*, *Festuca rubra*, *Juncus gerardii*, *Juncus maritimus* and forbs *Armeria maritima* and *Glaux maritima* are clustered. There is less distinction between species of the low-mid marsh and pioneer marsh. Although for example the pioneer species shows a preference to increased bare ground.

Figure 12 - Species-environmental variable biplot (a) and species-quadrats biplot (b) using CCA (of the first two axes) with environmental variables selected by forward selection procedure. Total variation is 7.73, explanatory variables account for 16.0% (adjusted explained variation is 14.7%); 1st Axis pseudo-F=4.4, p=0.002; All Axes pseudo-F=12.7, p=0.0002. The species (shown as blue triangles) are labelled by the first three letters of the generic name and the first three letters of the specific name. Quadrats are shown as green circles with the quadrat number.



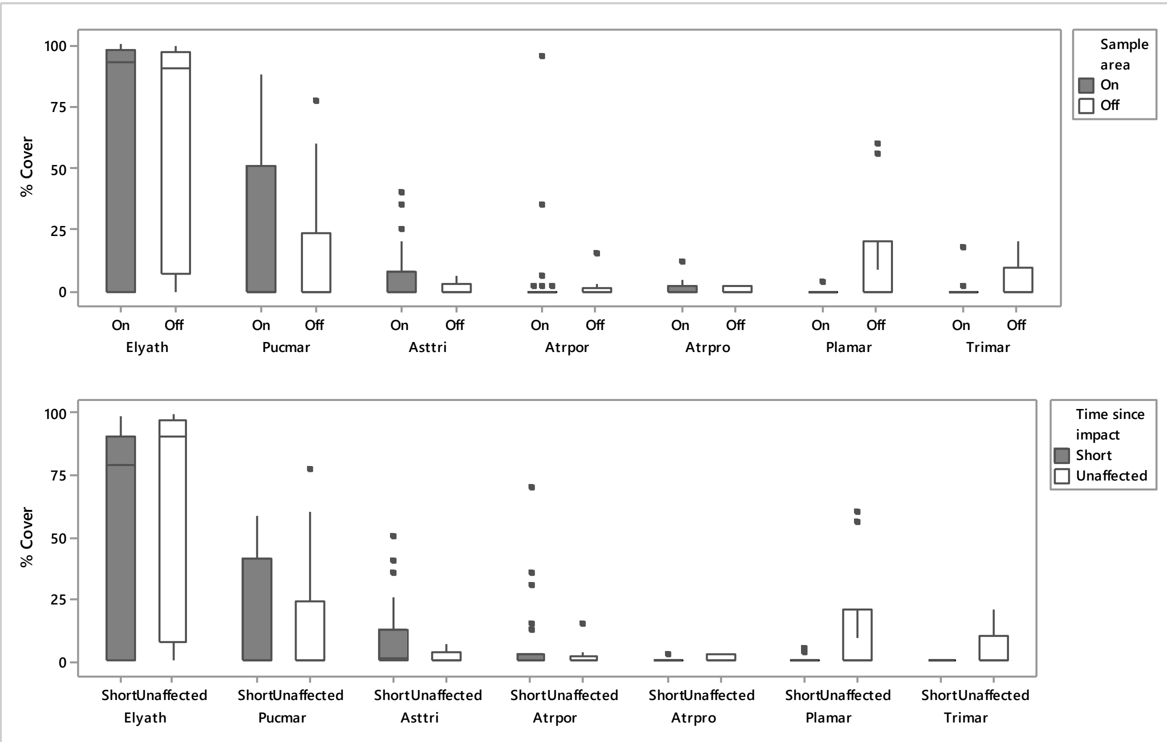
3.4 Results – Driftline

3.4.1 Vegetation Composition and Structure

Across the study sites, vegetation in the driftline was generally species-poor. In total 21 vascular plant species were recorded, although most of these were only recorded in only a few quadrats. The most species-rich quadrats had seven species, while the least diverse had just one (Figure 5, *Section 3.3* and Figure 17).

The driftline is typically dominated by *Elytrigia atherica* (which was recorded in 82% of the quadrats), with up to 100% cover. *Puccinellia maritima* and *Aster tripolium* were also frequent components especially On the pipeline and in the Short-term. In contrast species such as *Plantago maritima* and *Triglochin maritimum* showed a preference for the Unaffected areas. Boxplots showing cover of key species in this zone by sample area and time since impact are given in Figure 13.

Figure 13 - Boxplots showing the cover of key driftline species with sample area (On and Off) [top] and time since impact (Short-term and Unaffected) [bottom]. The species are labelled by the first three letters of the generic name and the first three letters of the specific name.



Species– Elytrigia atherica (Elyath); Puccinellia maritima (Pucmar); Aster tripolium (Asttri); Atriplex portulacoides (Atrpor); Atriplex prostrata (Atrpro); Plantago maritima (Plamar); Triglochin maritimum (Trimar)

General Linear Model and Tukey Pairwise Comparison Test

To test the hypotheses for driftline vegetation (*Section 3.2.3)*, analysis using a General Linear Model (GLM) and Tukey Pairwise Comparison test was used for each species or variable[25].

Hypotheses 1 – [*Elytrigia atherica* will have lower cover On the pipeline in the Short-term]. The difference in cover of *Elytrigia atherica* in the On and Off sample area was not statistically significant (df=2; F=1.22; p=0.302). Neither was the difference in cover between the Short-term and Unaffected areas (df=2; F=1.22; p=0.301).

Hypotheses 2 - [Cover of ruderal species will be higher On the pipeline compared with Off; while their cover is highest in areas impacted in the Short-term compared to Unaffected areas]. Only a small number of quadrats in the driftline had ruderal species, and where present these were only at low abundances. Cover of the annuals *Atriplex littoralis, Atriplex patula* and *Atriplex prostrata* along with the biennial *Cochlearia officinalis* was not statistically different between sample area, and *Atriplex* spp. showed no significant differences for time since impact. The cover of *Cochlearia officinalis* was significantly less in the Short-term compared to the Unaffected vegetation (df=2; T=2.68; p=0.026), which was unexpected. Annuals in the driftline did not support the hypothesis.

Hypotheses 3 - [Cover of typical lower-marsh species will increase On the pipeline in the Short-term, before returning to pre-construction levels in the Medium-term]. The cover of *Aster tripolium* and *Puccinellia maritima* was not significantly different for sample area or time since impact – disproving this hypothesis.

Hypotheses 4 - [*Spartina anglica* will have higher cover On the pipeline]. *Spartina anglica* was recorded in 11.5% of the quadrats in this zone. It was found only in quadrats from On (cover 2-25%) and Adjacent (cover 2-5%) to the pipeline. GLM of sample area and distance from pipe, showed cover of *Spartina anglica* was not significantly different (df=2; F=0.35; p=0.703), and its cover was not significant over time.

Hypothesis 5 – [Cover of bare ground in the On sample area will be higher immediately after pipeline installation]. There was no significant difference in the mean cover of bare ground between the On and Off sample area (Figure 6), this was supported by the GLM and Tukey Pairwise Comparison test (df=2; T=2.29; p=0.065). The GLM analysis identified a significant difference in the combined cover of perennial species with sample area, between On and Off the pipeline with the On sample area having a significantly lower cover compared to the Off sample area (df=2; T=-2.65; p=0.024). Perennial cover was also significantly lower in the Short-term compared to the Unaffected vegetation (df=2; T=7.63; p=0.000).

---

[25] with sample area or time since impact as a factor, and distance from pipe as a covariate

A full summary of the results of the GLM and Tukey Pairwise Comparison test for driftline vegetation is given in Appendix 3 Tables 15-18.

Canonical Correspondence Analysis

In CCA and forward selection of environmental variables with the driftline data, the Short-term factor explains the greatest amount of variation and is statistically significant. The other time since impact factors for this zone along with the sample area factors are also significant. In comparison years, bare ground cover and log distance were not statistically significant (Table 4).

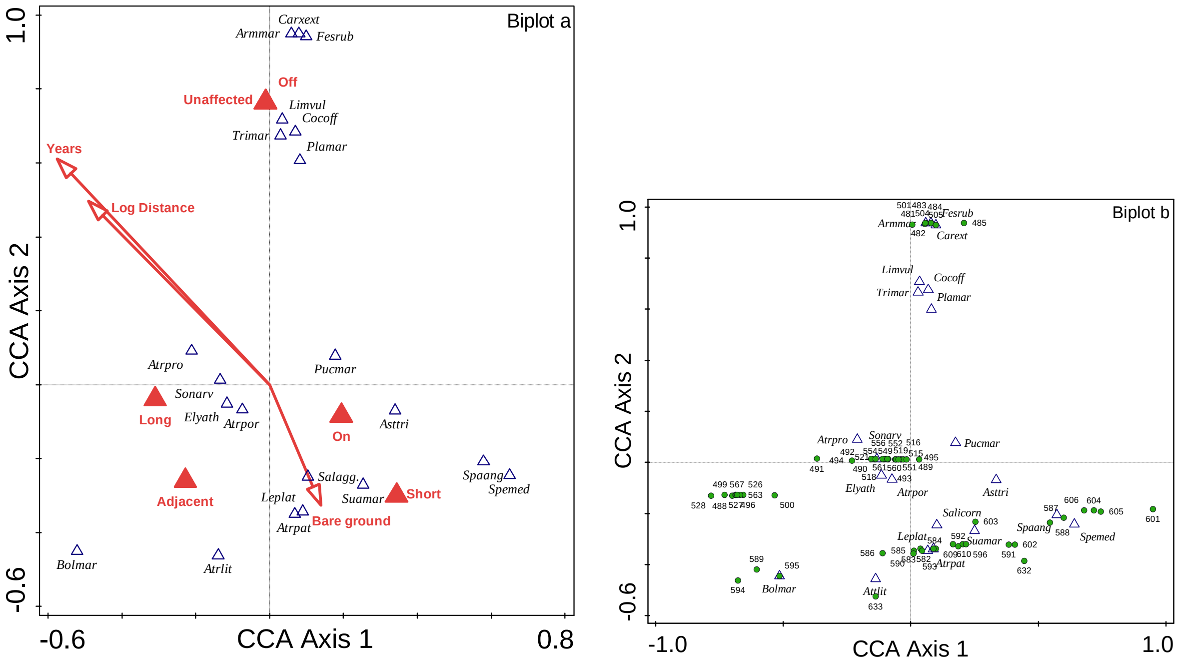
Table 4 - Explanatory power of environmental variables in CCA analysis for driftline. Significant effects are given in bold.

Environmental Variable	Explains %	Contribution %	Pseudo-F	P-value	P(adj)
Time since impact - Short	**6.7**	**31.1**	**4.2**	**0.0008**	**0.0045**
Sample area - Adjacent	**5.3**	**24.7**	**3.5**	**0.0030**	**0.0135**
Time since impact - Long	**4.4**	**20.4**	**3.0**	**0.0100**	**0.0153**
Time since impact - Unaffected	**4.4**	**20.4**	**3.0**	**0.0102**	**0.0153**
Sample area – Off	**4.4**	**20.4**	**3.0**	**0.0078**	**0.0153**
Sample area – On	**4.4**	**20.4**	**3.0**	**0.0082**	**0.0153**
Years	3	13.9	2.1	0.0914	0.1175
% Bare ground	1.2	5.7	0.9	0.5210	0.5861
Log distance from pipe	0.9	4.0	0.6	0.7492	0.7492

The species-environmental variable CCA biplot shows that there is a clear separation of the explanatory variables of sample area and time since impact (Figure 14a). The axis of years and log distance are highly correlated and have a similar effect on the species composition, with bare ground having an inverse relationship. The plot shows that the Unaffected/Off vegetation supports those species typical of upper-marsh vegetation *i.e. Armeria maritima, Carex extensa*, and *Limonium vulgare*. In contrast, the factors for On and Short-term correlate with the highest cover of bare ground and are associated with species typical of early successional saltmarsh *i.e. Salicornia* agg., *Spergularia media*, and *Suaeda maritima*; or ruderal species *i.e. Atriplex patula*. The factor for Long-term correlates to typical driftline vegetation *i.e. Elytrigia atherica* with *Atriplex portulacoides, Atriplex prostrata* and *Sonchus arvensis*.

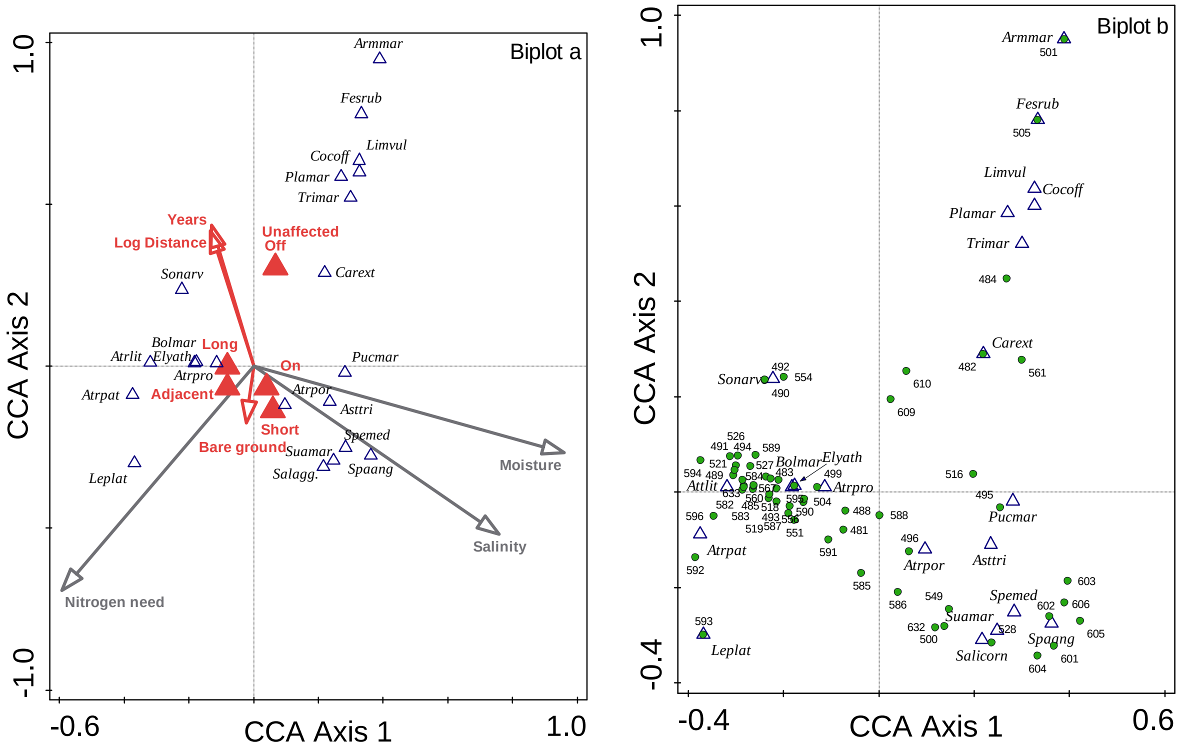
Figure 14b shows a species-quadrat biplot for the driftline zone. The plot provides an indication of the relative frequency (or probability of occurrence) of a species in each quadrat depending on the distance between the quadrat and species symbol. Those quadrats clustered around a particular species tend to have a higher frequency of that species *e.g.* quadrats 481-484, and 504-505 are close to *Armeria maritima*, *Carex extensa* and *Festuca rubra* indicating that they contain these species. These particular quadrats were recorded from Tetney Marshes where there have been significant changes since the installation of the pipeline and associated causeway, and it appears there has been a change from a species-poor driftline community to a more diverse mid-upper marsh community.

Figure 14 - Species-environmental variable biplot (a) and species-quadrats biplot (b) using CCA (of the first two axes) with environmental variables selected by forward selection procedure. Total variation is 2.19, explanatory variables account for 21.4% (adjusted explained variation is 12.7%); 1st Axis pseudo-F=5.4, p=0.0234; All Axes pseudo-F=2.5, p=0.0008. The species (shown as blue triangles) are labelled by the first three letters of the generic name and the first three letters of the specific name. Quadrats are shown as green circles with the quadrat number.



The inclusion of Ellenberg values (*e.g.* moisture, nitrogen requirement, and salinity published by Hill et al. (1999)) as additional explanatory variables in the CCA analysis increased the percentage variation explained by the environmental variables from 21.4% to 61.9%, and the forward selection process identified all five variables as being significant. Of these, moisture was the most significant explaining 29.8% of the variation (Figure 15). It appears that an increase in salinity and moisture corresponds with the On and Short-term factors, with species typical of early successional marsh. As would be expected ruderal species such as *Atriplex patula* and *Lepidium latifolium* are associated with an increased nitrogen requirement.

Figure 15 - Species-environmental variable biplot (a) and species-quadrats biplot (b) using CCA (of the first two axes) with environmental variables selected by forward selection procedure. The biplot includes Ellenberg values for moisture, nitrogen requirement and salinity as additional explanatory variables. Total variation is 2.19, explanatory variables account for 61.9% (adjusted explained variation is 55.2%); 1st Axis pseudo-F=22.9, p=0.002; All Axes pseudo-F=9.2, p=0.0002. The species (shown as blue triangles) are labelled by the first three letters of the generic name and the first three letters of the specific name. Quadrats are shown as green circles with the quadrat number.



Species Response Curves Distance and Time

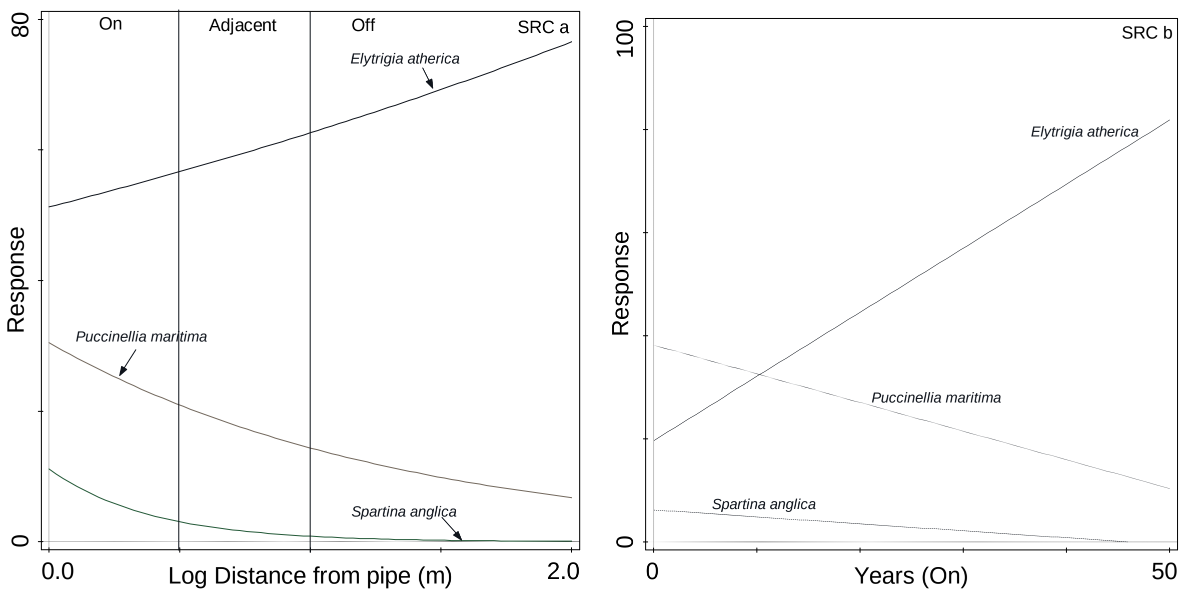
The species response curves produced in CANOCO use a Generalised Linear Model with species cover (the response) plotted against log distance (from the pipeline) and years On the pipeline[26] (Figure 16a-d). The cover of *Elytrigia atherica* increased with distance in particular comparing the On sample area to the Off sample area (supporting Hypothesis 1). It also shows that it recovers quickly On the pipeline in terms of years following the disturbance episode (with its initial cover of around 20%). Once established there was an ongoing increase in cover, from 30% by 10 years, ca. 50% cover within 25 years, and 80% cover in 50 years. *Puccinellia maritima* showed a decrease in cover with distance (especially in the On and Adjacent sample areas). This indicates this species initially colonises the pipeline following construction, but then decreases as *Elytrigia atherica* re-establishes – supporting Hypothesis 3. On the pipeline over 50 years, *Puccinellia maritima* shows a decrease in cover from ca. 40% to ca. 12% (similar to the mean cover for undisturbed quadrats at 12.7%). *Spartina anglica* showed a small reduction in cover with distance and time since impact, although it is only present at low-levels of abundance within the

[26] insufficient data was available to plot driftline vegetation with years Off the pipeline

zone. With distance On the pipeline its cover is around 10% which decreases to around 5% in the adjacent zone. Very little *Spartina anglica* was recorded Off the pipe. Similarly, On the pipeline over time its cover falls from 4% to 1% in 20 years, after which it is more or less absent. It appears that in some locations it is able to become established in the driftline zone after construction but is lost from the sward supporting Hypothesis 4. Its loss from the sward is probably due to it being less competitive here than *Elytrigia atherica* (Figure 16a&c).

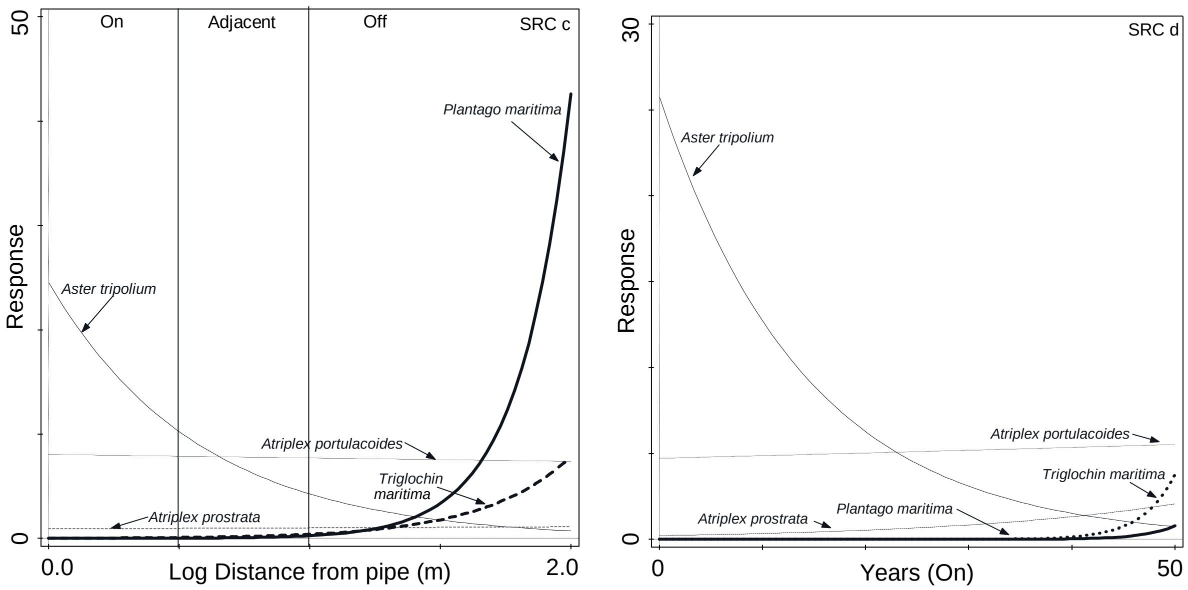
The cover of *Aster tripolium* showed a sharp decrease from ca. 25% On the pipe decreasing with distance to around 10% in the adjacent zone and less than 5% in the Off zone. When considering its cover On the pipeline with time it shows a rapid decrease in the first 10 years (ca. 25% to 12%), this decrease continued so that's its cover was around 6% by 20 years, and by 30 years it is only present at a low-level of abundance (<4%[27]) -supporting Hypothesis 3. The cover of *Atriplex portulacoides* remained stable with distance and with time on the pipeline (although it is only ever an occasional component of the sward in the driftline with a mean cover of around 2%). Similarly, *Atriplex prostrata* was only recorded at a low-level of abundance which remained stable both with distance and time since impact. The forbs *Plantago maritima* and *Triglochin maritimum* both showed an increase in cover in the Off sample area, after 40 years, indicating their increase may be due to ongoing succession rather than as a consequence of the pipeline installation (Figure 16b&d).

Figure 16 - Species Response Curves (SRC) of log distance from the pipeline (a & c) and years On the pipeline (b & d) with typical driftline species. The uppermost plots show graminoids, while the lower plots show forbs. The plot uses a poisson response distribution and a linear predictor. The response value indicates species abundance. For log distance (a & c) an indication of the sample area (On, Adjacent and Off) has been given.



[27] normal level of cover for SM24 (Rodwell, 2000)

Figure 15 continued

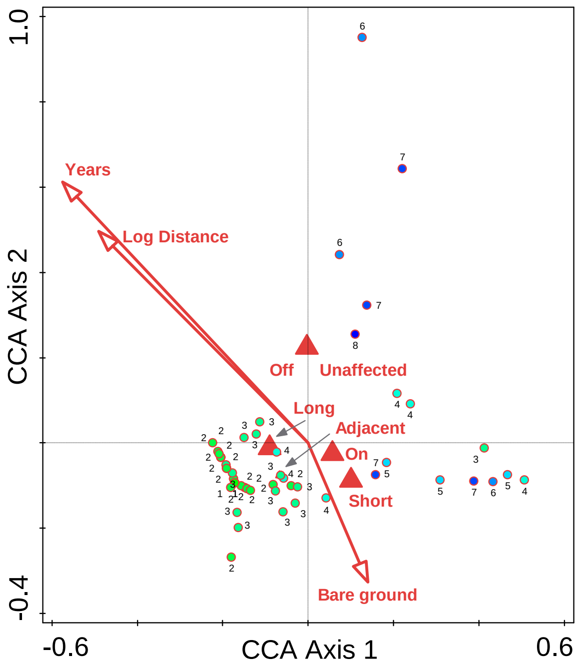


Species Diversity

Hypotheses 6 – [Species-richness will be highest On the pipeline at least in the Short-term]. The species diversity diagram (Figure 17) shows that the most species-poor quadrats are associated with the Long-term and Adjacent vegetation (*i.e.* the *Elytrigia atherica* dominated vegetation). Here quadrats typically have 2-3 species. In contrast, more species (4-7) are associated with the On and Short-term factors (probably the influence of ruderal species exploiting areas of created bare ground and a less dense sward) – supporting hypothesis 2. The Off and Unaffected factors are associated with species-rich quadrats (6-8 species) which are all areas of mid-upper marsh (classified as driftline vegetation prior to construction). Rodwell (2000) notes that SM24, which most of my driftline quadrats represent, had on average six species. The hypothesis is therefore in part proven in that the On and Short-term have more species than the Long-term and Adjacent vegetation; but where driftline vegetation develops to mid-upper marsh the hypothesis is not correct.

No nationally rare or scarce saltmarsh species were recorded in the driftline zone. One species listed as Near Threatened on the Vascular Plant England Red List (Stroh et al., 2014) was recorded, namely *Limonium vulgare* (recorded in five quadrats in this zone; four in the Off sample area and one from the On sample area).

Figure 17 - Species diversity diagram showing species number per quadrat in the driftline. Green circles indicate low species-richness, while blue indicate high-species richness within the zone; numbers are the actual number of species in the quadrat.



3.4.2 Ecosystem Function

The Common Standards Monitoring guidelines (JNCC, 2004a) notes "*extent of the saltmarsh is a fundamental attribute to be assessed in determining condition of the saltmarsh feature. The target is no decrease in extent from the established baseline with the caveat 'subject to natural change'*". Pipeline/ cable installation is likely to result in a change in the extent of the saltmarsh zones, with some vegetation types expanding in areas, while others decrease.

Driftline Resource

Driftline vegetation develops at the upper tidal limits of the saltmarsh (centred around extreme high-water spring tide level), at sites which are ungrazed or cattle-grazed. The driftline zone is frequently disturbed by high tides and during storms. Accumulating litter along the strandline provides nitrogen-enriched conditions. The main two NVC communities (Rodwell 2000) represented by this vegetation type (recorded as part of this study) are SM24 *Elymus pycnanthus* salt-marsh community and SM28 *Elymus repens* salt-marsh community.

Examples of SM24 were recorded at three main sites; at Thanet OWF (where it extends roughly 10m from the shore); at Inner Trial Bank where it extends to approximately 25m from the shore and was also found along the former causeway; and at Tetney Marshes where it was more extensive extending approximately 900m along the constructed causeway. Small patches of driftline vegetation were also recorded in saltmarshes at Walney Island (referable to the NVC type

SM28) and at Wytch Moor in Poole Harbour. The extent of driftline habitat at each of the study sites in 2015/2016 is given in Table 5. Due to differences in the size of the working width (*i.e.* the On sample area), the habitat areas (ha) are not directly comparable between sites, therefore the habitat resource is also provided as a percentage of the total site area.

Table 5 - Extent (ha and % of total area) of the driftline zone across study sites in 2015-16.

Location	Site	Area (ha) in 2015-16	% of survey area
Humber	Tetney Marshes	5.4	32
Pegwell Bay	Thanet	0.5	20
Poole Harbour	Cleavel Point	0.0	0
Poole Harbour	Shotover Marsh	0.0	0
Poole Harbour	Wytch Moor	0.1	3
The Wash	Inner Trial Bank	0.6	6
Walney Island	North Morecambe	0.0	0
Walney Island	Rivers Fields	0.0	0
Walney Island	South Morecambe	0.2	2
Total habitat area surveyed in 2015-16 (ha)		**63**	
Proportion of total survey area (%)		**10**	

Hypothesis 7 – [The extent (ha) of driftline habitats following construction, will fall in the Short-term, but in the Long-term will reach pre-construction extents. Along the pipeline or causeway, the extent of this vegetation type may increase over time if the local elevation is raised].

Inner Trial Bank

The availability of a pre-construction vegetation survey completed in 1971 (Randerson, 1975) at Inner Trial Bank allows the change in vegetation zonation over time to be documented. Intermediate survey maps are also available from between 1982-1985 (Hill, 1988) and 1999 (Ecological Services Ltd, 1999) along with the 2016 vegetation survey completed as part of this PhD. Vegetation maps showing the main vegetation zones and NVC types recorded at Inner Trial Bank are shown in Figures 18-21. Table 6 shows the extent (ha) of driftline vegetation and as a percentage of the total for each sample area *i.e.* On, Adjacent (Adj) and Off the causeway.

Table 6 - The extent of driftline vegetation at Inner Trial Bank following the installation of a causeway and the trial offshore reservoir.

Year	1971 pre-construction survey			1982			1999			2016		
Area	**On**	**Adj**	**Off**	**On**	**Adj**	**Off**	**On**	**Adj**	**Off**	**On**	**Adj**	**Off**
Extent (ha)	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.3	0.2	0.2
% of survey area	0	0	0	0	0	0	2	3	3	11	7	4

In 1971 (*i.e.* the pre-construction survey) driftline vegetation was not recorded at Inner Trial Bank. Although the vegetation survey map was less detailed in terms of habitat complexity depicted by the surveyor; by cross referencing it with historical Ordnance Survey maps[28], it shows that the overall saltmarsh resource here was much reduced in extent (extending (at the pipeline) approximately 280m from the shore compared to 680m today). The lack of driftline vegetation in 1972 is probably an accurate reflection of the site, as much of the upper-marsh would have been lost during the 1950s to land reclamation and the construction of a new sea wall. It is hypothesized that the construction of the Inner Trial Bank itself altered tidal patterns accelerating accretion of sediments therefore allowing the rapid development of saltmarsh vegetation. The 1982 survey (taken 10 years after the construction of Inner Trial Bank) also did not record driftline vegetation in the vicinity of the causeway (although it was found in the wider Wash area). In 1999 (27 years after construction) *Elytrigia atherica* dominated vegetation (SM24 *Elymus pycnanthus* salt-marsh community) was recorded in all three sample areas at roughly a similar proportion in each area. By 2016, the extent of *Elytrigia atherica* had increased across all zones. The greatest proportional increase was recorded On the pipeline (compared to the Adjacent and Off sample areas) – supporting hypothesis 7 that driftline vegetation is likely to increase On the pipeline, where there is an increase in elevation.

---

[28] National Grid 1:10 000 1st Metric Edition [TIFF geospatial data], Scale 1:10000, Tiles: tf52nw-5, Updated: 30 November 2010, Historic, using: EDINA Historic Digimap Service, <http://digimap.edina.ac.uk>, Downloaded: 2017-05-17

Figure 18 – Comparison of vegetation zones at Inner Trial Bank based on the 1971 (pre-construction) vegetation survey recorded by Randerson (1975) and the 1982-1985 (post-construction) vegetation survey recorded by Hill (1988).

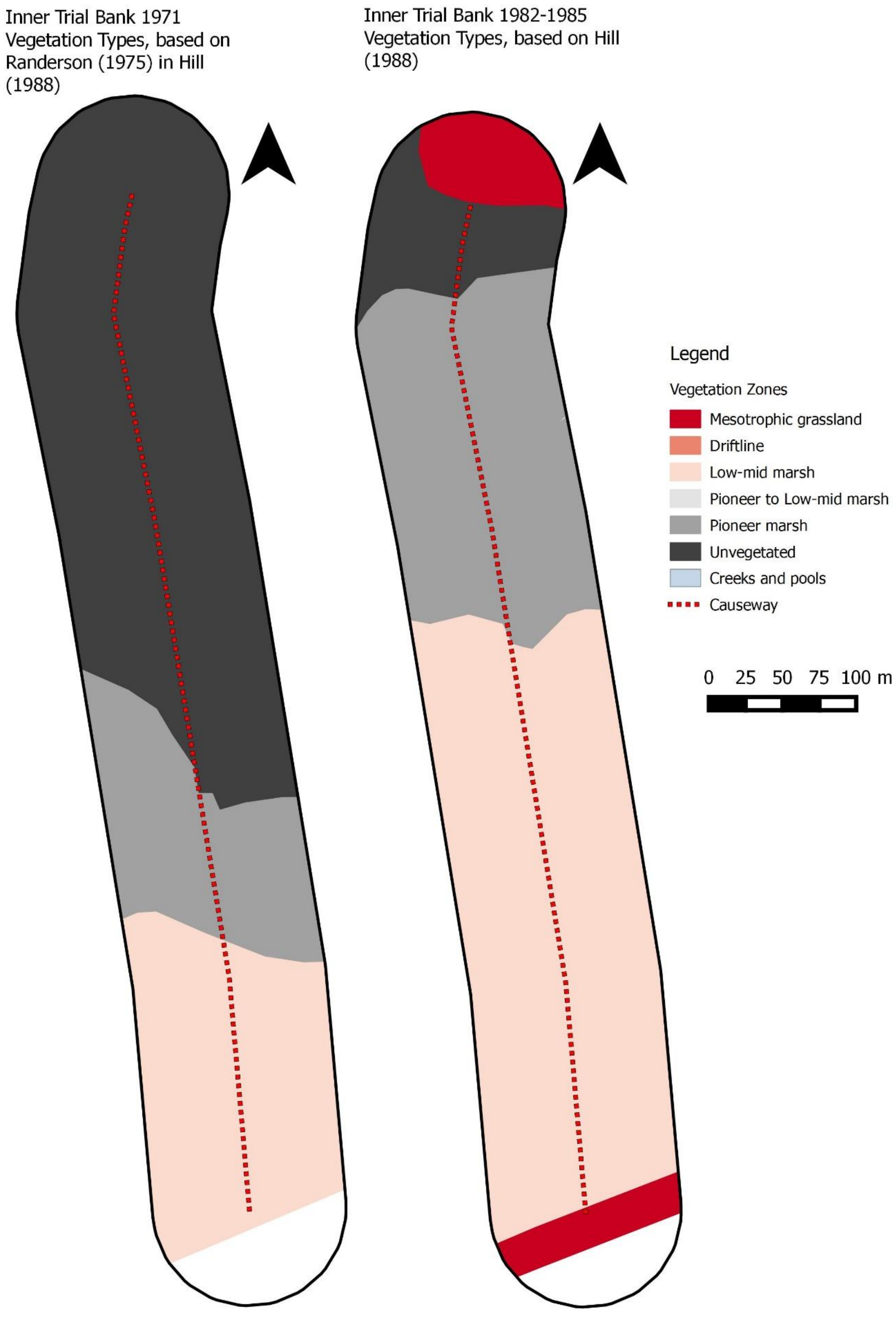


Figure 19 – Comparison of vegetation zones at Inner Trial Bank based on the 1999 (post-construction) vegetation survey by Ecological Services Ltd (1999) and the 2016 vegetation survey undertaken to determine the current vegetation condition as part of this thesis.

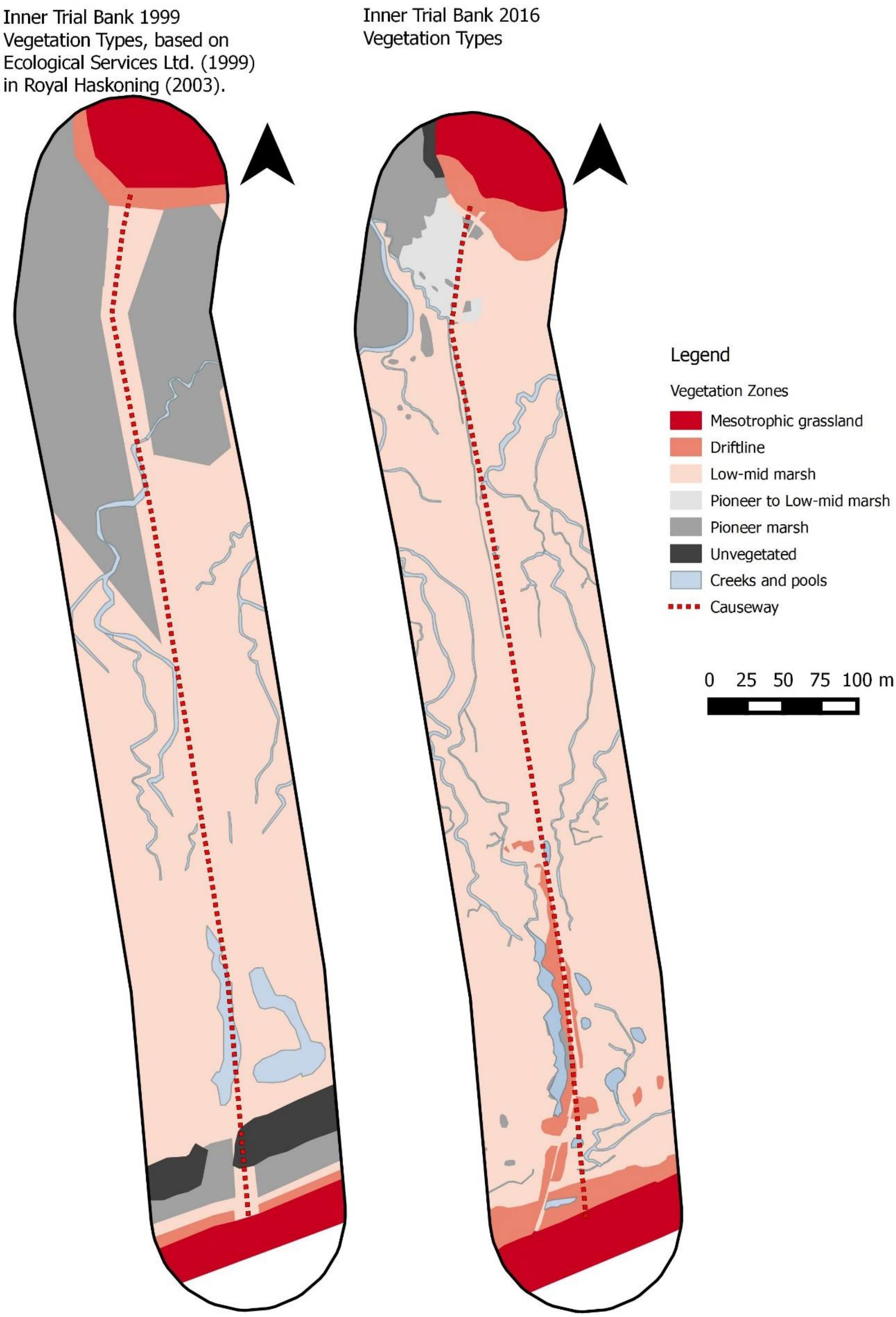


Figure 20 – Comparison of National Vegetation Classification types at Inner Trial Bank based on the 1971 (pre-construction) vegetation survey recorded by Randerson (1975) and the 1982-1985 (post-construction) vegetation survey recorded by Hill (1988). The causeway is given as a red dotted line.

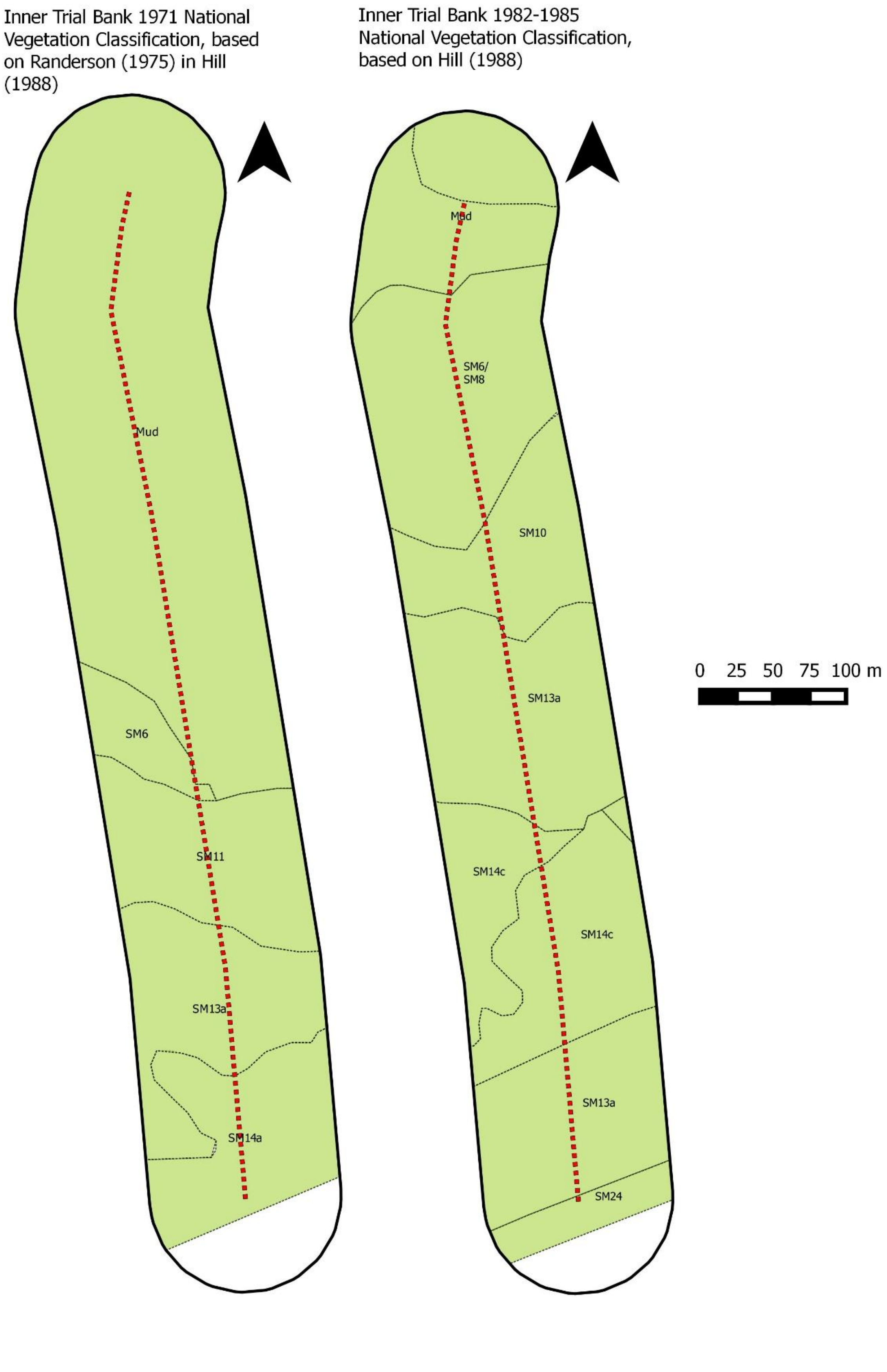
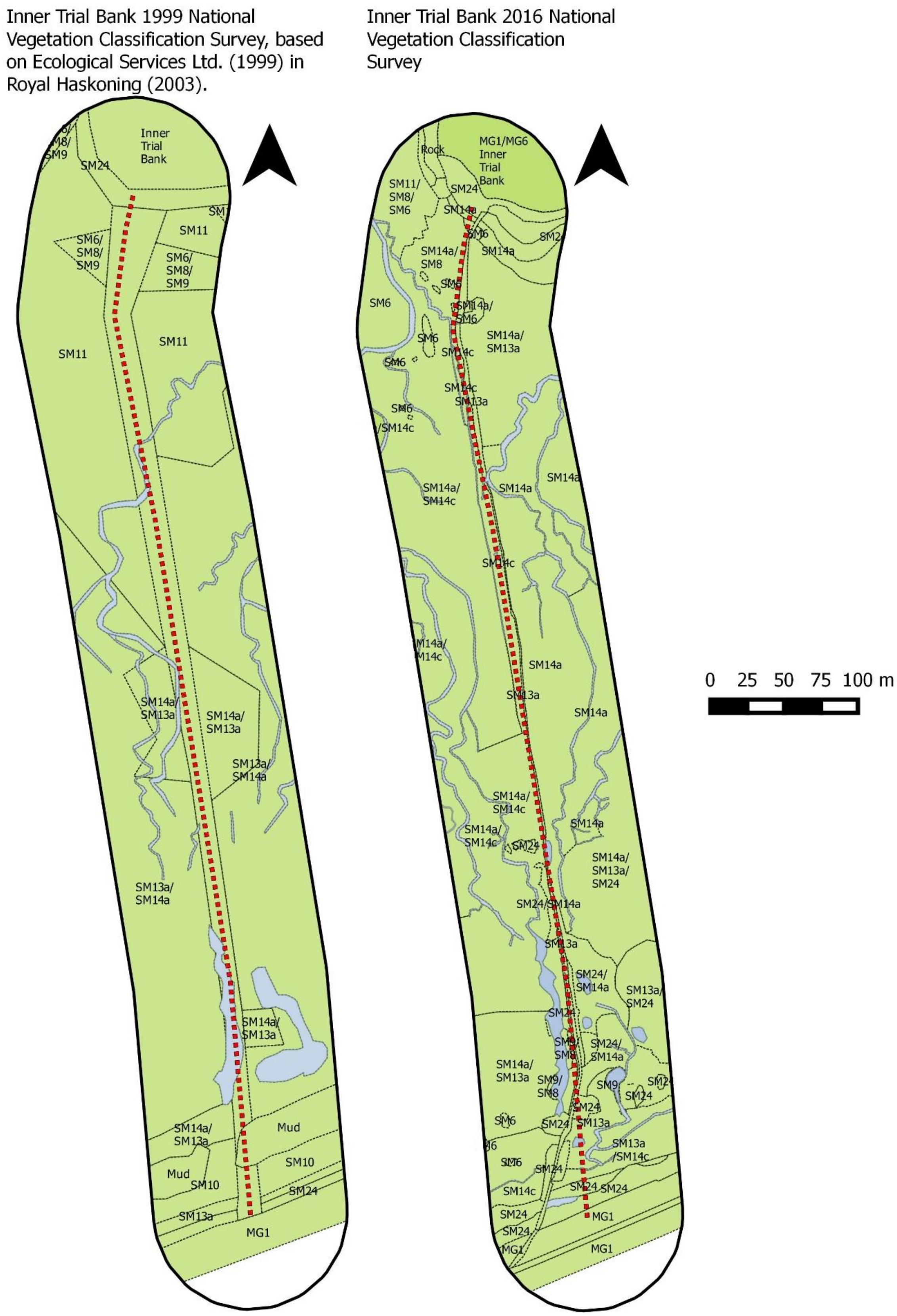


Figure 21 – Comparison of National Vegetation Classification types at Inner Trial Bank based on the 1999 (post-construction) vegetation survey by Ecological Services Ltd (1999) and the 2016 vegetation survey undertaken to determine the current vegetation condition as part of this thesis. The causeway is given as a red dotted line.



Tetney Marshes

At Tetney Marshes vegetation change has been documented by three main surveys, in 1987 (Burgess, 1988), 2001 (Dargie, 2001b) and 2016 (Table 7). Although there is no pre-construction survey[29] available for the site, there has been a considerable change in terms of the vegetation types present in the vicinity of the pipeline. As with the Inner Trial Bank project, at Tetney Marshes, a causeway was built alongside the pipeline, to enable access. However, the causeway was not removed at the end of the project. For much of its length the causeway is 2-3m higher than the surrounding marsh, supporting a mixture of mesotrophic grassland and ruderals along the top and upper slopes with SM24 on the lower slopes. One of the main changes is the expansion of driftline vegetation (*i.e.* SM24), while the amount of unvegetated bare mud has decreased substantially. It is hypothesised that the installation of the causeway has influenced the tidal regime of the site causing it to dry out. Consequently, the areas of bare mud have been colonised by pioneer marsh, and higher ground invaded by *Elytrigia atherica* – supporting hypothesis 7. As there is no pre-construction survey available to determine the original base-line conditions this can only be speculation. Figures 22-25 show the change over time in the vegetation zones at Tetney Marshes.

Table 7 - The extent of the main vegetation types at Tetney Marshes since 1987.

Vegetation Type	1987 (ha)	2001 (ha)	2016 (ha)
Mesotrophic grassland, ruderal vegetation along causeway	1.4	0.4	0.2
Driftline	3.6	3.2	5.4
Mid-upper marsh	0.9	0.8	0.6
Low-mid marsh	6.0	7.8	6.0
Pioneer to Low-mid marsh	0.0	0.5	1.1
Pioneer marsh	0.0	0.1	0.5
Creek/ Pool	1.4	2.1	2.2
Unvegetated (bare mud)	2.3	0.1	0.3

[29] Pipeline installation occurred in 1970

Figure 22 – Comparison of vegetation zones at Tetney Marshes (north-east section) based on the (post-construction) vegetation surveys recorded by Burgess (1988), Natural England in 2001 (Dargie, 2001b) and the 2016 vegetation survey undertaken to determine the current vegetation condition as part of this thesis. Note legend shown with Figure 22. The pipeline is given as a red dotted line.

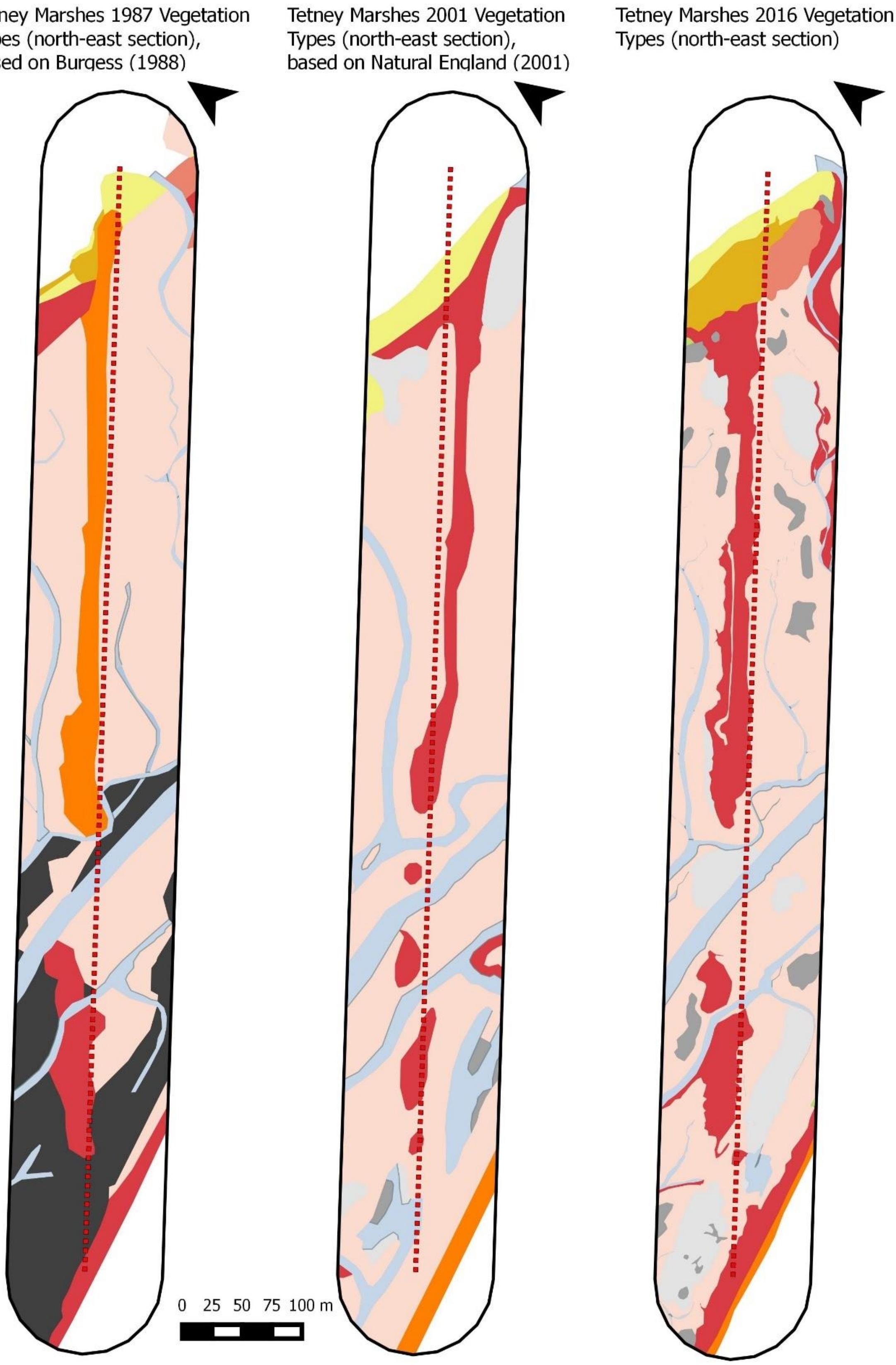


Figure 23 – Comparison of vegetation zones at Tetney Marshes (south-west section) based on the (post-construction) vegetation surveys recorded by Burgess (1988), Natural England in 2001 (Dargie, 2001b) and the 2016 vegetation survey undertaken to determine the current vegetation condition as part of this thesis. The pipeline is given as a red dotted line.

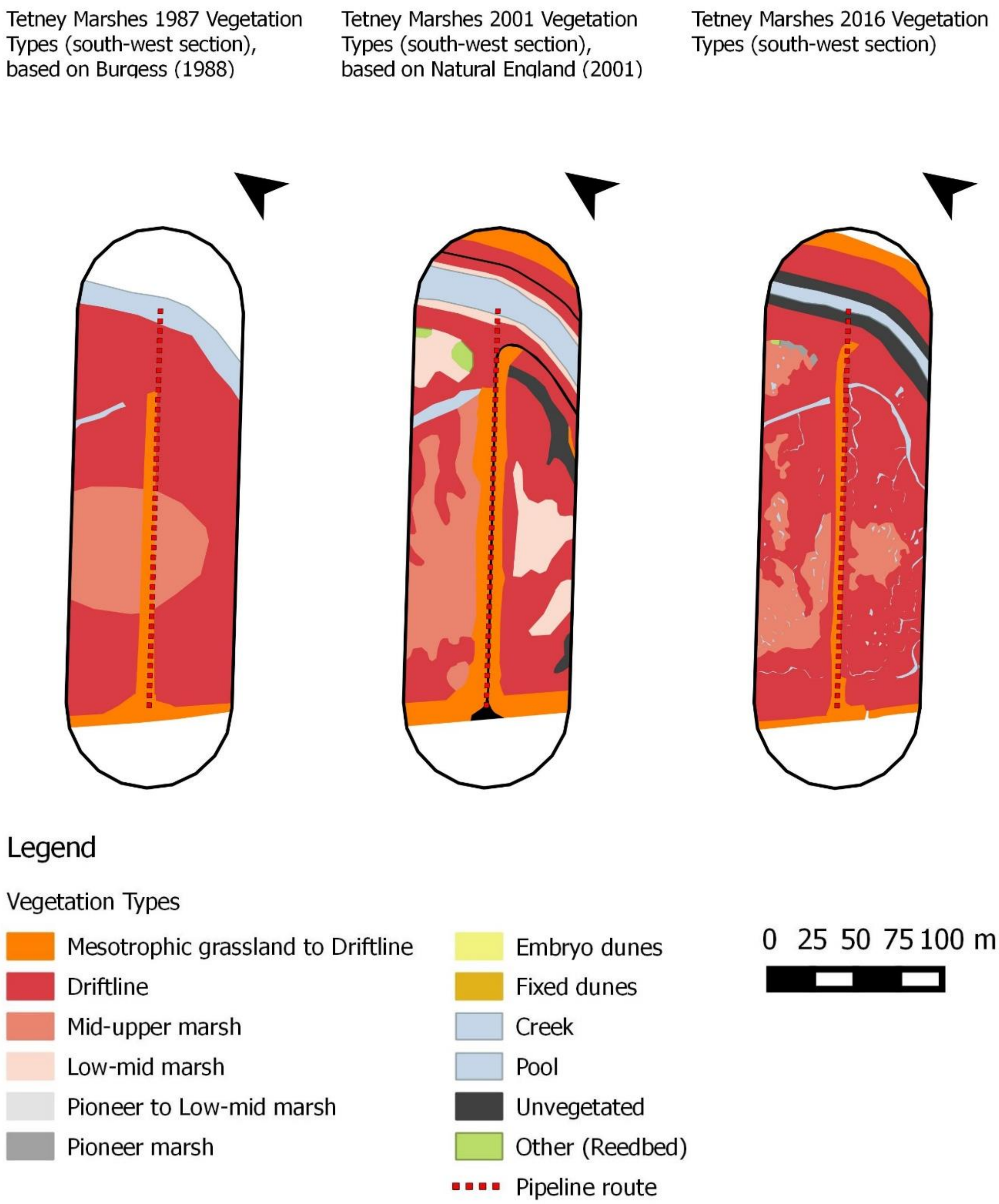


Figure 24 – Comparison of National Vegetation Classification types at Tetney Marshes (north-east section) based on the (post-construction) vegetation surveys recorded by Burgess (1988), Natural England in 2001 (Dargie, 2001b) and the 2016 vegetation survey undertaken to determine the current vegetation condition as part of this thesis. The pipeline is given as a red dotted line.

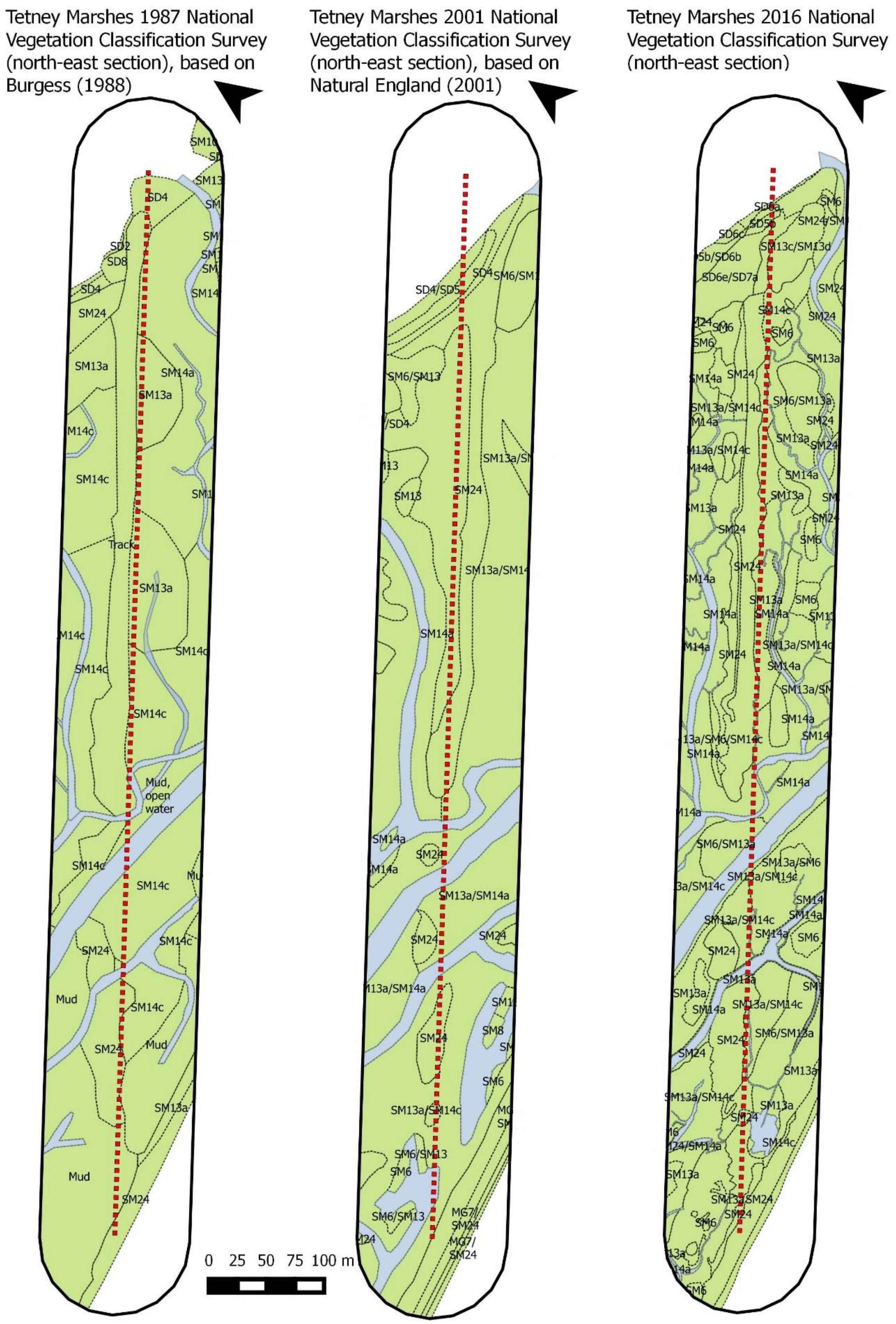
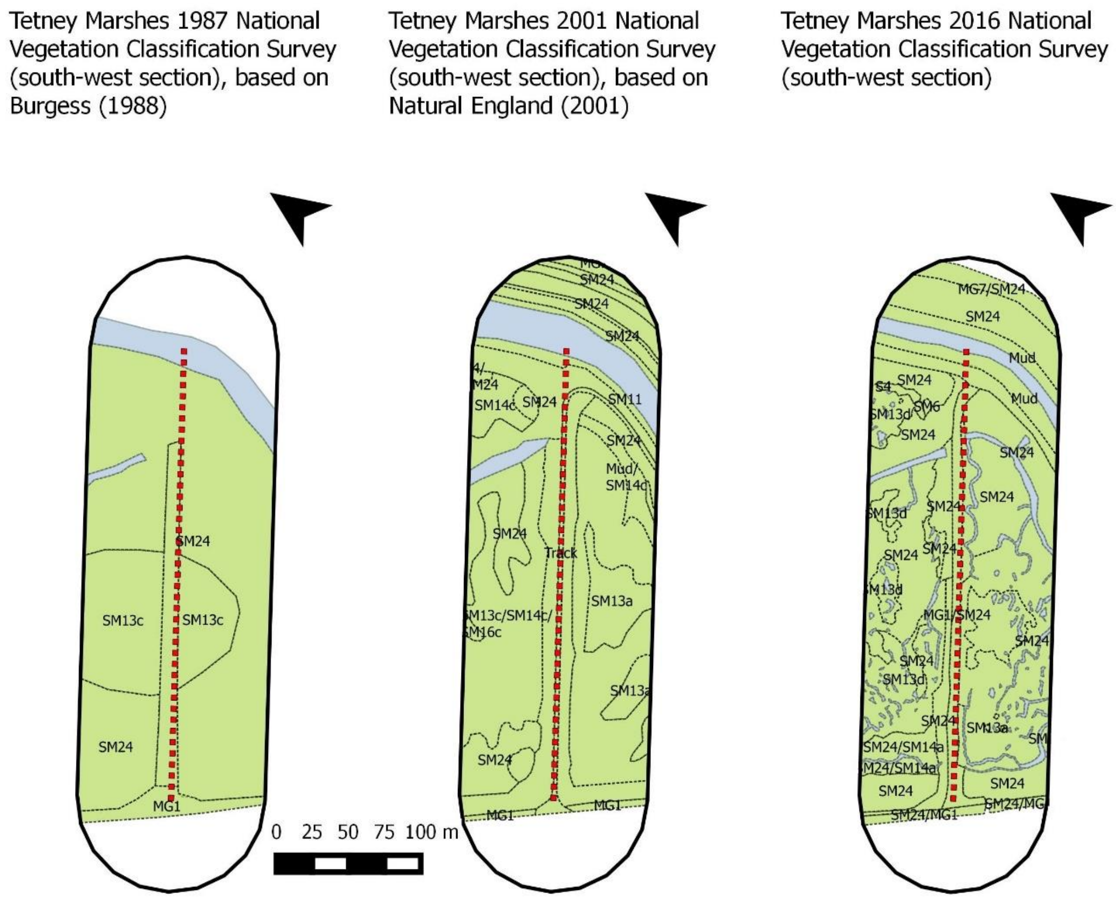


Figure 25 – Comparison of National Vegetation Classification types at Tetney Marshes (south-west section) based on the (post-construction) vegetation surveys recorded by Burgess in 1987 (Burgess, 1988), Natural England in 2001 (Dargie, 2001b) and the 2016 vegetation survey undertaken to determine the current vegetation condition as part of this thesis. The pipeline is given as a red dotted line.

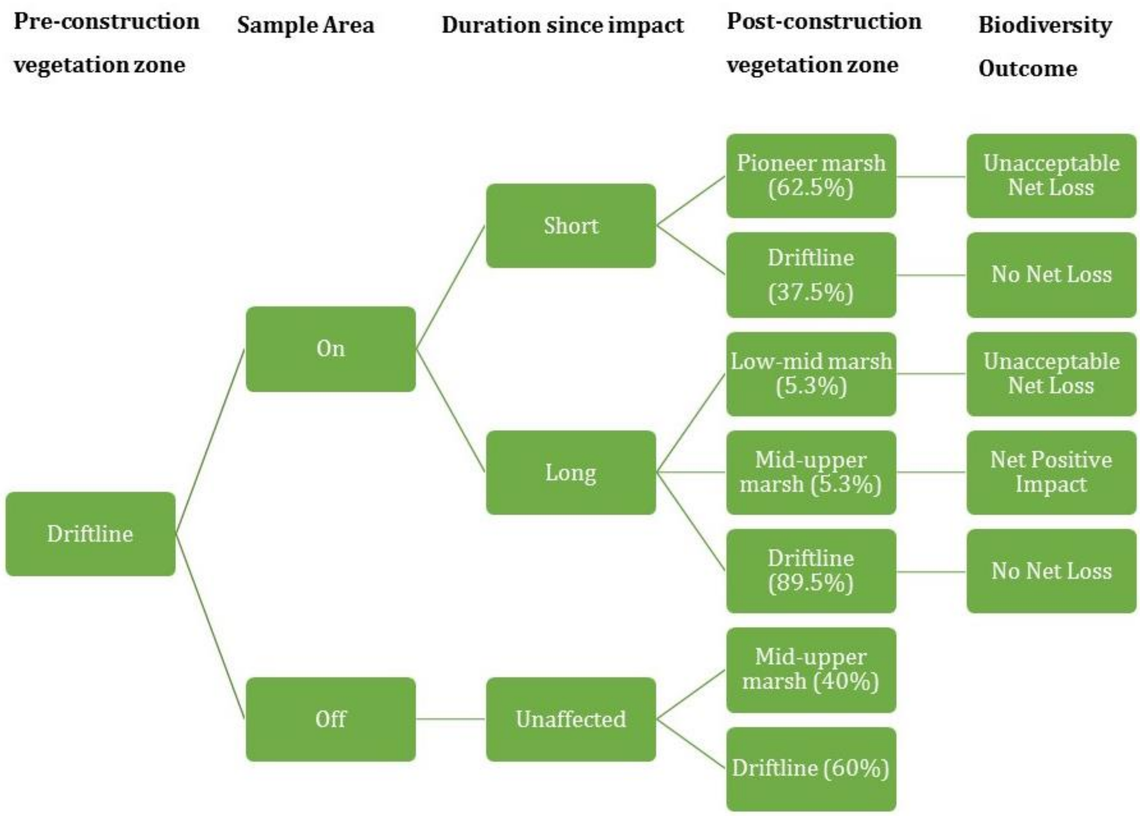


3.4.3 Outcomes of Recovery

By comparing the pre-construction vegetation types identified in the past, survey data against the current vegetation condition the likely direction of vegetation change following construction On and Off the pipeline can be determined over time.

Hypotheses 8 – [In the driftline zone, where impacts are minor the vegetation will recover quickly *i.e.* in the Short-term. Areas subject to heavy disturbance are likely however to support pioneer vegetation in the Short-term. In the Long-term driftline vegetation will fully recover]. Twenty quadrats were classified as supporting driftline vegetation prior to construction (Figure 26). After construction in the Short-term there was either the establishment of pioneer vegetation (62.5% of the quadrats) or the re-establishment of driftline vegetation (37.5% of the quadrats) – supporting the hypothesis. The outcome appears to be dependent on the severity of the construction impact. In areas where there was no change or an increase in topography and the root system remained intact (even if the above ground vegetation was lost), the recovery of driftline vegetation was recorded. However, where compaction or soil loss caused the topography to be lowered, and consequently there was an increase in tidal inundation, then the outcome was the loss of driftline species. In this scenario vegetation in the quadrats was replaced with early successional species that are more tolerant of frequent submersion. By the Long-term, driftline vegetation was the main vegetation type (supporting the hypothesis) with two individual occurrences where low-mid marsh or mid-upper marsh had established. In the Unaffected area (under what is presumed to be normal successional processes) driftline had either remained or had developed as mid-upper marsh (probably due to grazing).

Figure 26 – Likely vegetation outcomes of driftline vegetation following construction, based on a comparison of pre-construction vegetation types with current vegetation condition. Percentage values given represent the proportion of quadrats within each sample area and time since impact that result in each given post-construction vegetation type. The biodiversity outcome is based on those outlined in Theme 3 *Section 1.7.3*.



As described in *Section 1.6.5,* there are four possible outcome scenarios - No Net Loss, Acceptable Net Loss, Net Positive Impact and Unacceptable Net Loss. Considering the outcome pathway, a change of driftline vegetation to low-mid marsh or pioneer marsh would be an Unacceptable Net Loss. Where there is no change from driftline vegetation this would be a No Net Loss scenario. In a few cases the vegetation changed from driftline to mid-upper marsh. I consider this a Net Positive Impact as mid-upper marsh is typically more species-rich than driftline vegetation.

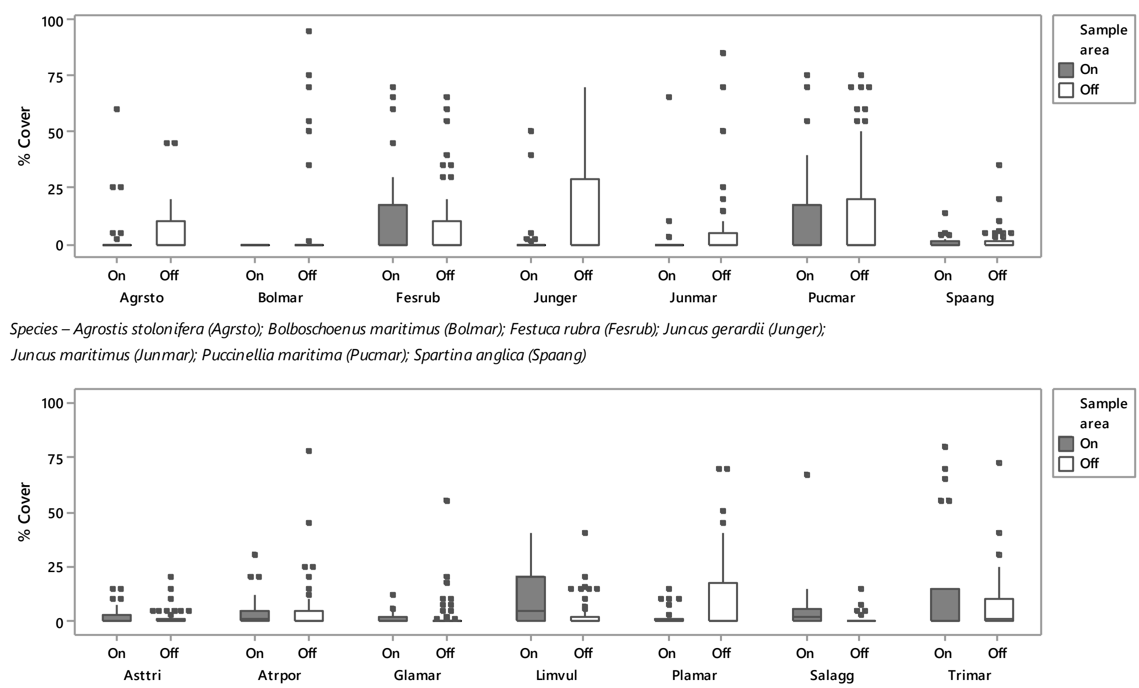
3.5 Results – Mid-upper Marsh

3.5.1 Vegetation Composition and Structure

The mid-upper marsh is the most species-rich zone recorded across the study sites. In total 35 vascular plant species were recorded. The most species-rich quadrats in this zone had eleven species, while the least diverse had two (Figure 5, *Section 3.3* and Figure 32).

Festuca rubra, *Puccinellia maritima* and *Juncus gerardii* were the most dominant graminoids. *Festuca rubra* appeared to have a slight preference to the On sample area but conversely was recorded as having a higher cover in the Unaffected area. *Agrostis stolonifera*, *Juncus gerardii* and *Plantago maritima* showed a preference to the Off/Unaffected sample areas. While *Puccinellia maritima* showed little difference between the On/Off sample areas but had a higher cover in the Short-term. A similar pattern was recorded for *Spartina anglica*. *Limonium vulgare* showed a clear preference for the On sample area, but showed little difference between the Short and Unaffected samples. The most frequent species, *Triglochin maritimum* was recorded in 63% of the quadrats in this zone. Boxplots showing cover of key species in this zone by sample area and time since impact are given in Figures 26-27.

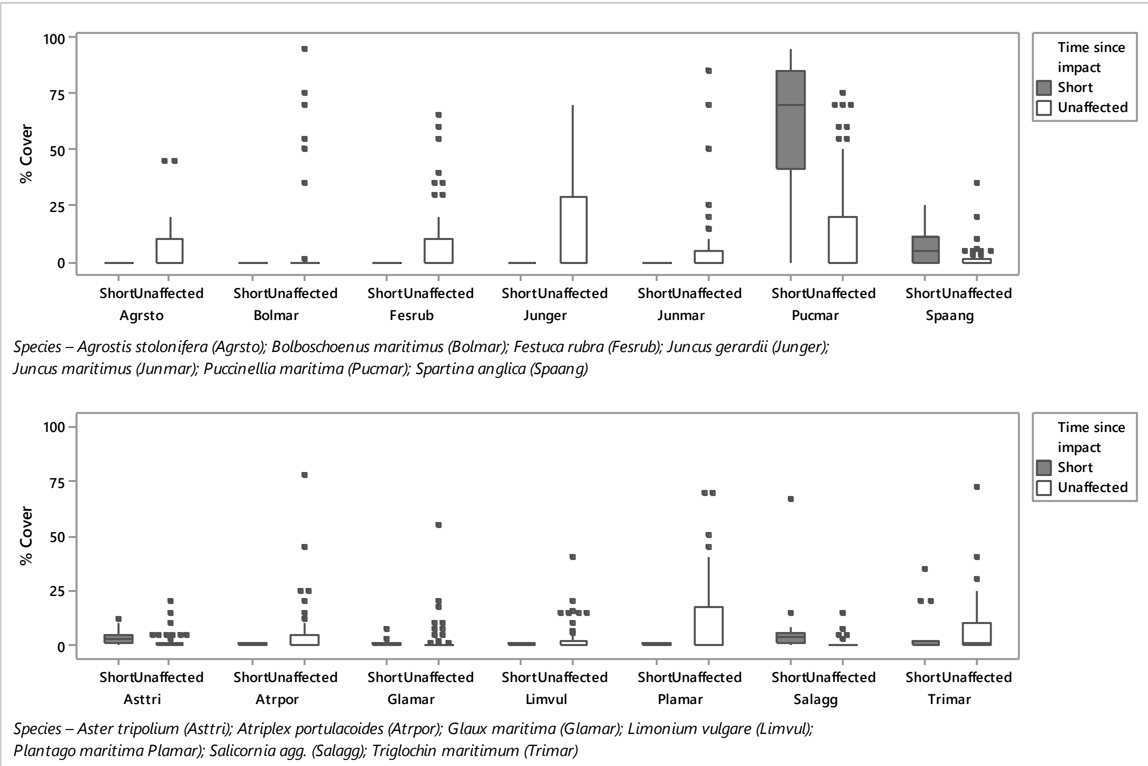
Figure 27 - Boxplots showing the cover of key mid-upper marsh species with sample area (On and Off). Typical graminoids are shown [top] and other herbs [bottom].



Species – Agrostis stolonifera (Agrsto); Bolboschoenus maritimus (Bolmar); Festuca rubra (Fesrub); Juncus gerardii (Junger); Juncus maritimus (Junmar); Puccinellia maritima (Pucmar); Spartina anglica (Spaang)

Species – Aster tripolium (Asttri); Atriplex portulacoides (Atrpor); Glaux maritima (Glamar); Limonium vulgare (Limvul); Plantago maritima Plamar); Salicornia agg. (Salagg); Triglochin maritimum (Trimar)

Figure 28 - Boxplots showing the cover of key mid-upper marsh species with time since impact (Short-term and Unaffected). Typical graminoids are shown [top] and other herbs [bottom].



General Linear Model and Tukey Pairwise Comparison Test

To test the hypotheses for the mid-upper marsh (*Section 3.2.4.*), analysis using a GLM and Tukey Pairwise Comparison test was used for each species or variable, with sample area or time since impact as a factor and distance from pipe as a covariate.

Hypothesis 9 – [Following construction the cover of typical grasses will be higher On the pipeline; and most marked between the Short-term and Unaffected vegetation]. *Festuca rubra* had a significantly higher cover in the On sample area (df=2; T=-2.57; p=0.030) - supporting the hypothesis for this species. However, neither *Agrostis stolonifera* nor *Puccinellia maritima* were significant for sample area – disproving the hypothesis for these species. For time since impact, *Agrostis stolonifera* and *Festuca rubra* showed no significant differences. However, the cover of *Puccinellia maritima* was shown to be significantly higher in the Short-term compared to the Unaffected vegetation (df=3; T=-4.25; p=0.000); but by the Medium-term the difference was not significant compared to the Unaffected vegetation indicating this species can quickly re-establish itself following disturbance but returns to the baseline abundance by the Medium-term.

Hypothesis 10 – [Slower growing graminoids initially have lower cover On the pipeline]. Cover of *Bolboschoenus maritimus* was significantly lower On compared to Off the pipeline (df=2; T=3.02; p=0.009) - proving the hypothesis for this species. Cover of this species was also significantly lower for the Short-term compared to Unaffected vegetation (df=3; T=2.65; p=0.044). Although not statistically significant, cover was also lower in Medium-term, compared to the Unaffected vegetation (df=3; T=2.57; p=0.055) and was significant in the Long-term compared to the Unaffected vegetation (df=3; T-2.95; p=0.020). This indicates that even in the long-term cover of this species may not recover to unaffected levels. However, for *Juncus gerardii* the difference in cover was significantly higher between the On and Off sample areas (df=2; T=-2.59; p=0.009), but not for time since impact, indicating that pipeline installation may actually favour its growth. The difference in cover of *Juncus maritimus* for both sample area and time since impact was not significant when using a GLM – disproving the hypothesis for this species.

Hypothesis 11 – [Characteristic herb species will have a lower cover On the pipeline]. The majority of the species recorded *e.g. Armeria maritima*, *Glaux maritima*, *Plantago maritima* and *Triglochin maritimum* did not show significant differences for either sample area or time since impact. *Limonium vulgare* did have significantly higher cover in the Unaffected vegetation compared to the Short-term (df=3; T=2.94; p=0.021), and for the Long-term compared to Short-term (df=3; T=-3.17; p=0.010). However, it was not significantly different for sample area.

Hypothesis 12 – [Cover of early successional species will be higher On the pipeline; and in the Short-term compared to Unaffected vegetation]. Neither *Aster tripolium* or *Salicornia* agg. was statistically significant for sample area. However, *Aster tripolium* had a higher cover during the Short- and Medium-term compared to Unaffected vegetation (Short-Unaffected df=3; T=-2.81; p=0.030 and Medium-Unaffected df=3; T=-5.61; p=0.000). Cover of *Salicornia* agg. was not significant for time since impact (Short-Unaffected df=3; T=-2.46; p=0.071).

Hypothesis 13 – [*Spartina anglica* will have a higher cover in the On sample area]. *Spartina anglica*, was recorded in 32.8% of the quadrats in this zone. It was found in all sample areas (22 quadrats On, 13 Adjacent and 14 Off); and had higher cover in the On sample area (mean cover 5.8%) compared to the Off (mean cover 0.8%). However, when considered using GLM of sample area and time since impact, the cover of *Spartina anglica* was not statistically significant.

Hypothesis 14 – [Following pipeline installation there will be an increase in the cover of bare ground in the On sample area]. Cover of bare ground showed a significant increase in bare ground in the Short (df=3; T=3.24; p=0.008), Medium (df=3; T=4.12; p=0.000), and Long-term (df=3; T=3.95; p=0.001), compared to the Unaffected vegetation. The difference in the means for cover of bare ground remained relatively constant over time[30] (Figure 6). The cover of algae species, herbs, and graminoids were not significant.

A full summary of the results of the GLM and Tukey Pairwise Comparison for the mid-upper marsh is given in Appendix 3 Tables 19-22.

---

[30] Short-Unaffected DoM = 0.672; Medium-Unaffected DoM = 0.832; Long-Unaffected DoM = 0.735

Canonical Correspondence Analysis

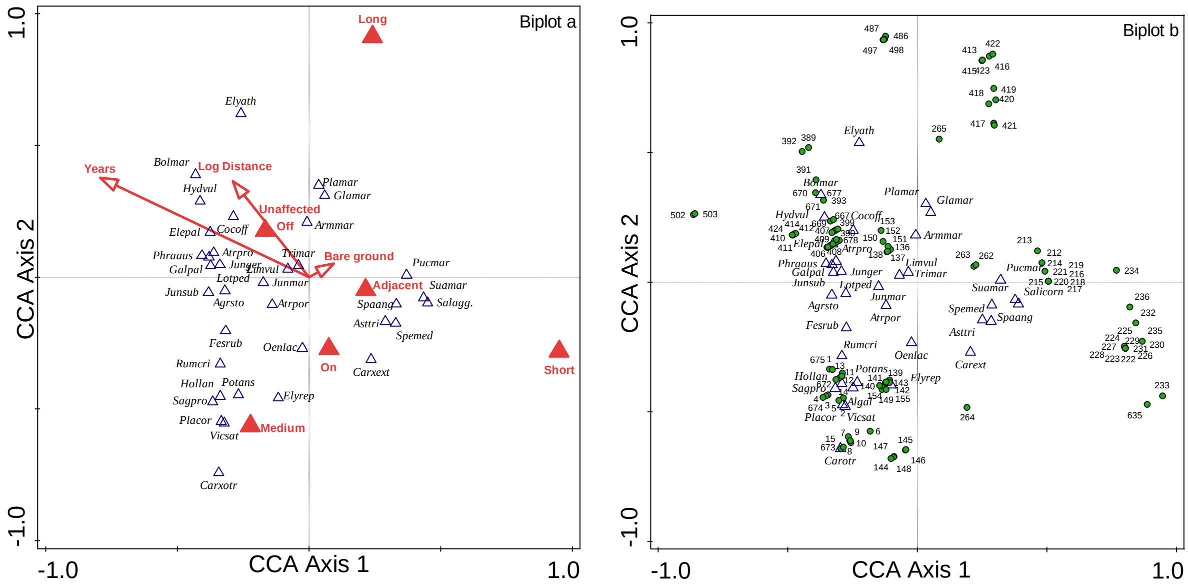
In CCA and forward selection of environmental variables with the mid-upper marsh data the year factor explains the greatest amount of variation in the data. Other significant factors were time since impact Long- and Medium-term (Table 8).

Table 8 - Explanatory power of environmental variables in CCA analysis for mid-upper marsh. Significant effects are given in bold.

Environmental Variable	Explains %	Contribution %	Pseudo-F	P-value	P(adj)
Years	**5.9**	**32.4**	**7.3**	**0.0002**	**0.0007**
Time since impact – Long	**4.6**	**25.5**	**6**	**0.0002**	**0.0004**
Time since impact – Medium	**3**	**16.3**	**3.9**	**0.0002**	**0.0004**
% Bare ground	1.8	9.8	2.4	0.0208	0.0520
Log distance from pipe	1.1	5.9	1.4	0.1300	0.1970
Time since impact – Unaffected	0.9	5	1.2	0.2282	0.2942
Time since impact – Short	0.9	5	1.2	0.2382	0.2942
Sample area – Adjacent	0.9	5	1.2	0.2388	0.2653

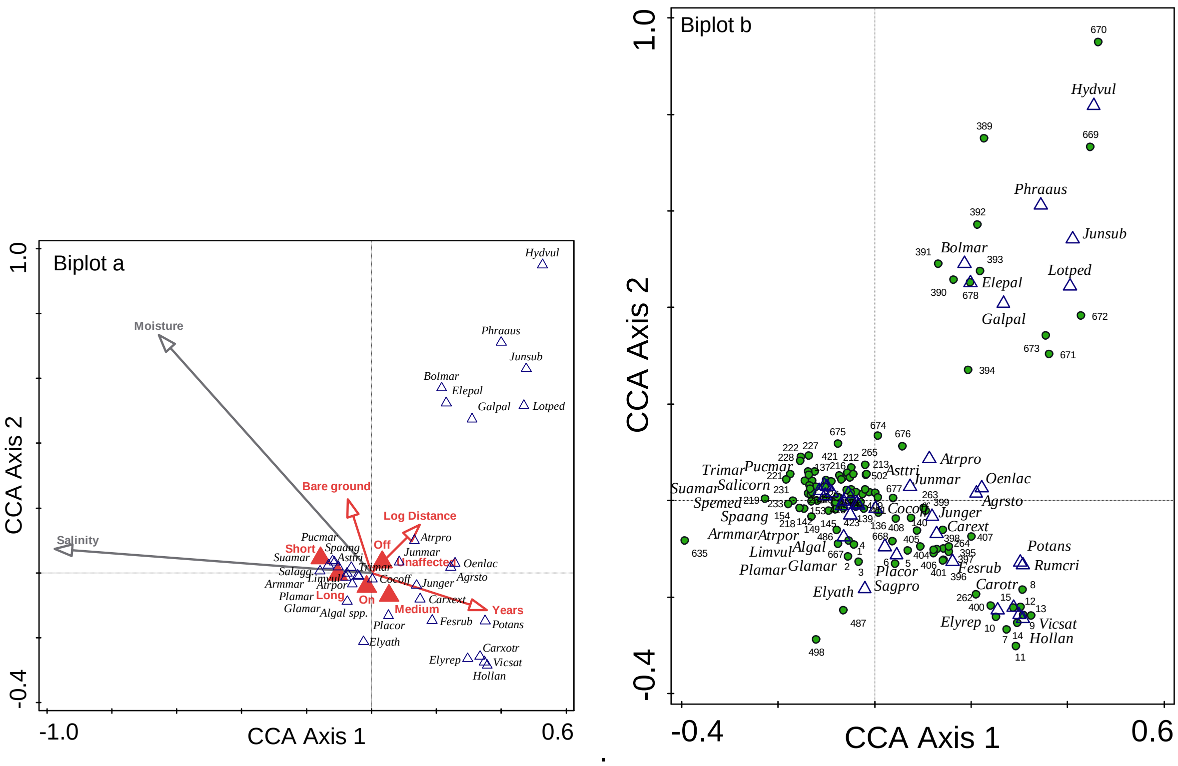
The CCA plot (Figure 29) shows that the explanatory variables of On and Adjacent are in close proximity to each other; and are associated with species typical of low-mid marsh or pioneer marsh *i.e. Aster tripolium*, *Puccinellia maritima*, *Salicornia* agg., *Spartina anglica* and *Suaeda maritima*. The Unaffected and Off factors are associated with species typical of the mid-upper marsh and represent a species-rich community. Species found in proximity to these factors include *Armeria maritima*, *Glaux maritima*, *Juncus gerardii*, *Plantago maritima*, and *Triglochin maritimum*. The Medium-term appears here to be associated with transitional vegetation (*i.e.* not true saltmarsh vegetation that develops at the uppermost section of the marsh) with species such as *Elytrigia repens*, *Holcus lanatus*, *Oenanthe lachenalii*, *Potentilla reptans*, *Vicia sativa* and *Rumex crispus*.

Figure 29 - Species-environmental variable biplot (a) and species-quadrats biplot (b) using CCA (of the first two axes) with environmental variables selected by forward selection procedure. Total variation is 4.02, explanatory variables account for 18.1% (adjusted explained variation is 13.0%); 1st Axis pseudo- F=9.2, P=0.0002; All Axes pseudo-F=3.5, P=0.0002. The species (shown as blue triangles) are labelled by the first three letters of the generic name and the first three letters of the specific name. Quadrats are shown as green circles with the quadrat number



The inclusion of Ellenberg values (Hill et al., 1999) as additional explanatory variables in the CCA analysis increases the percentage variation explained by the environmental variables from 18.1% to 56.0%, and the forward selection process identified all five variables as being significant. Of these, light was the most significant explaining 16.9% of the variation (Figure 30). As with the driftline zone there is a correlation between an increase in salinity and moisture with the On and Short-term factors, with species typical of early successional marsh. A cluster of quadrats (389-394 and 669-673 to the top right of the plot) distinguishes quadrats recorded from Poole which were dominated by either *Bolboschoenus maritimus* or *Juncus subnodulosus*. This vegetation develops as a mire community where there is impeded drainage.

Figure 30 - Species-environmental variable biplot (a) and species-quadrats biplot (b) using CCA (of the first two axes) with environmental variables selected by forward selection procedure. The biplot includes Ellenberg values for moisture and salinity. Total variation is 4.02, explanatory variables account for 39.6% (adjusted explained variation is 34.6%); 1st Axis pseudo- F=22.9, P=0.0002; All Axes pseudo-F=7.9, P=0.0002. The species (shown as blue triangles) are labelled by the first three letters of the generic name and the first three letters of the specific name. Quadrats are shown as green circles with the quadrat number.

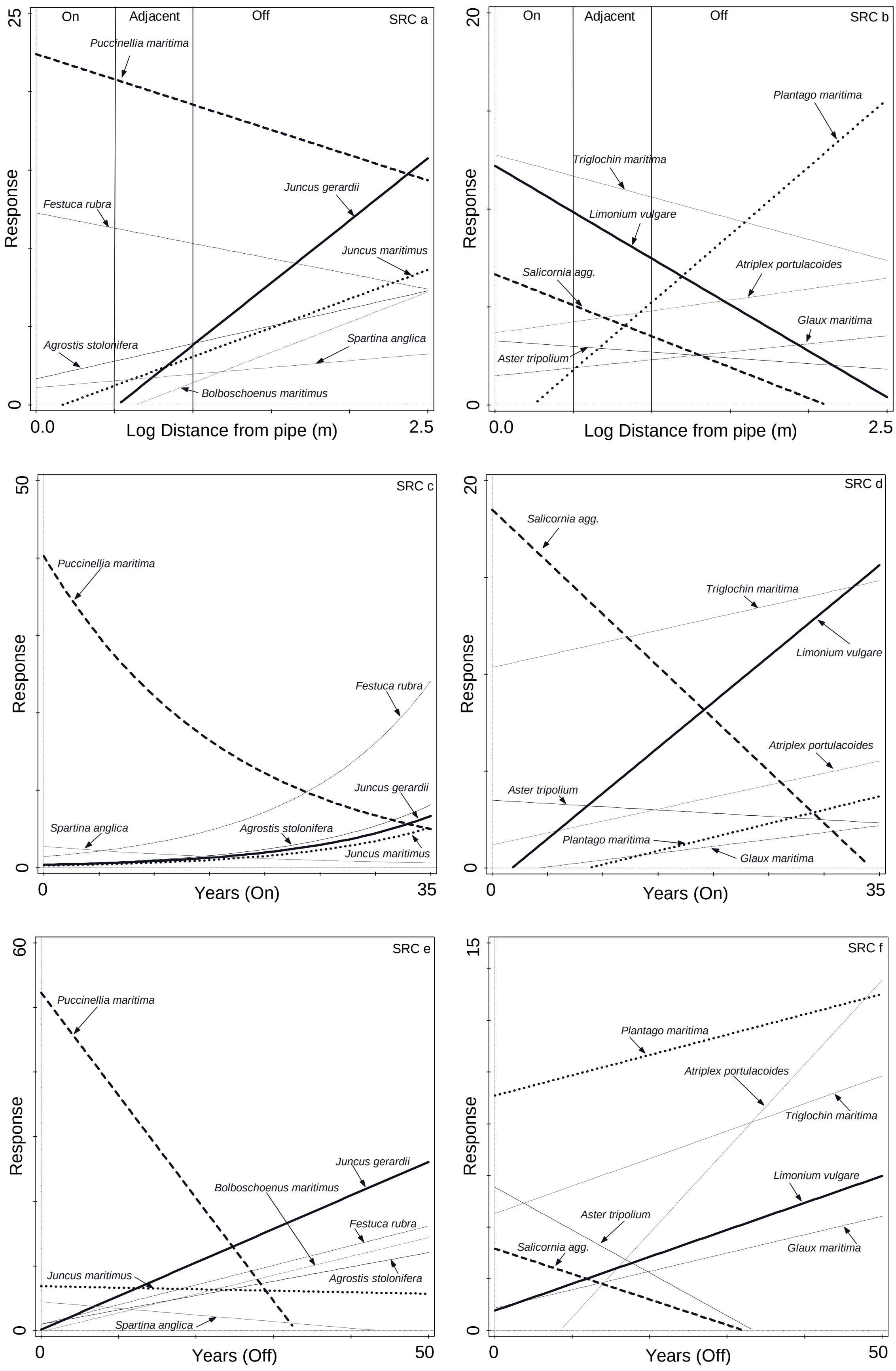


Species Response Curves

The Species Response Curves (Figure 31) for mid-upper marsh shows a rapid decrease in cover of *Puccinellia maritima* with distance from the pipe and over time following construction (On the pipeline) supporting the GLM analysis and hypothesis 9. For example, within the first 5 years after construction, cover of *Puccinellia maritima* had decreased from 40% to 30%, by 10 years it had fallen to ca. 22%, and by 20 years <12% (which is equivalent to the mean cover for this species 14.1% - see Figure 27). *Puccinellia maritima* is a species more typical of the low-mid marsh so this decrease was expected. *Festuca rubra* also shows a reduction in cover with distance (again supporting hypothesis 9). However, when its cover was considered with time On the pipeline it shows that it was initially slow to recover, but then increased rapidly around 20 years with its cover increasing from<10% to 25% by 35 years. This perhaps indicates that it can grow in the disturbed construction zone more readily than other typical mid-upper marsh species, although it takes some time to become established. Both *Agrostis stolonifera* and *Juncus maritimus* showed a similar recovery pattern, increasing with distance from the pipe. Over time on the pipeline both species take ca. 25 years before they show signs of recovery (indicating that it prefers the undisturbed areas and disproving hypothesis 9). *Bolboschoenus maritimus* and *Juncus gerardii* showed a strong increase in cover with distance but were not found in the On sample area. With time, *Juncus gerardii* became established but as with the *Agrostis stolonifera* and *Juncus maritimus* this took until ca. 25 years. *Bolboschoenus maritimus* was not present in quadrats On the pipeline. *Spartina anglica* showed a small increase in cover with distance, but with time On the pipeline its cover fell so that it was virtually absent by 15-20 years.

The SRC shows that the pioneer species *Salicornia* agg. decreased rapidly in cover with distance (not being found in undisturbed quadrats away from the pipeline). Over time its cover decreased from ca. 18% immediately after construction to 0% by 35 years. This supports hypothesis 12 and 17. Both *Limonium vulgare* and *Triglochin maritimum* showed a similar response to that of *Festuca rubra i.e.* with a strong reduction in cover with distance from the pipe but an increased in cover over time. For example, cover of *Limonium vulgare* with distance deceased from 12% close to the pipe to 0% in undisturbed areas; and increased from being absent after construction to around 16% cover by 35 years. *Atriplex portulacoides*, *Glaux maritima* and *Plantago maritima* all increased in cover with distance and time (supporting hypothesis 11). On the pipe both *Plantago maritima* and *Glaux maritima* showed an initial delay in recovery taking between 5 and 10 years before they appeared. This indicates that these species are not tolerant of disturbance.

Figure 31 - Species Response Curves of log distance from the pipeline (a & b) and years On the pipeline (c & d) and years Off the pipeline (e & f) with typical mid-upper marsh species. The plot uses a poisson response distribution and a linear predictor. The response value indicates species abundance. For log distance (a & c) an indication of the sample area (On, Adjacent and Off) has been given.

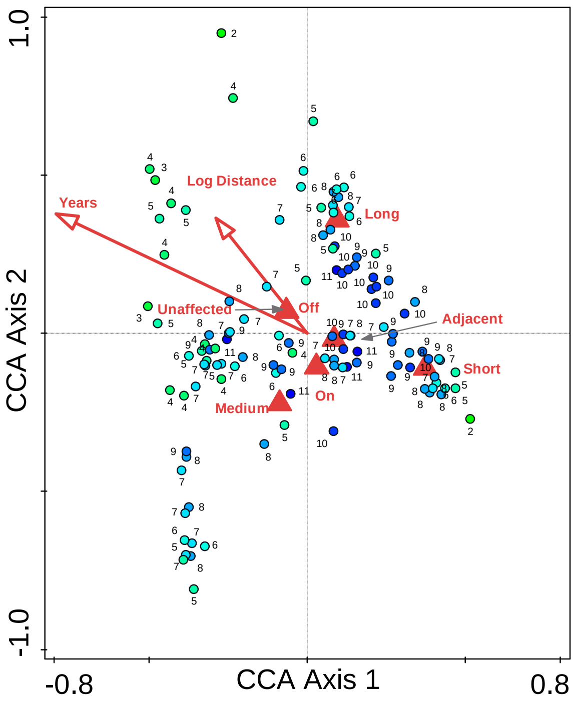


Species Diversity

Hypotheses 15 – [In the Short-term species-richness of the mid-upper marsh will be lower than the Unaffected or Long-term vegetation]. The species diversity diagram shows that in the mid-upper marsh species-richness for most of the environmental variables are similar (Figure 32). Quadrats associated with On and Short-term generally have between 5-10 species, similar to that recorded in the Long-term and Unaffected quadrats – disproving the hypothesis. Individual quadrats with low species-richness in the top-left hand section of the plot (associated with increased years and distance) are those which were previously classified as mid-upper marsh but have undergone succession to driftline vegetation.

No nationally rare or scarce plant species was recorded in this zone. Three species listed as Near Threatened (Stroh et al., 2014) were recorded in this zone, namely *Hydrocotyle vulgaris* (recorded in 2 quadrats; both Off the pipe), *Limonium vulgare* (recorded in 56 quadrats; 20 On, 15 Adjacent and 21 Off), and *Oenanthe lachenalii* (recorded in 6 quadrats; 2 On, 1 Adjacent and 3 Off).

Figure 32 - Species diversity diagram showing species number per quadrat in the mid-upper marsh. Green circles indicate low species-richness, while blue indicate high-species richness within the zone; numbers are the actual number of species in the quadrat.



3.5.2 *Ecosystem Function*

Mid-upper Marsh Resource

The best examples of mid-upper marsh develop at grazed sites where often no single species attain dominance. It typically develops in the zone between mean high water and the extreme high-water spring tide level. So, in general terms mid-upper marshes are covered by less than 360 tides per year, have a minimum of 10-days continuous exposure and less than an hours daily daylight submergence (Adnitt et al., 2007). Several NVC types are represented in this zone; those present at the study sites include SM13 *Puccinellia maritima* salt-marsh community (sub-communities SM13b-d); SM16 *Festuca rubra* salt-marsh community (sub-communities SM16a-b); and SM18 *Juncus maritimus* salt-marsh community (sub-community SM18b).

Examples of mid-upper marsh were restricted within the study sites. The best examples of this vegetation type were recorded at Walney Island, Poole Harbour and at Tetney Marshes. At Walney Island the most significant area of mid-upper marsh was found at South Morecambe, where it extends roughly 50m from the shore. It was also recorded as a narrow strip (a couple of meters wide) at the North Morecambe and Rivers Fields. At Poole Harbour, large areas of mid-upper marsh were recorded on Wytch Moor, with smaller areas at Shotover Moor and Cleavel Point. At Tetney Marshes discrete patches were recorded in-and-amongst the driftline vegetation. Mid-upper marsh was not recorded at Inner Trial Bank (probably due to the construction of the sea wall in the 1950's and subsequent agricultural land reclamation) and at Thanet where much of the shoreline has been truncated by the construction of roads and buildings. The extent of mid-upper marsh habitat at each of the study sites in 2015-16 is given in Table 9. Due to differences in the size of the working width (*i.e.* On sample area), the habitat areas (ha) are not directly comparable between sites, therefore the habitat resource is also provided as a percentage of the total site area.

Table 9 - Extent (ha and % of total area) of the mid-upper marsh across study sites in 2015-16.

Location	Site	Area (ha) in 2015-16	% of survey area
Humber	Tetney Marshes	0.6	4
Pegwell Bay	Thanet	0.0	0
Poole Harbour	Cleavel Point	0.3	14
Poole Harbour	Shotover Marsh	0.2	29
Poole Harbour	Wytch Moor	0.6	13
The Wash	Inner Trial Bank	0.0	0
Walney Island	North Morecambe	0.4	4
Walney Island	Rivers Fields	0.1	1
Walney Island	South Morecambe	0.7	9
Total habitat area surveyed in 2015-16 (ha)		**2.8**	
Proportion of total survey area (%)		**4**	

Hypothesis 16 – [The extent (ha) of mid-upper marsh habitats following construction, will fall in the Short-term, but in the Long-term will reach pre-construction extents].

South Morecambe

The availability of a pre-construction vegetation survey completed in 1981 (Rae, 1981) at South Morecambe allows the change in vegetation zonation, in particular the mid-upper marsh resource to be documented. Vegetation maps showing the main vegetation zones and NVC types recorded at South Morecambe are shown in Figures 33 and 34. Table 10 shows the extent (ha) of mid-upper marsh vegetation and as a percentage of the total for each sample area *i.e.* On, Adjacent and Off the pipeline.

Table 10 - The extent of mid-upper marsh at South Morecambe over 35 years following the installation of a pipeline.

Year	**1981 (pre-construction survey)**			**2016**		
Area	**On**	**Adjacent**	**Off**	**On**	**Adjacent**	**Off**
Extent (ha)	0.2	0.2	0.2	0.2	0.2	0.2
% of survey area	7	6	6	9	9	7

Figure 33 – Comparison of vegetation types at South Morecambe based on the 1981 (pre-construction) vegetation survey by Rae (1981) and the 2016 vegetation survey undertaken to determine the current vegetation condition as part of this thesis.

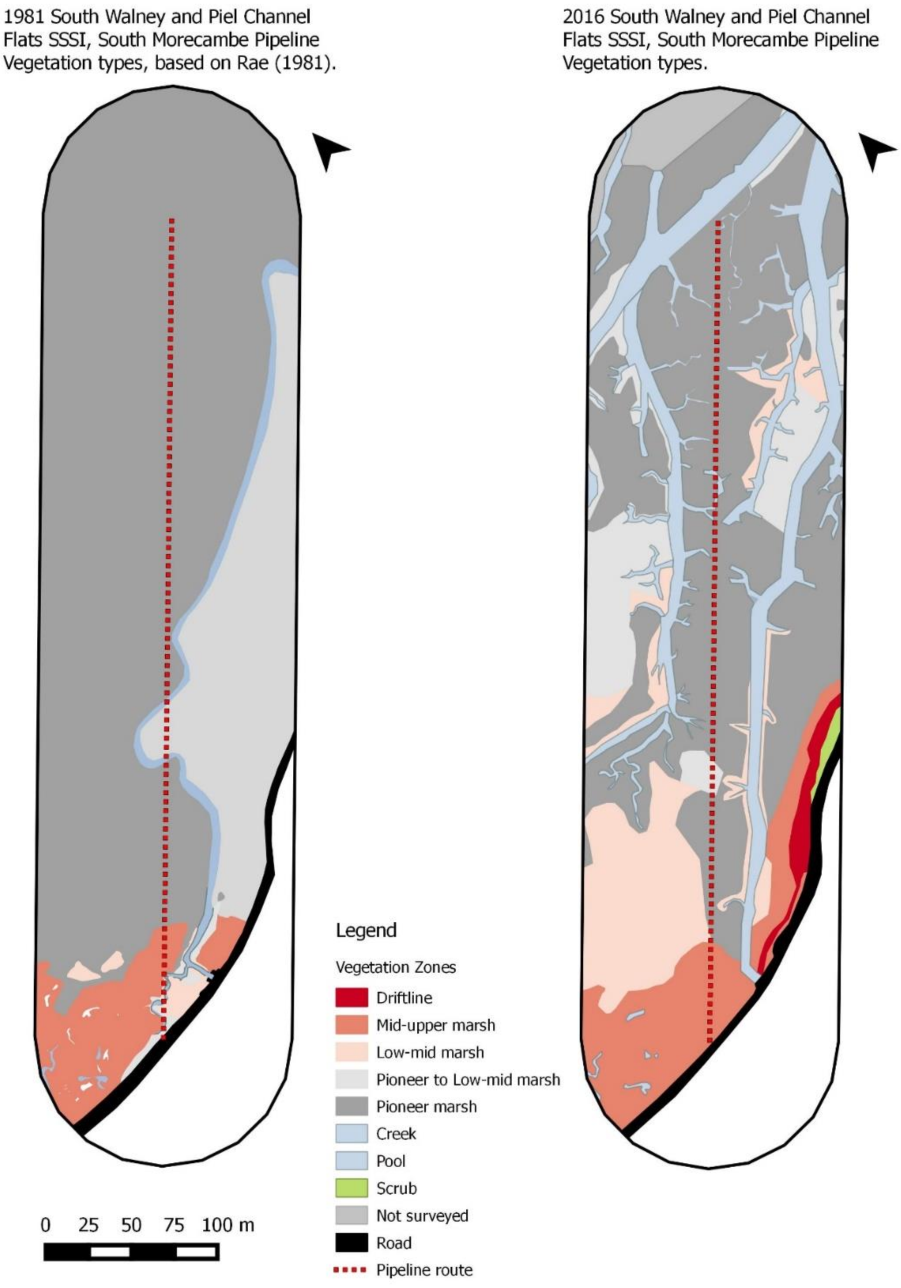


Figure 34 - Comparison of National Vegetation Classification types at South Morecambe based on the 1981 (pre-construction) vegetation survey by Rae (1981) and the 2016 vegetation survey undertaken to determine the current vegetation condition as part of this thesis.

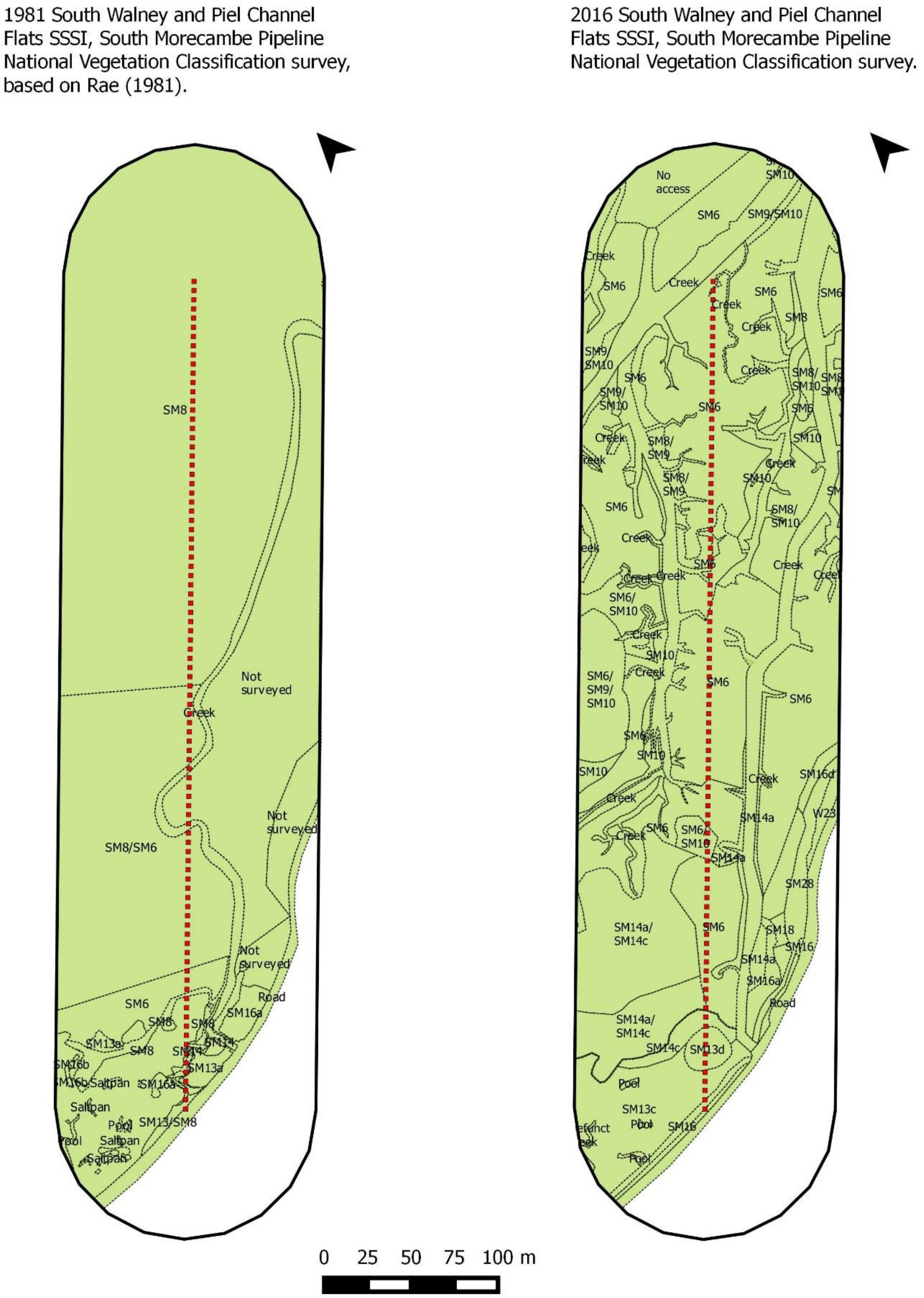


Table 10 and Figures 33-34 shows that in 1981 (*i.e.* the pre-construction survey), mid-upper marsh was recorded in all three sample areas, with a slightly higher area On the pipeline compared to the Adjacent and Off sample areas. This was also the case in the 2016 survey, although in all sample areas the amount of mid-upper marsh had increased – disproving hypothesis 16. It appears from the habitat maps (from 1981 (Rae) and 2016) that the increase in upper marsh has occurred in three ways. The construction of the pipeline resulted in the main creek (known as Wylock Eea) and a side tributary being rerouted, the change in creek position probably resulted in this part of the marsh becoming drier, consequently allowing the development of mid-upper marsh where low-mid marsh was previously recorded. There has also been a reduction in the number of saltpans in the mid-upper marsh since 1981, these appear to have been infilled and colonised by the surrounding mid-upper marsh. Finally, it appears that mid-upper marsh has developed further along the shore.

The pre-construction survey by Rae (1981) records that in the mid-upper marsh 16 different species were recorded. Of these *Aster tripolium*, *Festuca rubra*, *Puccinellia maritima* and *Triglochin maritimum* were the most abundant. The survey also noted that the saltmarsh was subject to summer grazing by cattle. This resulted in *Atriplex portulacoides* being restricted to the steep creek edges (as it is not tolerant to trampling), and abundant *Juncus gerardii* and *Triglochin maritimum* which are less palatable to cattle than the other herbs. In 2016 (at the time of the survey), there was no evidence of cattle grazing at this location, but it was recorded further to the north.

The 1981 habitat map shows broad habitat types with dominant species; and the data from the quadrat sampling allows an accurate identification of the NVC types recorded. Much of the mid-upper marsh supported SM16a *Festuca rubra* salt-marsh community, *Puccinellia maritima* sub-community with smaller areas of SM16b *Festuca rubra* salt-marsh community, sub-community with *Juncus gerardii* dominant recorded around the saltpans. In 2016, much of this area was recorded as SM13c *Puccinellia maritima* salt-marsh community, *Limonium vulgare-Armeria maritima* sub-community with some SM16a. This change in NVC type may be due to a relaxation in grazing here as *Armeria maritima*, *Limonium vulgare* and *Plantago maritima* are all susceptible to grazing. A discrete area of SM13d *Puccinellia maritima* salt-marsh community, *Plantago maritima-Armeria maritima* sub-community appears to have developed in the vicinity of the original creek alignment which was previously recorded as low-mid marsh.

Tetney Marshes

As discussed in the driftline section, at Tetney Marshes vegetation change has been documented since 1987. Mid-marsh vegetation is represented by the NVC sub-communities SM13c, SM13d and SM16c. Table 7 shows the total area of mid-upper marsh has fallen slightly from 0.86ha in

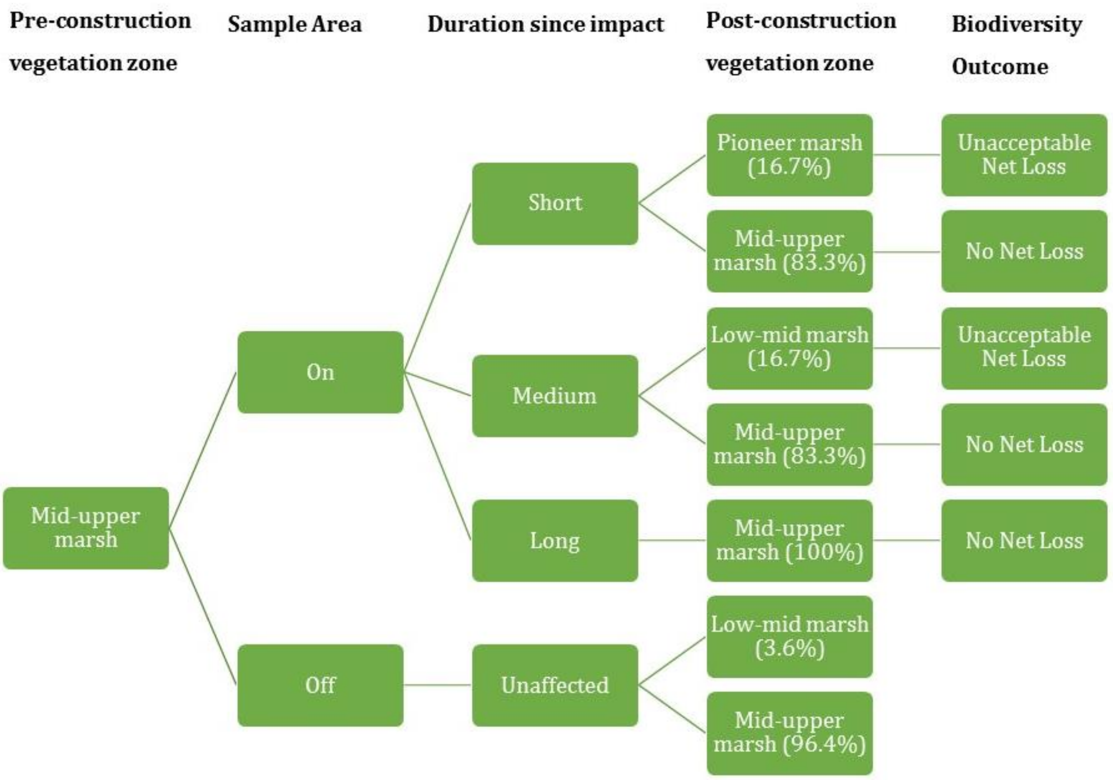
1987 to 0.6ha in 2016. From the vegetation maps (Figures 22-25) much of this change is due to the expansion of driftline vegetation. The loss of mid-upper marsh over time supports hypothesis 16, although as noted previously without an available pre-construction survey map this is speculation.

3.5.3 Outcomes of Recovery

Hypotheses 17 – [The mid-upper marsh is expected to respond poorly to construction activities and in the Short-term there will be increase in early successional communities *i.e.* pioneer marsh or low-mid marsh]. The recovery outcome of 119 quadrats classified prior to construction as mid-upper marsh vegetation (Figure 35). On the pipeline in the mid-upper marsh, most (83%) of the vegetation was classified as mid-upper marsh in the Short-term (disproving the hypothesis), with a small proportion classified as pioneer vegetation. This perhaps surprising outcome may be attributed to the fact that in the majority of situations where the pipeline crossed mid-upper marsh turves were lifted prior to construction and were then replaced following works (*e.g.* Poole Harbour sites). Similarly, at South Morecambe for example, saltmarsh turves were sourced from a nearby marsh and these were re-laid following installation. The areas of pioneer marsh developed at those sites where the vegetation was not protected. In the Medium-term similar proportions of mid-upper marsh are noted, but the pioneer marsh had succeeded to low-mid marsh vegetation. By the Long-term all the vegetation had recovered to mid-upper marsh. In the unaffected area (under what is presumed to be normal successional processes) mid-upper marsh was recorded in 96.4% of the quadrats. Two quadrats supported low-mid marsh.

Considering the outcome pathway, a change from mid-upper marsh vegetation to low-mid marsh or pioneer marsh would be an Unacceptable Net Loss as this change is probably due to sediment compaction, or a change in elevation, redox potentials or drainage through a loss in topography. Where there is no change from mid-upper marsh vegetation this would be a No Net Loss scenario.

Figure 35 - Likely vegetation outcomes of mid-upper marsh vegetation following construction, based on a comparison of pre-construction vegetation types with current vegetation condition. Percentage values given represent the proportion of quadrats within each sample area and time since impact that result in each given post-construction vegetation type. The biodiversity outcome is based on those outlined in Theme 3 *Section 1.7.3*

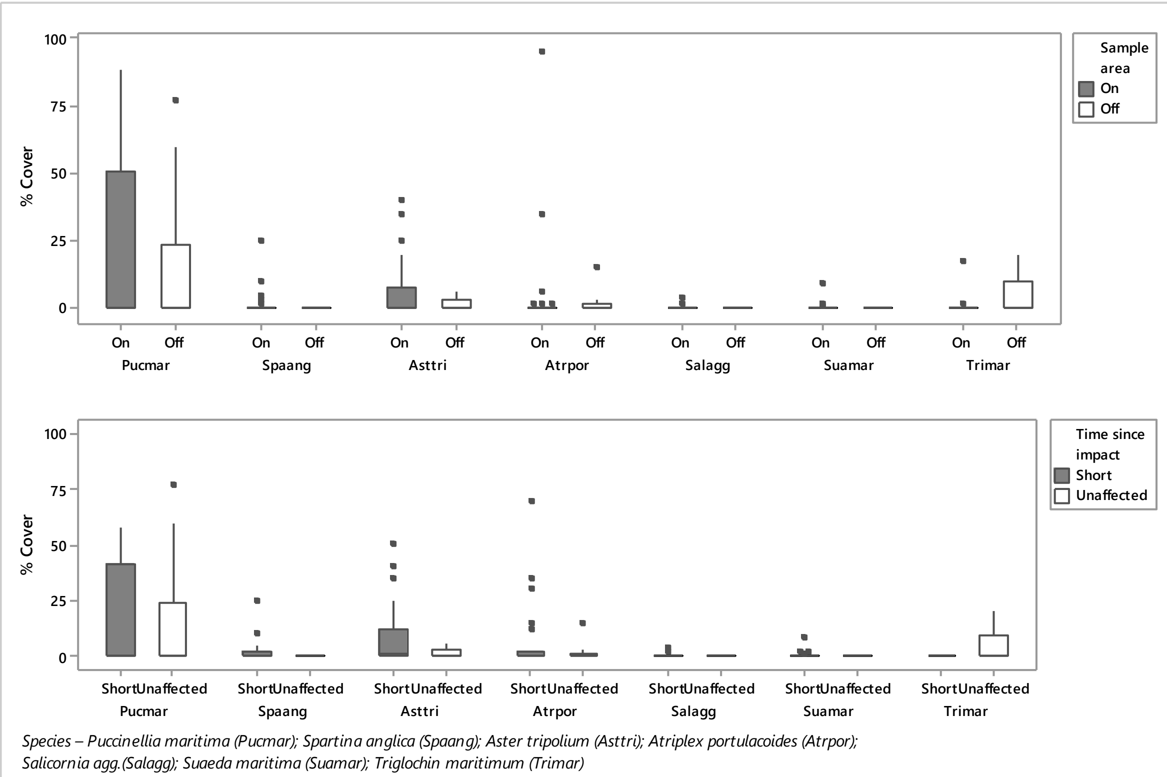


3.6 Results – Low-mid Marsh

3.6.1 Vegetation Composition and Structure

The low-mid marsh was generally species-poor, in total 16 vascular plant species were recorded in the study sites. The most species-rich quadrats in this zone had eleven species, while the least diverse had one (Figure 5, *Section 3.3* and Figure 40). *Puccinellia maritima* was the dominant species and showed a preference (as with the other zones) for On the pipeline and in the Short-term. Similarly, *Aster tripolium* appeared to have a greater cover On and in the Short-term. Inversely *Triglochin maritimum* showed a preference to the Off and Unaffected areas. *Puccinellia maritima* was the most frequent species in this zone, recorded in 73.2% of the quadrats. Boxplots showing cover of key species in this zone by sample area and time since impact are given in Figure 36.

Figure 36 - Boxplots showing the cover of key low-mid marsh species with sample area (On and Off) [top] and time since impact (Short-term and Unaffected) [bottom].



General Linear Model and Tukey Pairwise Comparison Test

To test the hypotheses for low-mid marsh (*Section 3.2.5.*), analysis using a GLM and Tukey Pairwise Comparison test (TPC) was used for each species or variable, with sample area or time since impact as a factor and distance from pipe as a covariate.

Hypothesis 18 – [*Atriplex portulacoides* will have a lower cover On the pipeline; and in the Short- and Medium-term]. Cover of *Atriplex portulacoides* is significantly lower on the pipe (df=2;

T=4.25; p=0.000) – proving this part of the hypothesis. However, its cover was not significantly lower during the Short- and Medium-term (Short-Unaffected df=3; T=2.49; p=0.062; Medium-Unaffected df=3; T=2.43; p=0.071) – disproving the hypothesis. In the Long-term the cover of *Atriplex portulacoides* was not significantly different when compared to the Unaffected vegetation (df=3; T=-0.05; p=1.000) indicating cover had returned to pre-construction levels.

Hypothesis 19 – [Cover of early successional species *i.e. Salicornia* agg. will be higher On the pipeline, at least in the Short-term]. The early successional species *Salicornia* agg. had a significantly higher cover On the pipeline compared to Off (df=2; T=-2.53; p=0.030). Cover was also higher in the Short-term (df=3; T=-3.78; p=0.001), and in the Medium-term (df=3; T=-2.78; p=0.028), when compared to the Unaffected vegetation – proving the hypothesis.

Hypothesis 20 – [Following construction, typical species (*Aster tripolium*, *Puccinellia maritima* and *Suaeda maritima*) will quickly re-establish (although cover On the pipe is expected to be lower at least in the Short-term)]. *Puccinellia maritima* and *Suaeda maritima* showed no significant differences between the On and Off sample area – proving the hypothesis for these species. However, *Aster tripolium* had a higher cover Off the pipe (df=2; T=2.98; p=0.008) – disproving the hypothesis for this species. None of the three species were statistically significant over time. It is expected that species of the low-mid marsh are able to quickly re-establish themselves following disturbance and therefore differences are minimal in the Long-term.

Hypothesis 21 – [*Spartina anglica* will have a higher cover On the pipeline]. *Spartina anglica*, was recorded in 67.2% of the quadrats in this zone, and it was found in all sample areas. The cover of *Spartina anglica* was statistically significant between the On and Off sample areas with a higher cover recorded along the pipeline (df=2; F=-3.85; p=0.000) – supporting the hypothesis. However, the cover of *Spartina anglica* was not statistically significant between the Short-term and Unaffected vegetation (df=2; T=-1.47; p0.457), but cover was significantly higher in the Medium-term compared to the Unaffected vegetation (df=2; T=-5.33; p0.000). This indicates that the cover of this species increased over time reaching significantly higher cover in the Medium-term *i.e.* after 25 years.

Hypothesis 22 – [Cover of bare ground in the low-mid marsh will be higher in the On sample area]. Cover of bare ground in the On sample area was double that compared to the Off sample area (Figure 5). Similarly, algae cover was three-times higher On the pipeline. This is supported by the GLM analysis using sample area; cover of bare ground was statistically significantly higher On the pipeline (df=2; T=-5.43; p=0.000) – proving the hypothesis; and so too was algae species cover (df=2; T=-3.29; p=0.003). GLM analysis also showed that herb cover was significantly lower Off the pipeline (df=2; T=2.42; p=0.042), although graminoid cover was not statistically significant.

Bare ground, algae species cover, herb cover and graminoid cover were not statistically significant over time.

A full summary of the results of the GLM and Tukey Pairwise Comparison for the low-mid marsh is given in Appendix 3 Tables 23-26.

Canonical Correspondence Analysis

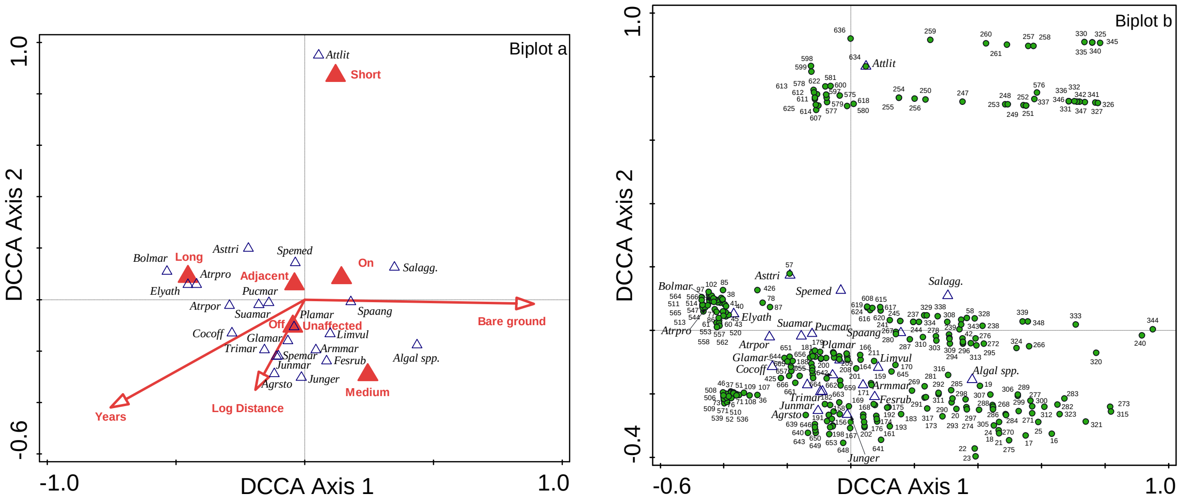
In CCA and forward selection of environmental variables with the low-mid marsh data the cover of bare ground explains the greatest amount of variation in the data. Other significant factors were years, time since impact Short- and Long-term (Table 11).

Table 11 - Explanatory power of environmental variables in CCA analysis for low-mid marsh. Significant effects are given in bold.

Environmental Variable	Explains %	Contribution %	pseudo-F	P-value	P(adj)
% Bare ground	**14.7**	**58.6**	**56.8**	**0.0002**	**0.0005**
Years	**5.6**	**22.5**	**23.2**	**0.0002**	**0.0004**
Time since impact - Short	**2.6**	**10.3**	**11.0**	**0.0002**	**0.0004**
Time since impact - Long	**1.3**	**5.1**	**5.5**	**0.0002**	**0.0005**
Sample area – On	0.4	1.7	1.8	0.055	0.1100
Time since impact - Unaffected	0.2	1.0	1.0	0.3886	0.4371
Time since impact - Medium	0.2	1.0	1.0	0.3892	0.4371
Sample area - Adjacent	0.2	1.0	1.0	0.3934	0.4371
Log distance from pipe	0.2	1.0	1.0	0.3924	0.4371

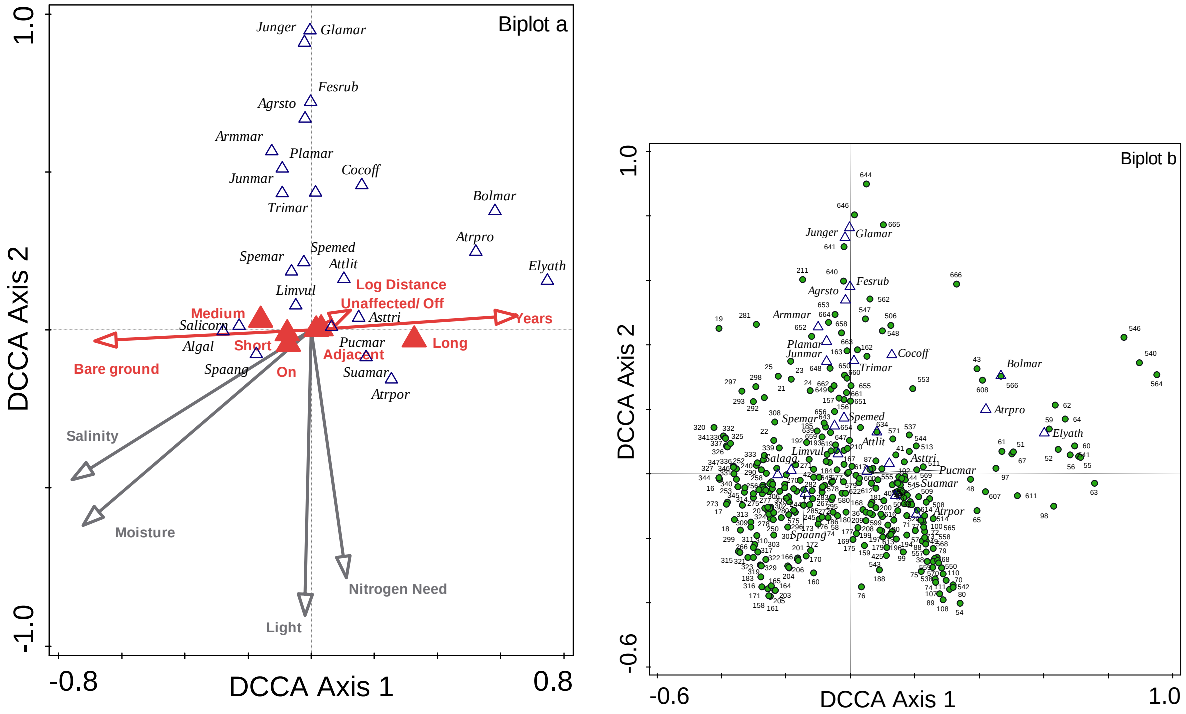
Using CCA for the low-mid marsh resulted in a plot with a strong 'arch effect' (*Section 2.4.3*) to compensate for this a DCCA was used. The DCCA plot (Figure 37) shows the On factor to be associated with early successional species *i.e. Salicornia* agg. and *Spartina anglica* with increased bare ground. The Short-term factor is associated with *Atriplex littoralis* but is otherwise quite distinct from the other factors. Examining the quadrats associated with this part of the plot shows the quadrats are from three of the case studies North Morecambe, River Fields and Thanet. The River Fields and Thanet sites are the most recent of the study sites and show the greatest evidence on the ground of the pipeline/ cable installation. The Long-term factor is associated with species often recorded in the driftline with *Atriplex prostrata*, *Bolboschoenus maritimus* and *Elytrigia atherica*, perhaps indicating long-term succession. The Adjacent factor is associated with typical low-mid marsh species *i.e. Atriplex portulacoides*, *Puccinellia maritima*, and *Spergularia media*. The Off and Unaffected factors (which are close to the Adjacent factor) are associated with the greatest diversity of species (many of which are typical of mid-upper marsh) including *Armeria maritima*, *Festuca rubra*, *Glaux maritima*, *Limonium vulgare* and *Triglochin maritimum*.

Figure 37 - Species-environmental variable biplot (a) and species-quadrats biplot (b) using DCCA (of the first two axes) with environmental variables selected by forward selection procedure. Total variation is 2.40, explanatory variables account for 25% (adjusted explained variation is 23.4%); 1st Axis pseudo-F=69.9, p=0.0002; All Axes pseudo-F=15.5, p=0.0002. The species (shown as blue triangles) are labelled by the first three letters of the generic name and the first three letters of the specific name. Quadrats are shown as green circles with the quadrat number.



The inclusion of Ellenberg values for moisture, salinity, light and nitrogen requirement (Hill et al., 1999) as additional explanatory variables in the DCCA analysis increased the percentage variation explained by the environmental variables from 25.0% to 59.2%, and the forward selection process identified all five variables as being significant. Of these, salinity was the most significant explaining 17.7% of the variation (Figure 38).

Figure 38 - Species-environmental variable biplot (a) and species-quadrats biplot (b) using DCCA (of the first two axes) with environmental variables selected by forward selection procedure. The biplot includes Ellenberg values for moisture, salinity, nitrogen requirement and light as additional explanatory variables. Total variation is 2.39, explanatory variables account for 59.2% (adjusted explained variation is 57.6%); 1st Axis pseudo-F=94.9, p=0.0002; All Axes pseudo-F=38.3 p=0.0002. The species (shown as blue triangles) are labelled by the first three letters of the generic name and the first three letters of the specific name. Quadrats are shown as green circles with the quadrat number.

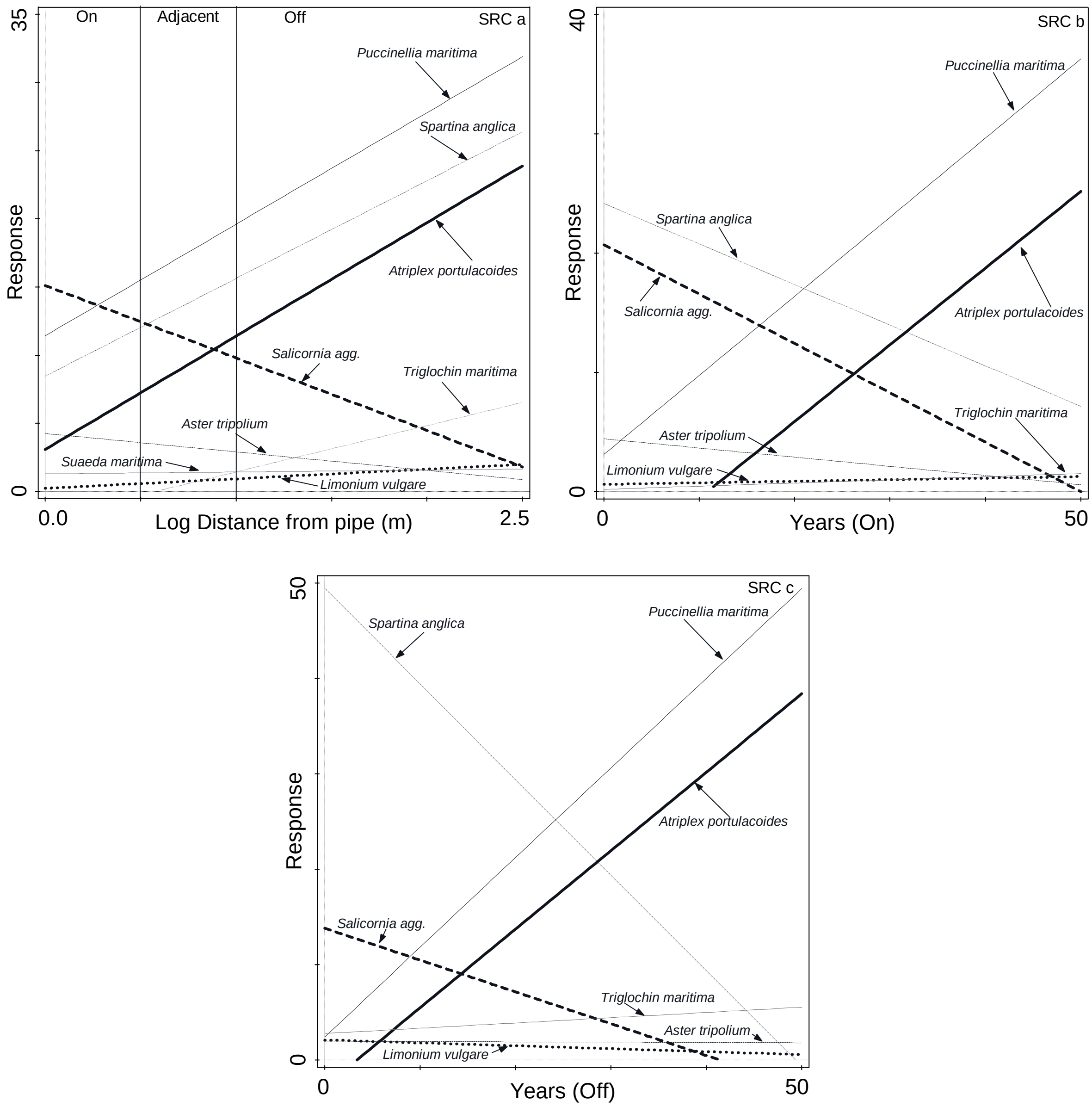


Species Response Curves

The Species Response Curve[31] for the low-mid marsh (Figure 39) shows that *Puccinellia maritima* and *Atriplex portulacoides* increase sharply with increased distance and over time On the pipeline. Cover of *Puccinellia maritima* increases quickly and rapidly from ca. 4% after pipeline installation to ca. 10% by 10 years, and 18% by 20 years. By 50 years cover is ca. 35%. *Atriplex portulacoides* also increases but shows a delay in its recovery time, not appearing in the sward in the first 10 years after installation. The cover of *Spartina anglica* rapidly increases with distance but decreases over time On the pipeline from ca. 25% initially to 20% by 20 years and 10% by 50 years. *Salicornia* agg. decreases in cover over distance and time- supporting hypothesis 19. The other species *i.e. Aster tripolium*, *Limonium vulgare* and *Triglochin maritimum* show relatively small differences over distance and time On the pipeline and their cover remains fairly constant.

[31] Using a Generalised Linear Model modelled with a Poisson distribution and Log link function

Figure 39 - Species Response Curves of log distance from the pipeline (a) and years On the pipeline (b) and years Off the pipeline (c) with typical low-mid marsh species. The plot uses a poisson response distribution and a linear predictor. The response value indicates species abundance. For log distance an indication of the sample area (On, Adjacent and Off) has been given.

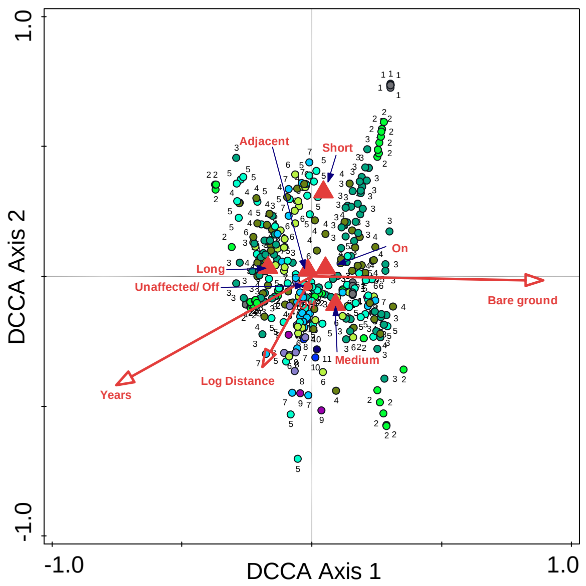


Species Diversity

Hypotheses 23– [Where the low-mid marsh is impacted in the Short-term, species-richness will be lower than the Unaffected or Long-term vegetation]. The large number of quadrats recorded from the low-mid marsh is reflected in the species diversity diagram (Figure 40). The detrended CCA plot shows that the quadrats associated with On, Short- and Medium-term (found on the right of the plot) have 3-5 species and have changed from low-mid marsh to pioneer marsh. Over time species-richness increases very slightly *i.e.* the Long-term plots support 3-6 species; while the Unaffected and Adjacent quadrats support 5-8 species. Those quadrats with the highest number of species are associated with the greatest distance from the pipeline. Therefore, the data supports the hypothesis.

No nationally rare or scarce plant species was recorded in this zone. *Limonium vulgare* (listed as Near Threatened (Stroh et al., 2014)) was recorded in 54 quadrats; 12 On, 21 Adjacent and 21 Off).

Figure 40 - Species Diversity Diagram showing species number per quadrat in the low-mid marsh. Green circles indicate low species-richness, while purple and blue indicate high-species richness within the zone; numbers are the actual number of species in the quadrat.



3.6.2 Ecosystem Function

Low-mid Marsh Resource

The low-mid marsh typically develops in the zone below mean high water. This means in general terms it is covered by more than 360 annual tides, are never exposed continuously for more than nine days and are submerged daily in daylight for more than 1-2 hours (Adnitt et al., 2007). Several NVC types are represented in this zone; those present at the study sites include SM10 Transitional low-marsh vegetation with *Puccinellia maritima*, annual *Salicornia* species and *Suaeda maritima*; SM13 *Puccinellia maritima* salt-marsh community (sub-community SM13a); and SM14 *Halimione portulacoides* salt-marsh community (sub-communities SM14a and SM14c).

Areas of low-mid marsh formed the most extensive habitat within the study sites (with 31% of the total habitat resource). All locations had examples of this vegetation type, with the exception of two sites (Rivers Fields and Shotover Moor). The largest areas were recorded at Inner Trial Bank (71%), Wytch Moor (44%) and at Tetney Marshes (42%). Low-mid marsh also formed a large proportion of the vegetation at both South and North Morecambe.

No low-mid marsh was recorded at Rivers Fields, this site was one of the most recently impacted within the study with works completed in 2003. Much of the site supports unvegetated mud (17%), pioneer marsh (34%) or creeks (48%). Therefore, it is expected that construction impacts have resulted in the low-mid marsh being degraded to early successional habitats. It is expected, given time, that succession here will increase the low-mid marsh resource. As there is not a habitat map showing the pre-construction vegetation types, this is conjecture on my part.

In contrast, at Shotover Moor in Poole Harbour, no low-mid marsh or pioneer marsh was recorded, as much of the site supports either mid-upper marsh (28%) or transitional habitats, namely swamp (63%).

The extent of low-mid marsh habitat at each of the study sites in 2015/2016 is given Table 12. Due to differences in the size of the working width (*i.e.* the On sample area), the habitat areas (ha) are not directly comparable between sites, therefore the habitat resource is also provided as a percentage of the total site area.

Table 12 - Extent (ha and % of total area) of the low-mid marsh across study sites in 2015-16.

Location	**Site**	**Area (m^2) in 2015-16**	**% of survey area**
Humber	Tetney Marshes	7.1	42
Pegwell Bay	Thanet	0.9	34
Poole Harbour	Cleavel Point	0.0	1
Poole Harbour	Shotover Marsh	0.0	0
Poole Harbour	Wytch Moor	1.8	44
The Wash	Inner Trial Bank	7.1	71
Walney Island	North Morecambe	2.2	23
Walney Island	Rivers Fields	0.0	0
Walney Island	South Morecambe	1.8	23
Total habitat area surveyed in 2015-16 (ha)		**20.8**	
Proportion of total survey area (%)		**31**	

Hypothesis 24 – [The extent (ha) of low-mid marsh habitats following construction, will fall in the Short-term, but in the Long-term will reach or exceed pre-construction extents].

Inner Trial Bank

Analysis of the habitat maps at Inner Trial Bank (Figures 18-21) since the pre-construction survey in 1971 (Randerson, 1975) allow the change in area of low-mid marsh to be documented. Table 13 shows the extent (ha) of low-mid marsh and as a percentage of the total for each sample area *i.e.* On, Adjacent and Off the pipeline.

Table 13 - The extent of low-mid marsh at Inner Trial Bank over 44 years following the installation of a causeway and trial offshore reservoir.

Year	1971 pre-construction survey (Randerson, 1975)			1982 (Hill, 1988)			1999 (Ecological Services Ltd, 1999)			2016		
Area	**On**	**Adj**	**Off**	**On**	**Adj**	**Off**	**On**	**Adj**	**Off**	**On**	**Adj**	**Off**
Extent (ha)	0.6	1.0	1.0	1.2	2.0	2.0	1.6	1.9	2.1	1.5	2.7	2.8
% of survey area	27	26	25	57	58	57	74	55	57	69	82	79

The pre-construction survey in 1971, noted that roughly equal proportions (around 25%) of low-mid marsh were recorded On, Adjacent and Off the causeway. Within 10 years, after the construction of the causeway and Inner Trial Bank reservoir the extent of low-mid marsh had doubled to around 57% of the site (again all three sample areas supported roughly equal proportions). In contrast, the area of unvegetated mud had reduced significantly from approximately 57% in 1971 to 9% in 1982. By the 2016 survey much of the site supported low-mid marsh habitat. This further increase correlates with the reduction in pioneer marsh and the almost complete loss of bare mud habitat. The Adjacent and Off areas supported roughly 10% more low-mid marsh than the On sample area. This difference appears to be due to the On sample area along the causeway having an increased cover of driftline habitat (see *Section 3.4.1*). Therefore, the example at Inner Trial Bank partially supports hypothesis 24 *i.e.* that the cover of low-mid marsh will increase over time, but that this appears to be due to an overall expanding saltmarsh resource and succession rather than a conversion of habitats along the pipeline to this habitat type.

Tetney Marshes

The area of low-mid marsh (SM13a) at Tetney Marshes has remained stable *i.e.* 6ha between 1987 and 2016 (Table 7/ Figures 22-25). This supports hypothesis 24.

South Morecambe

At South Morecambe, comparing the 1981 pre-construction survey with the 2016 survey shows that the areas of low-mid marsh have increased, along with areas of pioneer to low-marsh. The habitat map shows that much of this change appears to be due to succession of pioneer marsh. This also supports hypothesis 24.

Table 14 - The extent of the main vegetation types at South Morecambe since 1981.

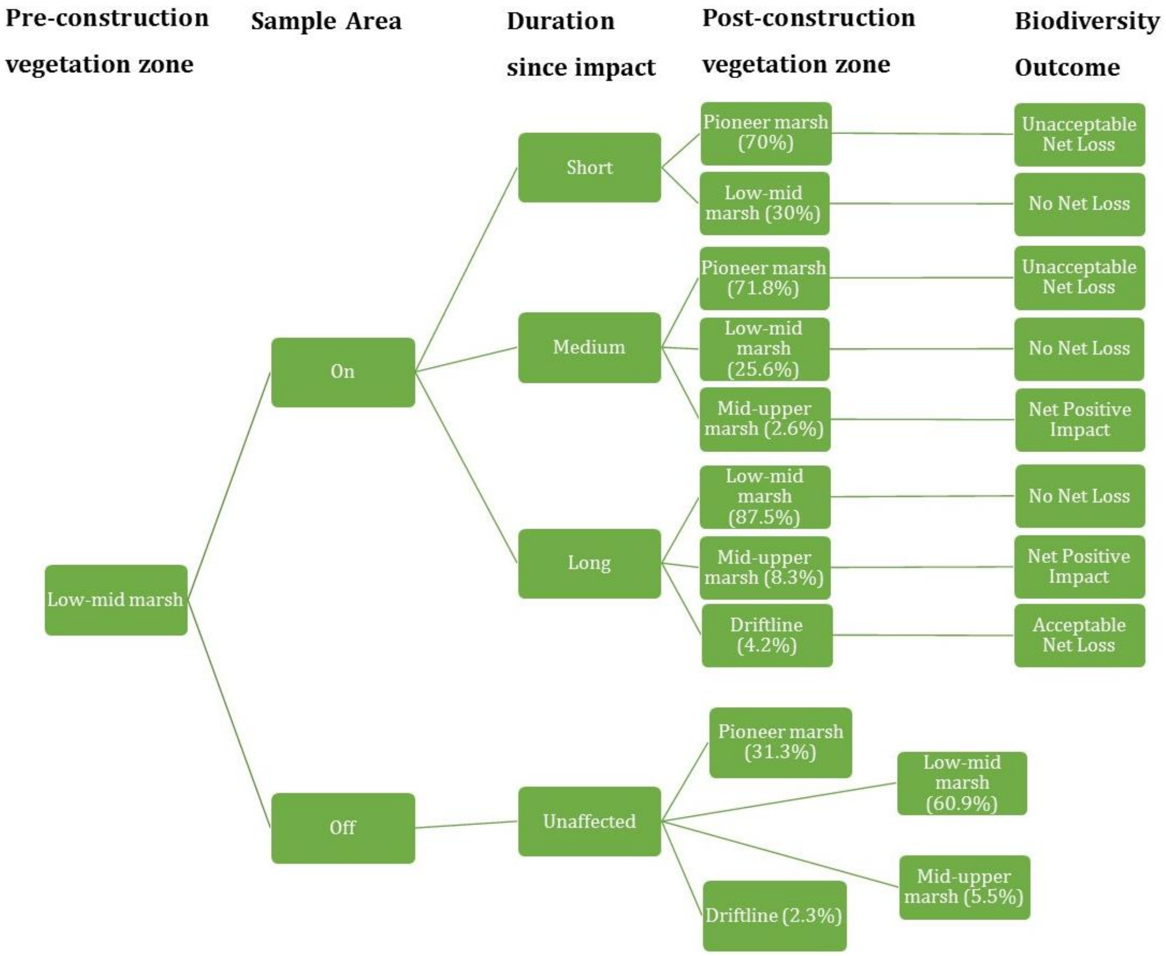
Vegetation type	1981 (ha)	2016 (ha)
Driftline	0.0	0.2
Mid-upper marsh	0.5	0.7
Low-mid marsh	0.1	1.0
Pioneer to Low-mid marsh	0.1	0.8
Pioneer marsh	5.4	3.6
Creek	0.3	1.5
Pool	0.0	0.1
Saltpan	0.1	0.0
Not surveyed	1.4	0.2

3.6.3 Outcomes of Recovery

Hypotheses 25 – [In the Short-term, low-mid marsh vegetation will be lost during construction resulting in an increase in pioneer marsh. In the Medium-Long-term, low-mid marsh vegetation will fully recover]. The recovery outcomes of 332 quadrats classified as low-mid marsh prior to construction is illustrated in Figure 41. After construction in the Short-term, 70% of the quadrats was classified as pioneer marsh (an Unacceptable Net Loss) and 30% as low-mid marsh (No Net Loss). Similar proportions of pioneer and low-mid marsh were also recorded in the Medium-term. By the Long-term, pioneer marsh was no longer present and in the majority of cases low-mid marsh (87.5%) was the dominant habitat (Not Net Loss) – supporting this hypothesis. There was a small number of cases where mid-upper marsh (Net Positive Impact) and driftline vegetation had developed (Acceptable Net Loss).

In the Unaffected quadrats, much of the vegetation remained as low-marsh (60%), while 31% was classified as pioneer marsh. A small proportion of the quadrats were classified as mid-upper marsh and driftline vegetation. The backward course of succession in Unaffected quadrats may be down to natural fluctuations, or perhaps due to discrepancies in the classification of habitats. More likely, in some cases the Unaffected quadrats were subject to undocumented damage beyond the working width in this zone. This is perhaps supported by examining the data for the low-mid marsh in the Adjacent sample area (not shown in Figure 41). Here in the Short-term 45% of the quadrats were classified as pioneer marsh and 48% as low-mid marsh. This indicates that in almost half of the situations following construction, the Adjacent area was impacted upon (either through direct impacts *i.e.* vehicle movements, increased footfall, sediment loss *etc.* or indirect affects through changes in tidal movements, alterations to the course of creeks *etc.*). These impacts in the Adjacent area were seen to continue through to Medium-term, but by the Long-term 95% of the quadrats were classified as low-mid marsh.

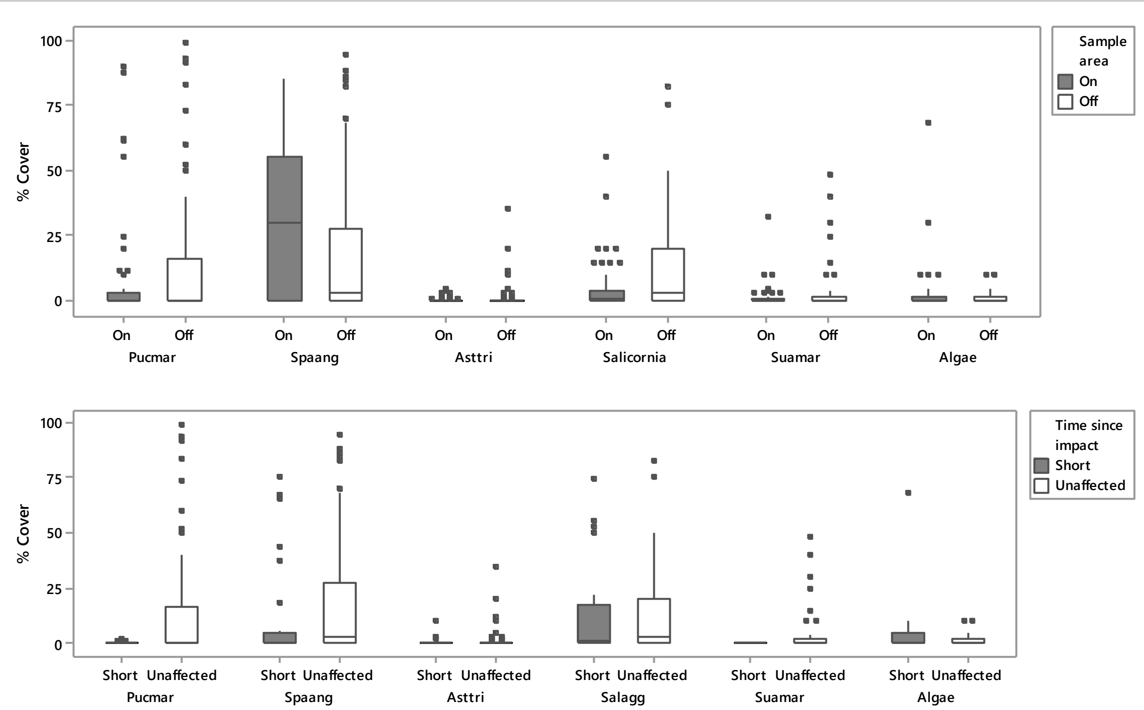
Figure 41 - Likely vegetation outcomes of low-mid marsh following construction, based on a comparison of pre-construction vegetation types with current vegetation condition. Percentage values given represent the proportion of quadrats within each sample area and time since impact that result in each given post-construction vegetation type. The biodiversity outcome is based on those outlined in Theme 3 *Section 1.7.3.*



3.7 *Results – Pioneer Marsh*

Across the study sites, vegetation in the pioneer zone was generally species-poor. In total 12 vascular plant species were recorded, as well as Algae spp. The most species-rich quadrats in this zone had eight species, while the least diverse had two (Figure 5, *Section 3.3* and Figure 46). In this zone, *Spartina anglica* showed differences in cover between On and Off the pipeline and between the Short-term and Unaffected vegetation although this appeared to contradict each other (with a higher cover On the pipeline and in the Unaffected area). Both *Puccinellia maritima* and *Salicornia* agg. had a higher cover in the Off /Unaffected sample areas. The most frequent species, *Spartina anglica* was recorded in 72.5% of the quadrats in this zone. Boxplots showing cover of key species in this zone by sample area and time since impact are given in Figure 42.

Figure 42 - Boxplots showing the cover of key pioneer marsh species with sample area (On and Off) [top] and time since impact (Short-term and Unaffected) [bottom].



Species – Puccinellia maritima (Pucmar); Spartina anglica (Spaang); Aster tripolium (Asttri); Salicornia agg.(Salagg); Suaeda maritima (Suamar); Algae spp.(Algae)

3.7.1 *Vegetation Composition and Structure*

General Linear Model and Tukey Pairwise Comparison Test

To test the hypotheses for pioneer marsh (*Section 3.2.6.*), analysis using a GLM and Tukey Pairwise Comparison test (TPC) was used for each species or variable, with sample area or time since impact as a factor and distance from pipe as a covariate. A full summary of the results of the GLM and Tukey Pairwise Comparison for the pioneer marsh is given in Appendix 3 Tables 27-30.

Hypotheses 26 – [Following construction, the pipeline will be colonised by early successional species, with cover of *Salicornia* agg. being higher On the pipeline]. The GLM showed that cover of *Salicornia* agg. was statistically higher On the pipeline (df=2; T=-3.26; p=0.004); in the Short-term compared to the Unaffected vegetation (df=2; T=-3.04; p=0.008); and in the Long-term compared to the Unaffected vegetation (df=2; T=-2.54; p=0.032). Cover of Algae spp. was not significantly different for either sample area or time since impact.

Hypothesis 27 – [*Spartina anglica* will have a higher cover On the pipeline compared to Off. Cover would increase over time resulting in a lower cover in the Short-term compared to the Unaffected vegetation]. *Spartina anglica* was recorded in 72.5% of the quadrats in this zone and was found in all sample areas. Its mean cover On the pipeline (30.4%) was almost twice that of the Adjacent (17.1%) and Off (18.4%) sample areas. When considered using a GLM of sample area, the cover of *Spartina anglica* was not statistically significant (df=2; F=1.54; p=0.218). However, its cover was significantly higher in the Unaffected vegetation compared to the Short-term (df=2; T=-3.04; p0.008).

Hypothesis 28 – [Following pipeline installation, cover of bare ground will be higher in the On sample area]. There was little difference in the mean cover of bare ground between the On and Off sample area (Figure 5); although analysing the data using a GLM showed it was statistically higher On the pipeline (df=2; T=-2.38; p=0.048) and in the Short-term (df=3; T=-3.99 p=0.000) – proving the hypothesis. The total cover of graminoids was slightly higher On the pipeline (but not statistically significant), and it was shown using a GLM to be significantly higher in the Unaffected vegetation. The total cover of herbs was not statistically significant for either sample area of time since impact.

Canonical Correspondence Analysis

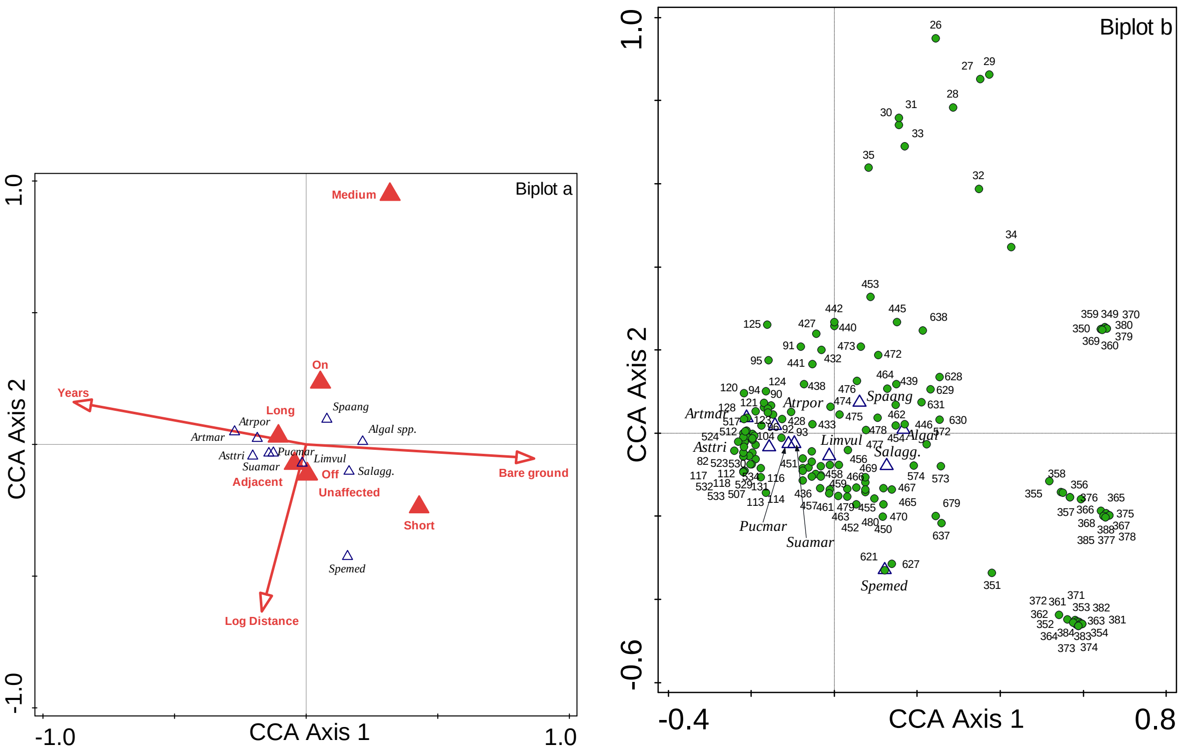
In CCA and forward selection of environmental variables with the pioneer marsh data the years factor explained the greatest amount of variation in the data. Other significant factors were cover of bare ground and time since impact Medium-term (Table 15).

Table 15 - Explanatory power of environmental variables in CCA analysis for mid-upper marsh. Significant effects are given in bold.

Environmental Variable	Explains %	Contribution %	Pseudo-F	P-value	P(adj)
Years	**10.8**	**56.1**	**20.0**	**0.0002**	**0.001**
% Bare ground	**3.2**	**16.6**	**6.1**	**0.0002**	**0.001**
Time since impact - Medium	**2.1**	**10.8**	**4.0**	**0.0204**	**0.041**
Time since impact - Short	1.6	8.4	3.2	0.0162	0.051
Log distance from pipe	1.0	5.2	2.0	0.0706	0.141
Time since impact - Long	0.4	2.1	0.8	0.525	0.656
Time since impact - Unaffected	0.4	2.1	0.8	0.5228	0.656
Sample area -On	0.2	0.9	0.3	0.908	1.000

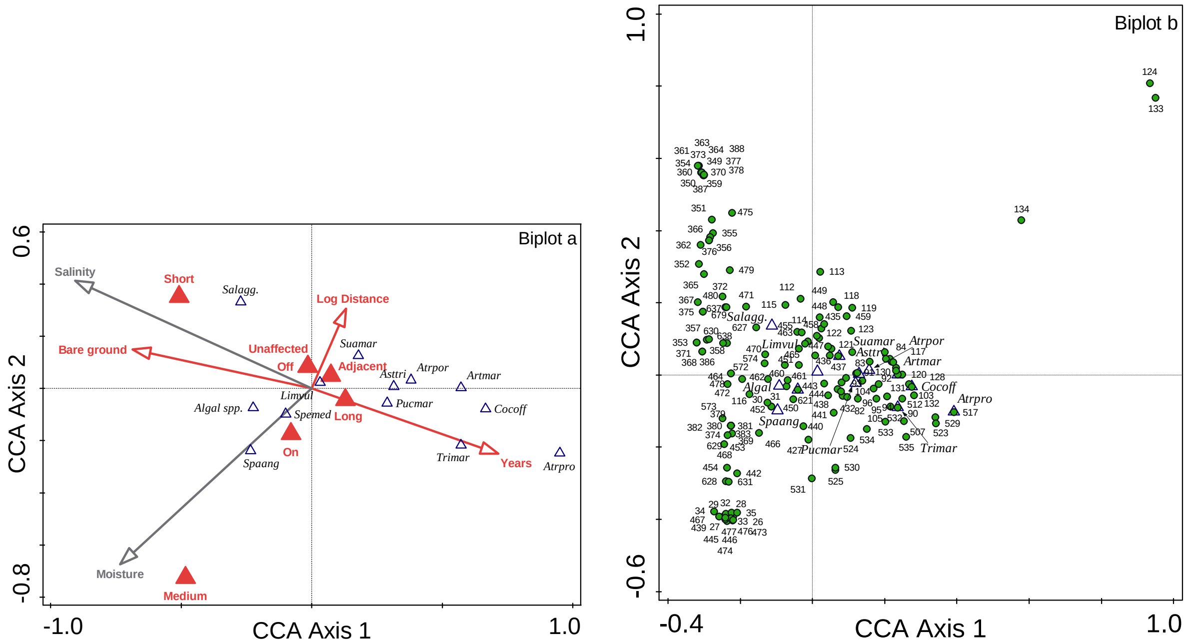
Using CCA for the pioneer data the explanatory variables of Adjacent, Off, Unaffected, and Long-term are all clustered close together showing that there is little separation in these factors for defining the vegetation (Figure 43). The On, and Short-term factors are more distinct and explain the greatest variation. *Spartina anglica* is associated with the On factor, whereas *Salicornia* agg is associated with the Short-term. The Medium factor is isolated from the rest of the data with no associated species, the quadrats associated with this factor are all from a single case study site namely Cleavel Point, Poole. The plot shows that the Long-term factor is associated with the greatest number of species and these are more typical of low-mid marsh. All the quadrats that are isolated (to the right-hand side of the plot) were recorded at the River Fields case study site, which is one of the most recently installed pipes. On the ground the quadrats in the pioneer zone had the greatest amount of bare ground and Algae, and typically the *Spartina anglica* plants that were present were often stunted and showed poor growth.

Figure 43 - Species-environmental variable biplot (a) and species-quadrats biplot (b) using CCA (of the first two axes) with environmental variables selected by forward selection procedure. Total variation is 1.41, explanatory variables account for 29.5% (adjusted explained variation is 26.3%); 1st Axis pseudo-F=40.9, p=0.0002; All Axes pseudo-F=9.3, p=0.0002. The species (shown as blue triangles) are labelled by the first three letters of the generic name and the first three letters of the specific name. Quadrats are shown as green circles with the quadrat number.



The inclusion of Ellenberg values for salinity and moisture (Hill et al., 1999) as additional explanatory variables in the CCA analysis increased the percentage variation explained by the environmental variables from 29.5% to 69.5%, and the forward selection process identified both variables as being significant (Figure 44). Of these, salinity was the most significant explaining 29.3% of the variation.

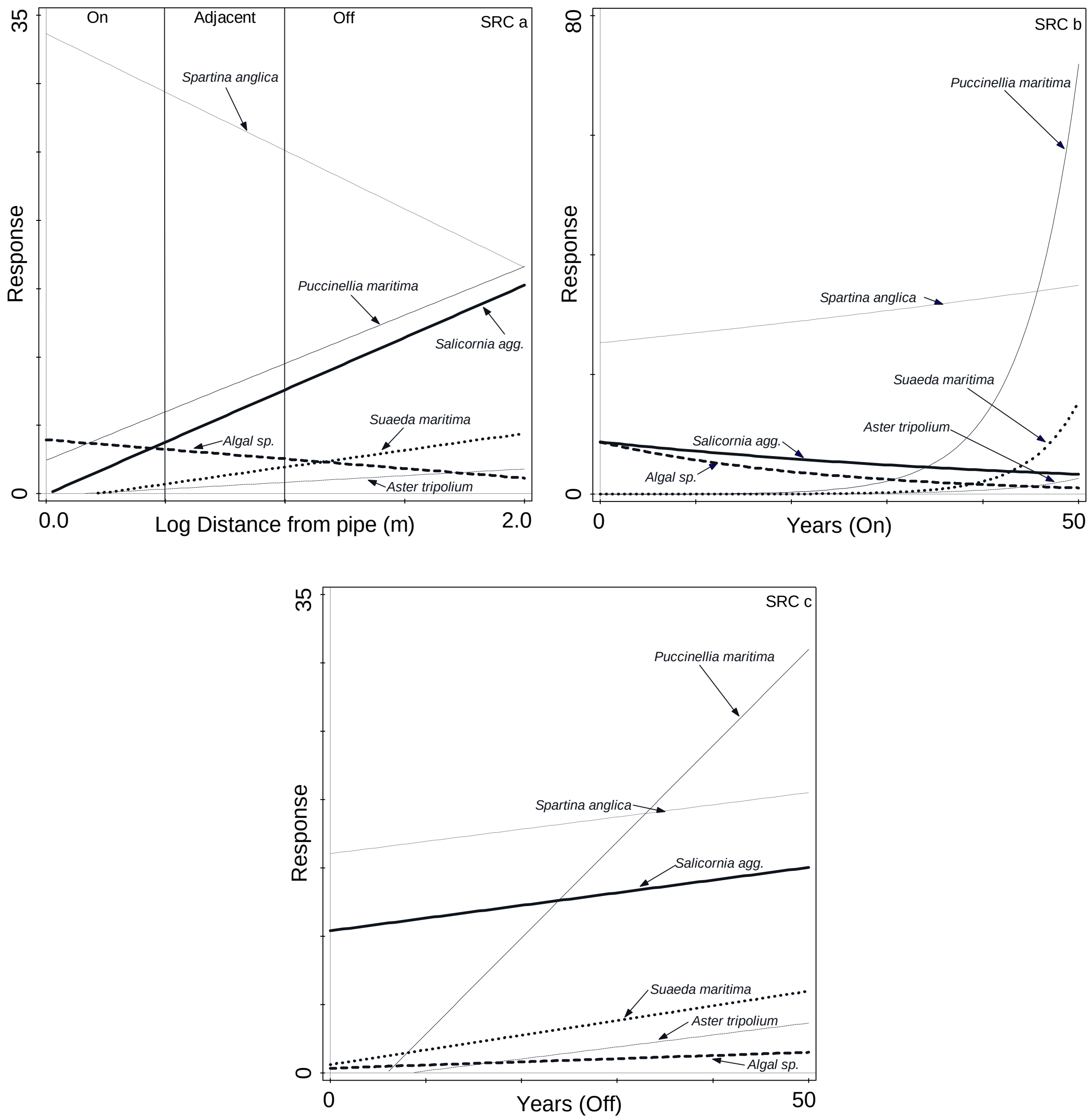
Figure 44 - Species-environmental variable biplot (a) and species-quadrats biplot (b) using CCA (of the first two axes) with environmental variables selected by forward selection procedure. The biplot includes Ellenberg values for moisture and salinity as additional explanatory variables. Total variation is 1.29, explanatory variables account for 53.3% (adjusted explained variation is 50.3%); 1st Axis pseudo-F=67.9, p=0.0002; All Axes pseudo-F=18.5, p=0.0002. The species (shown as blue triangles) are labelled by the first three letters of the generic name and the first three letters of the specific name. Quadrats are shown as green circles with the quadrat number.



Species Response Curves

The Species Response Curves for the pioneer marsh (Figure 45) shows that *Puccinellia maritima* increases in cover with distance. It also increases over time On the pipeline, but shows a considerable delay before returning *i.e.* it is not present for at least 20 years (and then at low-levels of abundance). After around 40 years its cover increases rapidly (from ca 10% to 70%) which probably represents a long-term succession to low-mid marsh. *Spartina anglica* shows a sharp decrease in cover with distance, although its cover increases slightly over time On the pipeline. This perhaps indicates that it can grow in the disturbed construction zone more readily than other pioneer marsh species. *Salicornia* agg. also increases in cover over distance, but over time its cover decreases slightly, probably as a result of competition from other species. The cover of Algae spp. decreases with distance and over time On the pipeline, presumably as other species become more abundant resulting in less bare ground and light at the sediment surface. This supports hypothesis 26. *Aster tripolium* and *Suaeda maritima* both increase with distance and over time, but do not becomes established in the zone until ca. 40 years, this delay is probably due to long-term succession to low-mid marsh rather than as a consequence of pipeline installation.

Figure 45 - Species Response Curves (SRC) of log distance from the pipeline (a) and years On the pipeline (b) and years Off the pipeline (c) with typical pioneer species. The plot uses a poisson response distribution and a linear predictor. The response value indicates species abundance. For log distance an indication of the sample area (On, Adjacent and Off) has been given.

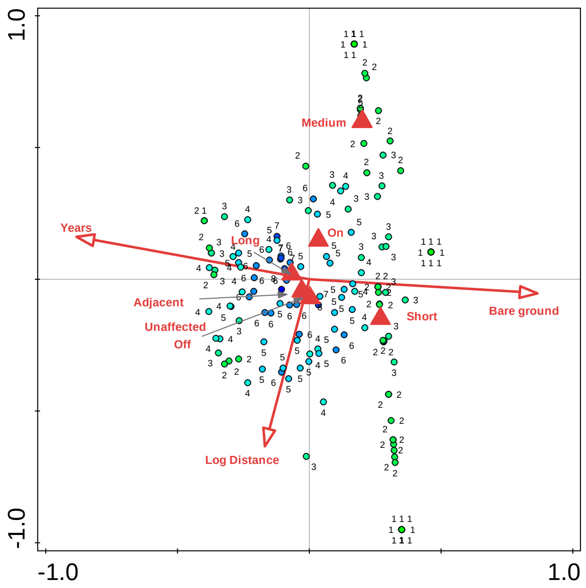


Species Diversity

Hypotheses 29 – [Where the pioneer marsh is impacted, species-richness will be lower than the Unaffected or Long-term vegetation]. The species diversity diagram shows that in the pioneer marsh species numbers for the On, Short and Medium-term are associated with lower species-richness (2-5 species)– proving the hypothesis (Figure 46). The most species-poor examples supporting only one species are divided into those with Algae spp., those with *Salicornia* agg., and those with *Spartina anglica*. The Adjacent, Long and Unaffected/ Off variables are associated with higher species numbers (5-7 species). These more species-rich quadrats reflect ongoing succession from pioneer to low-mid marsh.

No nationally rare or scarce plant species were recorded in this zone. *Limonium vulgare* (listed as Near Threatened (Stroh et al., 2014)) was recorded in 12 quadrats; 7 Adjacent and 4 Off.

Figure 46 - Species Diversity Diagram showing species number per quadrat in the pioneer marsh. Green circles indicate low species-richness, while blue indicate high-species richness within the zone; numbers are the actual number of species in the quadrat.



3.7.2 Ecosystem Function

Pioneer Marsh Resource

The pioneer marsh typically extends down to around the mean high-water neap tide (meaning it is covered by all tides except the lowest neap tide). Limited species are capable of growing in areas so frequently inundated, so the pioneer zone is generally the most species-poor. Several NVC types are represented in this zone; with four found at the study sites, these include SM6 *Spartina anglica* salt-marsh community; SM8 Annual *Salicornia* salt-marsh community; SM9 *Suaeda maritima* salt-marsh community; and SM11 *Aster tripolium* var. *discoideus* salt-marsh community.

Areas of pioneer marsh were extensive with 19% of the total habitat resource. Examples of this vegetation type were recorded at all sites with the exception of Shotover Moor and Wytch Moor. The largest area was recorded at Rivers Fields (4.8ha) and at South Morecambe (3.6ha). Pioneer marsh also formed a large proportion of the vegetation at Cleavel Point and Thanet.

As described in the section on low-mid marsh, Shotover Moor at Poole Harbour supports no pioneer marsh as much of the site supports either mid-upper marsh or transitional habitats namely swamp. Shotover Moor is situated at the mouth of the Owen Bay and is fed by a stream. The saltmarsh here, has developed along the channel and consequently supports both freshwater and brackish habitats. A similar situation occurs at Wytch Moor (situated approximately 1km to the west of Shotover Moor). Wytch Moor is situated at the mouth of the River Froome and supports extensive areas of mire and swamp.

The extent of pioneer marsh at each of the study sites in 2015/2016 is given Table 16. Due to differences in the size of the working width (*i.e.* the On sample area), the habitat areas (ha) are not directly comparable between sites, therefore the habitat resource is also provided as a percentage of the total site area.

Table 16 - Extent (ha and % of total area) of the pioneer marsh across study sites in 2015-16.

Location	Site	Area (ha) in 2015-16	% of survey area
Humber	Tetney Marshes	0.5	3
Pegwell Bay	Thanet	0.9	37
Poole Harbour	Cleavel Point	0.8	47
Poole Harbour	Shotover Marsh	0.0	0
Poole Harbour	Wytch Moor	0.0	0
The Wash	Inner Trial Bank	0.7	7
Walney Island	North Morecambe	1.5	16
Walney Island	Rivers Fields	4.8	34
Walney Island	South Morecambe	3.6	45
Total habitat area surveyed in 2015-16 (ha)		**12.9**	
Proportion of total survey area (%)		**19**	

Hypothesis 30 – [The extent (ha) of pioneer marsh habitats following construction, will increase in the Short-term, but in the Long-term it will be similar or less than the pre-construction area].

Inner Trial Bank

As discussed in *Section 3.6.1* for the low-mid marsh Inner Trial Bank has been subject to habitat change since the pre-construction survey in 1971. The area of pioneer marsh increased between the 1971 and 1982 surveys, almost doubling in each of the sample areas. The area of bare mud habitat decreased significantly over the same period from *c.* 57% of the site to *c.* 10%. By the 2016 survey much of the pioneer marsh had been lost, especially from On and Adjacent to the causeway, but the Off sample area still supported around 9% of this habitat. At the same time, bare mud habitat across the site has been lost. Therefore, in the case of Inner Trial Bank hypothesis 30 is proven, but this is probably as a result of long-term succession.

Table 17 shows the extent (ha) of pioneer marsh and bare unvegetated mud and as a percentage of the total for each sample area *i.e.* On, Adjacent and Off the pipeline.

Table 17 - The extent of pioneer marsh and bare mud at Inner Trial Bank over 44 years following the installation of a causeway and trial offshore reservoir.

Year		1971 pre-construction survey (Randerson, 1975)			1982 (Hill, 1988)			1999 (Ecological Services Ltd, 1999)			2016		
Area		On	Adj	Off	On	Adj	Off	On	Adj	Off	On	Adj	Off
Pioneer Marsh	Extent (ha)	0.3	0.6	0.7	0.7	1.2	1.1	0.3	1.2	1.2	0.0	0.1	0.3
	% of survey area	16	17	17	34	34	32	14	34	33	2	2	9
Bare mud	Extent (ha)	1.2	2.1	2.3	0.2	0.3	0.4	0.1	0.1	0.1	0.0	0.0	0.0
	% of survey area	57	57	58	9	9	11	3	3	4	0	0	1

Tetney Marshes

The area of pioneer marsh (SM6) at Tetney Marshes has increased since 1987 from 0ha to 0.5ha; there has also been an increase in pioneer to low-mid marsh habitat (SM6/SM13) over the same period (from 0ha to 1ha) (Table 7). The vegetation maps (Figures 22-25) show that this is due to succession from unvegetated bare mud. Therefore, in the case of Tetney Marshes hypothesis 30 is disproven.

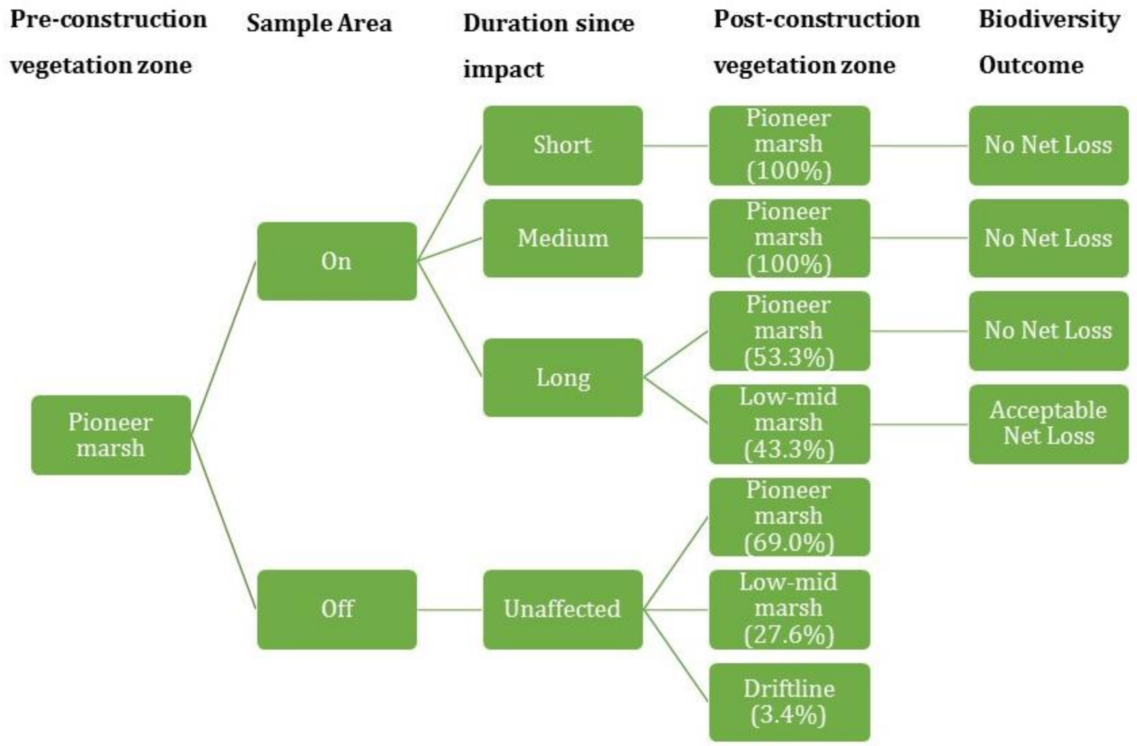
South Morecambe

At South Morecambe, the area of pioneer marsh has decreased through succession to low-mid marsh from 5.4ha to 3.6ha since 1981 (Table 14) - proving hypothesis 30.

3.7.3 Outcomes of Recovery

Hypotheses 31 – [Pioneer marsh will increase following construction at least in the Short-term. It will be retained at the outer reaches of the saltmarsh but will also develop in other zones where disturbance creates areas of bare ground]. The recovery outcome of 167 quadrats classified as pioneer marsh prior to construction is shown in Figure 47. In the Short-term following construction all areas of pioneer marsh remained as pioneer marsh (No Net Loss) and similarly in the Medium-term. By the Long-term just over half the quadrats were still classified as pioneer marsh, with the other half classified as low-mid marsh (probably as a result of ongoing succession) (Acceptable Net Loss). This conversion to low-marsh was at a slightly higher rate than in the unaffected vegetation, where approximately 70% of the quadrats were classified as pioneer marsh and 30% as low-mid marsh. A very small proportion (3.4%) of the quadrats were classified as driftline vegetation, these quadrats were recorded at Inner Trial Bank where driftline vegetation had developed around the base of the offshore reservoir.

Figure 47 - Likely vegetation outcomes of pioneer marsh following construction, based on a comparison of pre-construction vegetation types with current vegetation condition. Percentage values given represent the proportion of quadrats within each sample area and time since impact that result in each given post-construction vegetation type. The biodiversity outcome is based on those outlined in Theme 3 *Section 1.7.3.*



3.8 Creeks, Bare Ground and Saltpans

3.8.1 Creeks

Hypothesis 32 - [Following pipeline installation there will be a Short-term loss of creeks On the pipeline, however over time (by the Medium- to Long-term) natural processes will create new creek systems].

Habitat data from Inner Trial Bank, South Morecambe and Tetney Marshes all show an increase in area of creeks over time – supporting this hypothesis (Table 18). The habitat maps for the three sites (Figures 18-21, 22-25 and 33-34) show that as well as creeks increasing in extent they have also become more branched. At Inner Trial Bank, past aerial photographs were used to confirm creek absence in 1971, and later images to plot the recent creek patterns.

At South Morecambe, Rae (1981) notes that the main creek (known as Wylock Eea) was rerouted to the south of the pipeline as part of construction work. Since then, the creek system has been extensively altered with the formation on a new large creek in the lower-marsh. Aerial photographs of the site show that the newly developed creeks do not cross the pipeline, but run parallel to it, with small side creeks abruptly stopping as they reach the pipeline vicinity.

At Tetney Marshes the change in creek patterns since the 1987 survey is not as substantial as that seen at Inner Trial Bank or South Morecambe. However, care is needed when interpreting the habitat maps from Tetney Marshes as the 1987 survey is not a baseline survey but was carried out 17 years after the pipeline and causeway was installed.

Table 18 – Extent of creeks, pools and saltpans over time at Inner Trial Bank, South Morecambe and Tetney Marshes.

	Inner Trial Bank			South Morecambe		Tetney Marshes	
	1971	1999	2016	1981	2016	1987	2016
Creeks (ha)	0.0	0.2	0.5	0.3	1.5	1.4	1.4
Pools (ha)	0.0	0.3	0.3	0.0	0.1	0.0	0.5
Bare ground (ha)	5.6	0.3	0.0	0.0	0.0	1.3	0.4
Saltpans (ha)	0.0	0.0	0.0	0.1	0.0	0.0	0.0

3.8.2 Bare Ground

Hypothesis 33 – [It is expected that new pools and areas of bare ground will develop along the pipeline in the Short-term due to vegetation loss, impeded drainage and low creek densities].

At Inner Trial Bank, there has been the development of pools and bare ground in the upper section of the low-mid marsh. Two main pools developed along the former causeway at some point between 1985 and 1999 (based on aerial photographs and the previous surveys). By 2016, one of the main pools had become connected to a creek system. It appears that this has increased drainage and consequently the area of pool habitat at this location has decreased as vegetation has become established – supporting hypothesis 33. However, the overall area of pools has not decreased as a new area of bare mud has formed near to the foot of the Trial Bank structure.

Similarly, at Tetney Marshes there has been an increase of pools, particularly in the driftline zone and mid-upper marsh since 2001. However, considering the amount of time since the pipeline and causeway was installed, and the lack of baseline information, it is difficult to determine whether this change has been caused by the pipeline installation or through natural processes.

There has been a small increase in pools at South Morecambe, in 1981 the only pools documented were found in the mid-upper marsh, most of these have been retained, although along the pipeline route it appears the original pools have been lost – disproving the hypothesis. New pools have developed in the low-mid marsh near to the newly formed creeks.

Lawrence et al. (2018) notes that at managed realignment sites there is often a dominance of low-lying depressions (with pools of water and poorly drained areas) that have poor vegetation establishment. This is attributed to a lack of topographic diversity (*i.e.* rugosity, curvature, slope, topographic wetness, creek density and diversity) compared to natural marshes. Vegetation establishment at low elevations is in part governed by sediment redox potentials (which is typically lower at managed realignment sites (Mossman et al., 2012b)) which is influenced by drainage patterns.

3.8.3 Saltpans

Hypothesis 34 - In the mid-upper marsh, it is expected that new saltpans will develop (where sediments become hypersaline), limiting plant growth. These features are expected to become permanent saltmarsh features.

The only saltpans recorded at any of the sites was at South Morecambe. Several saltpans were recorded in the 1981 survey in the mid-upper marsh, On and Adjacent to the pipeline, however it appears that over time they have been lost through vegetation establishment and infilling by sediment – therefore disproving hypothesis 34.

Photo Plate 2 – Photos of the main saltmarsh species recorded at my case study sites.

Aster tripolium rayed-form

Aster tripolium rayless-form

Armeria maritima

Samolus valerandi

Glaux maritima

Cochlearia officinalis

Limonium vulgare

Suaeda maritima

Spergularia marina

Salicornia agg.

Bolboschoenus maritimus

Oenanthe lachenalii

Carex extensa

Plantago maritima

Atriplex littoralis

3.9 Discussion

3.9.1 Driftline

In the driftline the General Linear Model (GLM) analysis was unable to identify any significant differences between the distance from pipe (On, Adjacent, Off) for any of the species. This is likely to be caused by the sample size, which in the pre-construction driftline vegetation was not as large as in the other zones. By separating the data into the three sample areas (On, Off, Adjacent) or four time since impact groups (Short, Medium, Long, Unaffected) the number of degrees of freedom was increased when considered as a factor in the GLM analysis. In contrast, the Species Response Curves (SRC) used the log distance of individual quadrats from the pipeline and the actual number of years since impact, therefore utilising the entire dataset in each analysis.

Elytrigia atherica

Elytrigia atherica showed no significant differences when using the GLM for sample area or time since impact. However, using the SRC for distance and years On the pipeline, the cover of *Elytrigia atherica* increased with distance, and over time after construction, which was expected (Figure 16a&b). After construction, its cover was around 20%, which increased to over 30% by 10 years, 50% cover of the species was achieved by 25 years. *Elytrigia atherica* was the dominant species of the driftline within my samples for sites on the east and south coast forming stands of SM24 *Elymus pycnanthus* salt-marsh community. On the west coast (around Walney Island) it was replaced by *Elytrigia repens* (referable to the NVC type SM28 *Elymus repens* salt-marsh community) but there was insufficient data for this species to undertake analysis, although it was observed that there was limited *Elytrigia repens* On the pipeline.

In a managed realignment study by Davy et al. (2011) *Elytrigia atherica* was found to be restricted to areas on the marsh with a higher redox potential (where water was able to move freely) and high elevation. The process of pipeline installation often causes sediment consolidation through compaction, lowering of topography and the loss of creeks which in turn results in a lowered redox potential and elevation. Therefore, the recovery of this species will depend on the severity of the impact. This was seen when reviewing the recovery outcomes, in the Short-term *c.* 63% of the quadrats classified as driftline prior to construction supported vegetation resembling pioneer marsh (whose species are capable of dealing with low redox potentials and elevations). The remaining 37% of quadrats supported driftline vegetation dominated by *Elytrigia atherica* indicating that in these areas the conditions had remained favourable for this species. For example, at Inner Trial Bank, the construction of the causeway, raised the topography[32], this has

[32] In 2016, the causeway was only a few centimetres higher than the surrounding marsh, but evidence of stones was noted.

allowed the spread of *Elytrigia atherica* to colonise along it, extending its distribution beyond its natural tidal limit (compared to the surrounding marsh). It is speculated that this is caused by differences in drainage or elevation which favours *Elytrigia atherica* growth.

Beeftink (1977), in a study looking at effects of increased tidal frequency of upper-marsh in the Netherlands noted that a decrease in topography of 45cm would result in the loss of the original community. The study found there was a regression of the original community to a community characteristic of lower marsh. The study also noted that some communities were more susceptible to regression than others.

Measuring the extent of the driftline zone over time can show post-construction changes in vegetation. At Inner Trial Bank and at Tetney Marshes the cover of *Elytrigia atherica* has increased rapidly along the former causeway. It is clear that the causeway has altered the drainage (with the use of stones to make an access track) and elevation (in particular at Tetney Marshes where the causeway is *c.* 1m above the rest of the marsh).

It can therefore be concluded that in the driftline zone the cover of *Elytrigia atherica* (where SM24 is the dominant vegetation community) is probably the most important species in defining vegetation recovery.

Puccinellia maritima

Puccinellia maritima showed no significant differences when using the GLM for sample area or time since impact. The Species Response Curves (Figure 16a&b) showed a high cover of *Puccinellia maritima* On the pipeline which decreased with distance (from around 30% On the pipeline to 12% Off the pipeline). Similarly, its cover fell over time from around 40% following construction to around 12% after 50 years (which is a similar abundance to undisturbed areas in this zone).

Puccinellia maritima has a wide ecological tolerance, capable of growing in areas with low redox potentials independent of elevation (Davy et al., 2011). It produces different growth forms depending on its location in the marsh, and is capable of producing far-reaching stolons (up to 1m in length) which root at the node (Gray and Scott, 1977b). This is supported by a study by De Leeuw et al. (1992) looking at the effects of experimental disturbance in saltmarsh communities. De Leeuw et al. (1992) found that *Puccinellia maritima* typically was the first perennial to become dominant after disturbance and attributed this to its ability to produce long stolons which allow rapid invasion of bare patches. The SRC for this species on the pipeline over time showed that its cover decreased, probably due to increased competition from *Elytrigia atherica*.

Spartina anglica

As with the other species in this zone, *Spartina anglica* showed no significant differences when using the GLM for sample area or time since impact. The SRC for *Spartina anglica* showed a reduction in cover with distance, from around 10% cover On the pipeline to absent in the Off area (Figure 16a&b). Similarly, the SRC over time showed a decrease in *Spartina anglica* with it becoming more or less absent after 20 years. Its loss may be due to increased competition from *Elytrigia atherica*; poor seed viability in plants growing in the upper reaches of the saltmarsh (Marks and Truscott, 1985); or through *Spartina anglica* ability to bind sediments, in effect raising the elevation and allowing the establishment of other species.

Ruderal Species

The increased cover of ruderal species on the pipeline, at least in the Short-term could not be adequately assessed using the GLM due to sparse data for key species. A second consideration was that the Short-term grouping used for the analysis was rather broad (*i.e.* a time period covering the first 10 years). It is probable that for ruderal annual species, which in the saltmarsh respond very quickly to the availability of resources, 10 years is too long a period to record changes following pipeline installation, and a period of perhaps 1-3 years would help identify the change. Grime (2001) states "*the drift-line vegetation is subject to frequent disturbance at high tides and during storms, and the colonising species suffer high rates of mortality but an outstanding adaptive feature appears to be the ability of the survivors to grow and to produce seeds rapidly during the relatively short intervals between disturbances". Atriplex prostrata* is shown in the SRC for this zone, but its cover remains constant (at a very low-level of abundance) with distance from the pipeline; there is small increase in cover over time which does not support my hypothesis of a higher cover On the pipeline at least in the Short-term (Figure 16c&d).

One exception, in the driftline, was *Cochlearia officinalis* that showed a significant difference when considered with the GLM between the Short-term and Unaffected vegetation. *Cochlearia officinalis* generally has a local distribution forming small discrete patches. It colonises areas of disturbed ground following tidal scour and utilises available nitrogen deposited from accumulated drift litter. Adam (1990) notes that in northern Europe, the most-wide spread plant communities on litter are characterised by annual nitrophiles.

Triglochin maritimum

Triglochin maritimum showed no significant differences when using the GLM for sample area; but had a significantly lower cover in the Short-term compared to the Unaffected vegetation. This was supported by the SRC which showed that *Triglochin maritimum* was more or less absent from the driftline other than in the Off sample area (Figure 16c&d). On the pipeline it only became established after 40 years. This species is a long-lived perennial. Hutchings and Russell (1989) noted that while seed production was prolific, seedling survival of *Triglochin maritimum* as exceeding rare (0.2% of the seeds produced in one summer survived as established seedlings in the following summer), and therefore it is more likely to be present in the Unaffected vegetation compared to the disturbed pipeline.

Bare Ground

There was no significant difference (with GLM) between bare ground On or Off the pipeline or over time. The CCA (Figure 14) showed a correlation between the On and Short-term factors with the highest cover of bare ground. Bare ground was associated with species typical of early successional saltmarsh, while in the Long-term typical driftline vegetation with *Elytrigia atherica* was dominant.

Recovery of the Driftline Community

Considering the abundance of the individual species together provides an indication of the likely recovery timeframes for driftline vegetation. In particular the cover of *Elytrigia atherica* which was the dominant species recorded in the driftline zone in my study sites, took *c*. 25 years to achieve cover of 50% (which is comparable with the mean cover (59%) recorded in unaffected areas of SM24 – see Figure 13). A timeframe of around 20-25 years also corresponds with the decline in cover of *Aster tripolium*, *Puccinellia maritima* and *Spartina anglica* (at around 20 years) which are all species typical of low-mid marsh. However, these timeframes are of course dependent on the level of impact and where there has not been a change in topography, severe compaction, or complete loss of vegetation it is anticipated that driftline vegetation (where dominated by *Elytrigia atherica*) will recover quicker. Therefore, recovery of this vegetation type is likely to be in the Short- to Medium-term. This is further discussed and summarised in *Section 7.3* and Table 44.

3.9.2 Mid-upper Marsh

Agrostis stolonifera, Festuca rubra and Puccinellia maritima

The three main grasses in the mid-upper marsh recorded across the study sites were *Agrostis stolonifera*, *Festuca rubra* and *Puccinellia maritima*. It was hypothesized that the cover of these grasses would be higher On the pipeline (at least in the Short-term). The results however were more complicated than this. *Festuca rubra* had significantly higher cover On the pipeline (when considered with GLM), and its cover decreased with distance as shown with the SRC (Figure 31a&c). In contrast, cover of both *Agrostis stolonifera* and *Puccinellia maritima* were not significant with sample area (with GLM), but *Puccinellia maritima* had a significantly higher cover in the Short-term. The SRC with time (Figure 31c) showed interesting responses for all three species; cover of *Puccinellia maritima* rapidly declined following pipeline installation, while *Agrostis stolonifera* and *Festuca rubra* appeared to take around 20 years before showing signs of recovery similar the undisturbed vegetation.

These findings agree with a study by Gray and Scott (1977a) looking at the revegetation of areas stripped for turf-cutting in Morecambe Bay. The removed turfs were *c* 3.5cm deep, and cut from the mid-upper marsh, in areas dominated by *Festuca rubra*. They noted that *Festuca rubra*, in comparison to *Agrostis stolonifera* and *Puccinellia maritima*, was slow to recolonise. Unsurprisingly, the turf-cutters had noted that the quality of the turf had declined over the years and that *Festuca* dominated swards were more difficult to find. The study showed that *Puccinellia maritima* recolonised the bare areas within 3-5 years and recolonisation was often from adjacent strips left between the cut areas.

Bolboschoenus maritimus, Juncus gerardii and Juncus maritimus

The mid-upper marsh also supported taller, slower growing graminoids namely *Bolboschoenus maritimus, Juncus gerardii* and *Juncus maritimus*. It was hypothesised that as rhizomatous species, growth would be limited to clonal spread following disturbance, the cover of these species would be lower On the pipeline (at least in the Short-term). However, in reality three individual outcomes were observed.

Bolboschoenus maritimus is a long-lived clonal species which tends to spread by the production of ramets. It is classified as a shortly-creeping rhizome and a perennial hydrophyte (Hill et al., 2004), and a competitive-stress tolerator (Grime, 2001). In my study, *Bolboschoenus maritimus* had a significantly lower cover On the pipeline and in the Short-term to Long-term (when considered with GLM and SRC - Figure 31a&c). This is supported by a review of saltmarsh restoration following pipeline installation at Wytch Farm, Poole Harbour, where Gray (1986) noted that "*the 8-year-old pipeline route is revealed only by the absence of some large Scirpus maritimus*[33] *clones from the western section*". However, Charpentier et al. (1998) studying how disturbance caused by grazing and trampling altered *Bolboschoenus maritimus* growth, noted that artificial severing of rhizomes broke the dormancy of older ramets, which allowed rapid re-colonisation of disturbed areas.

In contrast, and unexpectedly, *Juncus gerardii* showed a significantly higher cover On the pipeline compared to Off (GLM), although this not shown in the SRC which shows *Juncus gerardii* is absent from On the pipe (Figure 31a). The SRC with time (On the pipe), shows that it took time to become established (around 25 years after installation) (Figure 31c). This follows the time frames recorded by Olff et al. (1997), who showed that the cover of *Juncus gerardii* increased after *c.* 40

[33] *Bolboschoenus maritimus*

years, and became one of the most dominant species in the later stages of succession. However, Bertness (1991) notes that *Juncus gerardii* appears to be important in colonising disturbed areas by oxygenating soils and by reducing substrate salinity by passively shading the substrate. It is classified as a tussock forming graminoid and a non-bulbous geophyte (Hill et al., 2004), and a stress-tolerator (Grime, 2001). In a study of competition and zonation in New England saltmarsh, Emery et al. (2001) noted that *Juncus gerardii* behaved as a competitor when there was an increase in available nitrogen. It is speculated that the pipeline installation process potentially makes available nitrogen, stimulating *Juncus gerardii* growth.

Juncus maritimus was not significant for sample area or time since impact when considered with GLM. The SRC showed that like *Juncus gerardii* it took time to become established *i.e.* around 25 years (Figure 31c). This species was recorded at the Walney Island sites (where it formed small localised patches and was only present in a small number of quadrats) and at the three Poole harbour sites (where it formed more extensive zones transitional to the adjacent swamp communities). The Poole Harbour pipeline was installed 30 years ago, and it is considered likely that impacts from installation are minimal over this time frame, resulting in insignificant results for this species. *Juncus maritimus* has a clonal reproductive strategy, and is classified as a far-creeping rhizomatous species and a hemicryptophyte Hill et al. (2004). Although it appears that its cover was not affected by pipeline installation in the study sites, in Mediterranean saltmarsh, Álvarez-Rogel et al. (2007) noted that its clonal growth is an advantage for invasive behaviour after disturbance by human activities. The speed of its establishment is highlighted by Packham and Liddle (1970) who noted that an area of bare sand, initially colonised by *Puccinellia maritima* became dominated by *Juncus maritimus* within 20 years at the Cefni Estuary.

The difference in response to disturbance of *Bolboschoenus maritimus*, *Juncus gerardii* and *Juncus maritimus* may be due to changes in water availability and salinity. In a study looking at salinity and the distribution of plants at Poole Harbour, Ranwell et al. (1964) noted that species of the upper marsh were divided into two main groups. The first were those typical of dry marshland where water content was less than 20%, (*i.e. Juncus gerardii* and *Juncus maritimus*); the second group contained species of permanently wet marshland *e.g. Bolboschoenus maritimus*. Species of the first group were capable of growing at locations which are submerged for short periods but could also survive in hypersaline conditions which may develop when dry weather follows an exceptionally high tide. It is speculated that following pipeline installation, areas of bare mud may become hypersaline in the mid-upper marsh as it is infrequently inundated by the tide; favouring *Juncus gerardii* growth. This is supported by research by Bertness (1991). In contrast, areas which were previously wetter and dominated by *Bolboschoenus maritimus* may have dried out reducing the suitability for this species. While, Ranwell et al. (1964) notes that *Juncus maritimus* is a species of drier marshland, at the three study sites at Poole Harbour, it grew in areas with impeded drainage that were permanently flooded.

Limonium vulgare and Triglochin maritimum

The study found that cover of *Limonium vulgare* in the mid-upper marsh had a complicated recovery. It was the only characteristic herb species that showed a significant response when analysed using the GLM. *Limonium vulgare* had significantly lower cover in the Short-term compared to the Unaffected and Long-term vegetation. This is supported by the SRC with time, which showed almost no recovery for the first few years, and a sharp increase thereafter (reaching around 16% cover by 35 years) (Figure 31 d). However, with increased distance the SRC showed its cover decreased, with the disturbed On sample area having the highest cover (around 12%) decreasing to 1% in undisturbed areas (Figure 31b). This indicates that once the species established itself (even if this took many years) it was able to cope with the altered environmental conditions associated with disturbance On the pipeline.

It is well documented that *Limonium vulgare* is slow to recolonise managed realignment sites (Bakker et al., 2002, Garbutt et al., 2006, Mossman et al., 2012a). It is a stress-tolerator with a slow growth rate and low phenotypic plasticity (Grime, 2001). Recovery following pipeline installation is likely to be hampered by seed viability. Hutchings and Russell (1989) showed that seed viability of *Limonium vulgare* was low (around 13%), and there was no persistent seed bank, with only 2% of seeds becoming established plants. This fits with the slow initial recovery and then increase in cover over time. This is also supported by Boorman (1967), who noted that *Limonium vulgare* was susceptible to trampling, especially where young buds are damaged; therefore, even where the physical impacts of pipeline installation were less severe and complete removal of plants did not occur, the impact of trampling in the adjacent areas may have resulted in slow initial recovery across the zone.

Triglochin maritimum showed a similar recovery pattern to *Limonium vulgare* with its cover decreasing slightly with distance but increasing slightly over time On the pipeline (Figure 31b&d). As with *Limonium vulgare*, this variation in recovery may be due to the seed bank and seed viability, as well as abundance of donor species in the surrounding unaffected marsh. Lawrence et al. (2018) notes in a study comparing topographic diversity between managed realignment sites and natural saltmarshes that the lack of diversity in topography in the mid-upper marsh (which would normally restrict the dominance of species such as *Elytrigia atherica* is absent). This maybe the limiting factor in the establishment and persistence of water-logging tolerant species such as *Triglochin maritimum* which are often rare or absent on restored marshes.

Armeria maritima, Glaux maritima and Plantago maritima

Armeria maritima, *Glaux maritima* and *Plantago maritima* showed no significant differences when using the GLM for sample area or time since impact. The SRC showed that both *Armeria maritima* and *Glaux maritima* had a slow recovery, taking around 5 years before being recorded On the pipeline. Both species were only recorded at low-levels of abundance even in the Long-term (Figure 31b&d). In contrast, the cover of *Plantago maritima* increased sharply with distance (from 0 to 16% cover), avoiding the most disturbed areas On the pipeline. It also increased sharply with time, although like *Armeria maritima* and *Glaux maritima* it showed a delay of around 8 years before it was recorded (Figure 31b&d). *Plantago maritima* reproduces exclusively by seeds (Jerling, 1988), which may explain its rapid increase in cover once established On the pipeline.

notes that *Armeria maritima* is shade intolerant short perennial. In the upper saltmarsh it favours open areas, in areas of higher elevation and better drainage. Chapman (1960) showed that it is only able to tolerates the narrowest elevational window (around 10cm), therefore small changes in the elevation, such as soil loss/ compaction following pipeline installation may result in its loss from the sward. Woodell and Dale (1993) also note that *Armeria maritima* is both vulnerable and can benefit from human disturbance. It is easily damaged by trampling and by removal of soil from around plants; but disturbance can allow *Armeria maritima* to persist in areas where it would normally be lost (through succession). It also notes that *Armeria maritima* produces seed, which are highly variable allowing it to rapidly colonise opportunities as they arise.

Glaux maritima is also shade intolerant and is a poor competitor (Jerling, 1988). It prefers open areas, with reduced vegetation height. It typically reproduces by vegetative propagation, through vegetative runners, but seed germination can be triggered by disturbance causing strongly fluctuating soil temperatures.

In experiments on the response of saltmarsh species to waterlogging and salinity, Cooper (1982) found that growth of upper marsh species such as *Armeria maritima*, *Plantago maritima* and *Triglochin maritimum* were strongly limited by both salinity and waterlogging. This supports my findings where impacts from construction are severe for example where vehicles cause sediment compaction leading to increased waterlogging, recovery of these species will take longer than in unaffected areas.

Salicornia agg.

Following pipeline installation, it was expected that early successional species would colonise areas of bare ground in the Short-term. Over time these species would be lost from the mid-upper marsh replaced by typical species of the zone. The GLM showed that *Salicornia* agg. was not significant for sample area or time since impact. However, it showed an interesting response in terms of cover with distance and years with the SRC in this zone (Figure 31b&d). With distance *Salicornia* agg showed a rapid decrease (On the pipeline cover was ca. 7% becoming absent Off the pipeline). It also showed a rapid decrease in cover over time, with its cover fall from just under 20% to around becoming absent by 35 years.

Local patches of *Salicornia* agg. dominated vegetation were also common along the pipeline in the mid-upper marsh, especially in low-lying areas. In a study in New England, Ellison (1987) showed that *Salicornia europaea* was the first coloniser of disturbed ground in the high marsh, although studies in Europe (De Leeuw et al., 1992) showed that *Puccinellia maritima* was the initial coloniser. *Salicornia* agg. is rapidly outcompeted by perennials such as *Puccinellia maritima* (due to competition for light), which supports the findings of my study.

Aster tripolium

Aster tripolium was not significant for sample area, however it had significantly higher cover in the Short-term compared to the Unaffected vegetation considered with GLM. It appears to be a fairly minor component of the mid-upper marsh, with more or less constant cover with distance and over time (Figure 31b&d).

Aster tripolium is a short-lived perennial species which is capable of altering its flowering behaviour depending on whether it is found in the lower marsh, where it has tendency for perennial behaviour, or in the mid-upper marsh where it behaves as an annual. Adam (1990) summarises this difference in ecotypic variation between the lower and upper marsh populations. In low-marsh sites, populations typically take two or more years to flower after germination, with flowering in August and September, these plants produce heavy fruit with no innate dormancy. In contrast, a large number of the plants in the upper-marsh population flower in the first year between September to October and produce light fruits, which often require a chilling treatment to break dormancy. This strategy, along with a seed dispersal method of combining wind (over short distances) and tidal dispersal, means this species is a well-adapted weed capable of colonising gaps (Ranwell, 1972).

Bare Ground

The cover of bare ground was significantly higher in the Short, Medium and Long-term when compared to the Unaffected vegetation (when considered with GLM). Although it was not significantly different between the On and Off sample areas. It appears that amount of bare ground remained fairly constant over this time, indicating that bare ground once created in the mid-upper marsh may not revegetate even in the Long-term. It is suspected that recovery of bare ground in this zone is dependent on several factors. A key factor, is the input of sediment, returning low-lying areas (damaged through construction) to the original marsh topography.

Rates of sediment supply and deposition in the upper marsh are low (Boorman, 2003, Brooks et al., 2015). This coupled with problems associated with high shear strength of over-compacted soils (caused by vehicle movements) result in poor seedling germination (as seedling roots struggle to penetrate the soil). The other key factor (touched on previously) is that large bare patches have higher salinities due to increased exposure to solar radiation. Bertness (1991) notes that while substrate salinities in vegetation decrease with marsh elevation, bare patch salinities increase with increasing marsh elevation, due to infrequent tides.

Recovery of the Mid-upper Marsh Community

Quadrats from the mid-upper marsh represented several different NVC types[34], and as such the cover of the key species will vary considerably. Considering the abundance of the key graminoid species provides an indication of the likely recovery timeframes for the differing NVC types. For example, a *Puccinellia maritima* dominated sward *i.e.* SM13a is likely to recover in the Short-term *i.e.* within 10 years, although it may represent a species-poor example with fewer of the characteristic species. It is also typically classified as a low-mid-marsh community so its establishment in the upper-mid marsh would suggest an intermediary recovery stage. In contrast the more diverse upper-mid marsh sub-communities (SM13b-d), which require greater cover of the key species such as *Armeria maritima, Glaux maritima*, *Limonium vulgare*, and *Plantago maritima* will have longer recovery times. These species (with the exception of *Limonium vulgare*) showed a delay in returning to the sward of around 5 to 10 years after installation, and then they were typically only present at low-levels of abundance. While cover of *Puccinellia maritima* is much reduced (*i.e.* 10% in SM13c) in favour of the wide range of herbaceous dicotyledons. Rodwell et al. (2000) notes that all four species have a minimum 4% cover in quadrats of the SM13 sub-communities (excluding SM13a). Using this as a guide for recovery *Armeria maritima* and *Glaux maritima* do not achieve this level of abundance within 35 years, *Plantago maritima* reaches *c.* 4% by 35 years, and *Limonium vulgare* reaches 4% cover by 10 years. Therefore, for SM13b-d full recovery is not anticipated until the Long-term (over 35 years).

In SM16 where the sward is dominated by *Festuca rubra* or *Juncus gerardii* recovery will take at least 20 to 35 years to recover. A similar time frame is expected for SM18 dominated by *Juncus maritimus.* It is likely that areas of *Bolboschoenus maritimus* (S21) will be completely loss as recorded by Gray (1986). As with the other zones, the actual recovery timeframes will depend on the severity of the impact. This is further discussed and summarised in *Section 7.3* and Table 44.

[34] SM13b *Puccinellia maritima* salt-marsh community, *Glaux maritima* sub-community, SM13c *Puccinellia maritima* salt-marsh community, *Limonium vulgare-Armeria maritima* sub-community and SM13d *Puccinellia maritima* salt-marsh community, *Plantago maritima-Armeria maritima* sub-community, SM15 *Juncus maritimus - Triglochin maritima* salt-marsh community, SM16 *Festuca rubra* salt-marsh community and SM18 *Juncus maritimus* salt-marsh community.

3.9.3 Low-mid Marsh

Puccinellia maritima

Where impacts were less severe, typical species of the low-mid marsh were expected to recover quickly with little difference in cover On and Off the pipeline and over time. This was true for both *Puccinellia maritima* and *Suaeda maritima* which showed no significant differences when considered using the GLM. The SRC for *Puccinellia maritima* however, showed a rapid increase in cover both with distance and time (Figure 39 a). *Puccinellia maritima* also increased with time from <5% cover after installation, increasing to ca. 10% by 10 years, 16% by 20 years and >35% by 50 years (Figure 39b).

As discussed in the driftline, *Puccinellia maritima* is capable of producing far-reaching stolons; and studies have shown it is often the first species to colonise and the first perennial to become dominant after disturbance (De Leeuw et al., 1992). Olff et al. (1997) showed succession from initial colonisation to low-marsh, took place over a 10-year period, during which the study site became dominated by *Limonium vulgare*, *Puccinellia maritima Spergularia marina*, and *Suaeda maritima.*

Spartina anglica

Cover of *Spartina anglica* was significantly lower On the pipeline compared to Off (GLM). The SRC shows the species increased with distance from the pipeline in the low-mid marsh. Cover close to the pipeline was around 8% which increased to just under 25% in undisturbed areas. In contrast, over time On the pipeline *Spartina anglica* cover fell from ca 25% after installation to ca. 20% after 10 years, to 15% after 30 years (Figure 39a&c). Marks and Truscott (1985) noted that *Spartina anglica* has a low seed viability, which may have affected its initial re-establishment On the pipeline, however this is offset by rapid clonal spread.

Atriplex portulacoides

Atriplex portulacoides is not tolerant of physical damage to above-ground growth and therefore is susceptible to compaction by pipeline installation vehicles resulting in its loss within the working width (*pers. obs.*). The species has short rhizomes and an estimated spread of 1.3cm per year (Chapman, 1950). Chapman also noted that seedlings and young plants cannot tolerate waterlogging. Therefore, one of the key hypotheses (hypothesis 18) in the low-mid marsh related to the difference in cover of *Atriplex portulacoides* On and Off the pipeline; and where lost, how long recovery would take. My own data supported the hypothesis that cover of *Atriplex portulacoides* was significantly lower On the pipe than Off it (using the GLM). The SRC for distance showed a continued increase in cover from less than 5% cover On the pipeline, increasing to between 6-10% Adjacent to it. In the most undisturbed sample areas cover was just under 25% (Figure 39a).

The GLM data for cover over time was less conclusive (Short- and Medium-term were lower than the Unaffected vegetation, but not statistically so). A non-significant difference in the cover in the Long-term suggests that the cover had returned to pre-construction levels after 25 years. However, the SRC for years, shows a more interesting response; initially (for the first 10 years) *Atriplex portulacoides* is absent from On the pipeline, after which its cover increases to around 5% after 20 years, 10% cover by 30 years, attaining 25% cover after 50 years (Figure 39b). This would support the hypothesis that *Atriplex portulacoides* is intolerant to physical damage and has a slow recovery.

Various studies have shown that *Atriplex portulacoides* is sensitive to physical damage (Beeftink, 1977, Chapman, 1950). For example, it is very sensitive to human trampling; Jensen (1985) noted that only a very limited number of passes creates a path in *Atriplex portulacoides* stands, which appears to be due partly to damage of the shoots and partly to compaction of the sediment. Therefore, it can be concluded, that the greater severity in terms of damage caused by pipeline installation, clearly has long lasting impacts on this species. In a study of succession in the Netherlands, Olff et al. (1997) showed that the highest abundances of *Atriplex portulacoides* were recorded at sites that had undergone between 40 and 60 years of succession.

Aster tripolium, Limonium vulgare, Suaeda maritima and Triglochin maritimum

The GLM showed that *Aster tripolium* had a significantly higher cover On the pipeline. The SRC for both distance and time do show a reduction in cover but this is not as strong a response as seen for other species in this zone. For example, initially after installation, cover of *Aster tripolium* was ca. 4-5% which dropped fell to around 1-2% (Figure 39a&b). Interesting the Scottish Saltmarsh Survey National Report (Haynes, 2016) notes that *Aster tripolium* dominated swards *i.e.* SM12 are typically found on areas of pioneer and lower marsh where the saltmarsh has been modified or recently disturbed. Martin et al. (2018) noted that *Aster tripolium* was more likely to occur on managed realignment sites than natural marshes, and that it occurred lower in the tidal frame than expected.

The cover of *Suaeda maritima* was not significant for either sample area or age class when considered with the GLM. The SRC for distance shows its cover as being constant. This observation contrasts with the results from managed realignment sites where it was recorded as being more likely to occur than in natural marshes. It was also found that it occurred higher in the tidal frame in management realignment sites (Martin et al., 2018). A similar situation was also noted for *Limonium vulgare* (Figure 39a&b).

The cover of *Triglochin maritimum* was not significant for either sample area or age class when considered with the GLM, however it does show a positive response with distance. It appears to be absent from the On the pipeline (Figure 39a&b). This pattern is similar to that noted in the mid-upper marsh.

Algae spp. and Salicornia agg.

The GLM showed that early successional species typical of pioneer marsh *i.e.* Algae spp. and *Salicornia* agg. had a higher cover On the pipeline. *Salicornia* agg. was significantly higher in the Short and Medium-term compared to the unaffected vegetation (using GLM). The SRC shows that *Salicornia* agg. decreases with distance from pipe and over time (Figure 39a&b). Bare ground was also significantly higher On the pipeline and in the Short-term. Early successional annual species are able to quickly establish themselves in areas of bare ground, which under normal conditions should then succeed to low-mid marsh. However, where severe damage to sediments occur (through compaction and sediment loss) the course of succession is inhibited at least temporarily. The outcomes of succession recorded in the low-mid marsh support this theory, in that, the change of vegetation type of quadrats between the pre- and post-construction data, showed that in the Short- and Medium-term quadrats, were likely to be defined as pioneer marsh (70% of the quadrats). This regression of vegetation communities follows findings recorded at managed alignment sites (Brooks et al., 2015, Mossman et al., 2012b), in which less oxygenated sediments, tended to shift the vegetation towards more inundation-tolerant, pioneer communities.

Construction Impacts

In the low-mid marsh impacts beyond the working width *i.e.* On sample area appear to be more frequent that in the other zones, this may be due to several factors. The low-mid marsh is perceived to be of low species-richness and therefore is less likely to be subject to restoration (compared to the mid-upper marsh or driftline). Its location in the tidal range also means access in this zone by vehicles for construction or restoration purposes is much harder than in the upper tidal areas. As I have observed, there is an increased likelihood that vehicles become stuck and require emergency actions to retrieve them, often resulting in access extending beyond the documented working width. Even with the use of marsh protection measures there is an increased chance of sediment compaction, changes in redox potentials and topography which all influence the outcome of recovery. In addition, creeks in the low-mid marsh are frequent, and may require rerouting or otherwise may collapse becoming infilled and losing their function.

Recovery of the Low-mid Marsh Community

The quadrats from the low-mid marsh typically represented vegetation from one main vegetation community SM13a *Puccinellia maritima* salt-marsh community, sub-community with *Puccinellia* *maritima* dominant; although locally there were areas dominated by SM10 Transitional low-marsh vegetation with *Puccinellia maritima*, annual *Salicornia* species and *Suaeda maritima* and SM14 *Halimione portulacoides* salt-marsh community. Cover of *Puccinellia maritima* in undisturbed quadrats of SM13a is between 10-100% (Rodwell, 2000). The mean cover of *Puccinellia maritima* in my unaffected quadrats was 15.4% (Figure 36). Therefore, it can be expected that recovery following construction in areas dominated by *Puccinellia maritima* is likely to be in the Short to Medium-term *i.e.* 10-20 years. Cover of *Atriplex portulacoides* in SM14 is also variable (between 10-100% Rodwell (2000)). Therefore, to achieve cover of *Atriplex portulacoides* equivalent, even to the lower end of this range, will take until the Long-term *i.e.* over 25 years. SM10 has three constant species *Puccinellia maritima*, *Salicornia* agg. and *Suaeda maritima* and is typically species-poor dominated by varying proportions of the constant species. Cover therefore of the constant species is variable 4-75%. It forms in the low-marsh above the pioneer marsh and could potentially recover in the Short-term (by considering the cover of these species as shown in the SRC). This is further discussed and summarised in *Section 7.3* and Table 44.

3.9.4 Pioneer Marsh

In the pioneer marsh recovery focuses on the presence and abundances of three main species, Algae spp., *Salicornia* agg., and *Spartina anglica* which colonise areas of bare sediment. These early successional species are all capable of growing at low elevations which are frequently inundated with poorly oxygenated sediments.

Bare Ground

Immediately after construction the pioneer marsh is left unvegetated and the extent of bare ground is a key attribute determining the rate of recovery. As expected, cover of bare ground was significantly higher in the Short-term on the pipeline, but by the Medium-term this difference was insignificant. This is supported by a review of the success of managed realignment projects Mossman et al. (2012b). The review showed that overall the managed realignment sites had significantly more bare ground than the natural reference marshes, but the coverage of bare ground decreased with increasing time since tidal restoration.

Algae spp.

The GLM analysis showed that in general the cover of Algae spp. across the study sites was not significantly different in terms of sample area or time since impact. Although the SRC showed a decrease in cover with distance from pipe and over time (with the highest cover after installation On the pipeline) (Figure 45a&b). In The Wash, Coles (1979) showed that populations of benthic microalgae, particularly epipelic diatoms, are vital precursors to saltmarsh growth. Benthic microalgae are capable of increasing sediment accumulation in mudflats immediately in front of the saltmarsh, by secreting mucus (which binds fine sediments and increases surface stability). The role of macroalgae is less clear (Adnitt et al., 2007), however the evidence suggests that the macroalgae *Enteromorpha* spp. and *Ulva lactuca* are sensitive to substrate stability (tolerating only very low sediment accretion rates). *Enteromorpha* spp. are also regarded as opportunistic species, able to respond to short-term fluxes of nutrients in seawater and are often associated with saltmarsh decay. Large patches of *Enteromorpha* spp., *Fucus spiralis*, and *Pelvetia canaliculata* were observed On the Rivers Fields pipeline in Walney Island[35]. The algae extended along the pipeline inland from the mudflats to the beach. In these areas, the growth of *Salicornia* agg. and *Spartina anglica* was limited and appeared less vigorous than the plants growing in the surrounding area. A similar observation has been recorded at the Tollesbury realignment site, where water-laden sediments have been associated with growth mats of *Enteromorpha*, which in turn has been linked to the poorer than expected establishment of *Salicornia* spp. (Reading et al. (2000) in Crooks et al. (2002)).

Salicornia agg.

Following pipeline installation *Salicornia* agg. was shown (using GLM) to have a higher cover On the pipeline, and in the Short-term. The SRC with distance showed a clear increase in cover with distance (Figure 45a&b) from it being absent at the pipeline increasing to ca. 15% in undisturbed areas. Over time, however, the response was less weak, with a gradual decrease in cover. This perhaps contrasts with data collected from the managed realignment sites by Mossman et al. (2012b) that showed that the cover of *Salicornia europaea* increased with time since restoration.

Spartina anglica

Spartina anglica is considered an invasive grass, in particular colonising areas of mud flat which are utilised by waders and wild fowl for feeding. Attempts have been made to control its spread at many locations (summarised in Lacambra et al. (2004)). One question I wished to answer, concerned whether *Spartina anglica* was likely to expand along the disturbed substrate of the pipeline. Many of the methods used for pipeline installation result in the burial of sediments and plant material. This is somewhat comparable to studies at Lindisfarne National Nature Reserve on the use of mechanical disturbance (known as rotoburying) to restore mud flats invaded by *Spartina anglica.* The process involves inverting the upper 25cm of sediment burying all above-ground vegetation. Frid et al. (1999) noted that the density of *Spartina anglica* was significantly reduced three years after disturbance. While Denny and Anderson (1999) noted that the process had killed over 95% of the *Spartina anglica* after two years. They also noted an increase in *Zostera* spp. and *Ruppia maritima* both target plant species. In an article in The Independent (Connor,

---

[35] installed 13 years prior to the survey

2001), the then site manager of the reserve said "*six years after plots of the weed had been rotoburied there was still no sign of it returning*". This therefore bodes well that the pipeline in the long-term is unlikely to be dominated by *Spartina anglica* and its cover may actually be reduced.

However, my findings for the pioneer zone showed that cover of *Spartina anglica* was not significantly different On or Off the pipeline when analysed using a GLM. Although the CCA (Figure 43 a) did show that *Spartina anglica* was closely associated with the On sample area. In contrast, the SRC showed a significant decline in the cover of *Spartina anglica* with distance falling from around 35% On the pipeline to ca. 15% in undisturbed areas (Figure 45a&b). When considered over time (using GLM), the Short-term had a significantly less *Spartina anglica* than the Unaffected vegetation. The SRC broadly follows these findings, showing a small increase in cover over time (from around 25% after installation to 30% cover by 50 years). At this point it is expected the increase in the cover of *Puccinellia maritima* (associated with succession to low-mid marsh) limits the growth of *Spartina anglica* as demonstrated by Scholten and Rozema (1990).

When the cover of *Spartina anglica* was assessed across all vegetation zones there was no significant difference On or Off the pipeline, and the Unaffected vegetation had a significantly higher cover in the Short-term. But, by the Medium-term the difference in cover between the pipeline and Unaffected vegetation was not significantly different, indicating *Spartina anglica* had returned to pre-construction levels.

Puccinellia maritima

Cover of *Puccinellia maritima* was not statistically significant when analysed using the GLM. However, the SRC did show a rapid increase in cover with distance from pipeline from ca. 3% cover On the pipe to >15% in undisturbed areas (Figure 45a&b). The cover of *Puccinellia maritima* when considered with time, shows an interesting response. It is more or less absent from the On the pipeline for the first 20 years. After *c.* 30 years it shows a rapid increase in cover (from <5% to >70% by 50 years). This indicates the long-term succession of the pioneer marsh to low-mid marsh. This ongoing succession to low-mid marsh was also supported by the CCA which showed increased species-richness by the Long-term with species more typical of low-mid marsh such as *Aster tripolium*, *Puccinellia maritima* and *Suaeda maritima* being recorded here. The outcomes of recovery for the pioneer zone support this, with in the Short and Medium-term 100% of the quadrats supporting pioneer marsh, while in the Long-term approximately half of the quadrats were defined as pioneer marsh, while the remainder supported low-mid marsh.

Recovery of the Pioneer Marsh Community

The quadrats from the pioneer marsh typically represent vegetation from two main communities in my data, SM6 *Spartina anglica* salt-marsh community, SM8 Annual *Salicornia* salt-marsh community, although SM9 *Suaeda maritima* salt-marsh community, and SM11 *Aster tripolium* var. *discoideus* salt-marsh community were also recorded. Vegetation cover in the pioneer zone is very variable (*e.g.* between 5-95% for SM8 (Rodwell, 2000)), therefore even quite sparsely developed vegetation can be classified as pioneer marsh. The mean cover of *Spartina anglica* in unaffected quadrats was 18.4% (Figure 42). Cover of this species from On the pipeline over time shows that its cover was over 20% indicating that vegetation referable to the NVC type SM6 is likely to be present in the Short-term. The mean cover of *Salicornia* agg in unaffected quadrats was 12.8% (Figure 42). Cover of this species from On the pipeline over time shows that its cover was around 10%, although it decreased over time. This indicates that vegetation referable to the NVC type SM8 is likely to be present in the Short-term. Recovery of SM9 is likely to take a lot longer, Rodwell (2000) notes the cover of *Suaeda maritima* in this community as a minimum of 26%. The SRC for this species shows *Suaeda maritima* only just starting to recover at 40 years. Similarly, *Aster tripolium* (the main constant of SM11) only appears in the pioneer zone at around 50 years. This is further discussed and summarised in *Section 7.3* and Table 44.

3.9.5 Creeks, Bare Ground and Saltpans

Creeks

The Saltmarsh Management Manual (Adnitt et al., 2007) states "*that the two prime functions of the networks of saltmarsh creeks are to transport new sediment into the saltmarsh and to drain tidal water from the marsh surface on the ebb tide*". Creeks help to dampen tidal energy, by causing frictional drag of tidal water over the channel banks and bed. The greater the channel length and area of the banks and bed, the greater this frictional drag is. In systems where there is high creek sinuosity water flow along creeks in the upper marsh maybe almost absent. Goudie (2013) found that high creek densities and sinuosity occurs on saltmarshes that have high tidal energies. In such situations, creek erosion is increased with creeks becoming wider, deeper and more frequent. More complex creek patterns are recorded where there is a moderate tidal range, with less complex patterns found where there is either a very high or very low tidal range (Luternauer et al. 1995 in Goudie 2013).

Adnitt et al. (2007) notes that issues can arise where creek systems are cut-off by the construction of embankments *"since the reduced channel system may be unable to fully dissipate the energy of the flood tide, resulting in relatively high current velocities and scour of the bed and banks close to the new sea wall. On many saltmarshes, truncated creeks can be seen to re-develop along the line of defence*". I have observed this at several locations along the sea defence in The Wash where the embankment was constructed in the mid-1970s as part of land reclamation. Here the creek now runs parallel to the sea defence, in contrast to the majority of creeks further out that run perpendicular to it. In addition, at my study site in Poole Harbour, road causeways have been built across the saltmarsh. These have cut across tidal creeks at two locations which appears to have changed the flood regime to some extent.

Studies at the managed realignment site at Tollesbury, Essex showed that creeks formed when deposited sediments exceed a critical depth of 20-30cm. Along the newly formed creek margins (which were rapidly colonised by *Salicornia* spp.) there was an increase in the sheer strength of sediment compared to the surrounding marsh, thought to be the result of rapid drainage and consolidation of sediments (Reading et al., 2008). As the marsh matures there are greater differences between the topography along the creek which is a few centimetres higher than the surrounding marsh (known as levees). Levees are raised ridges of sediment along the creek top where there is increased sediment capture and increased drainage leading to aerated soils. In England and Wales, *Atriplex portulacoides* is typically found along these creek banks as its growth is limited by prolonged inundation. In contrast *Puccinellia maritima* is typically abundant in lower marshes and in poorly drained pans and depressions (Crooks et al., 2002). This is supported by research by Kim et al. (2013) who notes that creeks influence fine-scale vegetation patterns by altering local conditions.

Bare Ground

One of the key factors following pipeline installation determining the likely success of restoration relates to the severity of damage to the soil structure. Disturbances that cause large alterations in structure of marsh soils by removing soil, adding sediment, compacting the soil, or draining the marsh are especially severe and result in long recovery times for the disturbed area. Allison (1995) looked at the creation of bare ground through the burial of saltmarsh plants caused by sediment deposition. The study showed that vegetation recovery was typically from lateral growth of surrounding perennial plants; or by growth of buried plants through the sediment. Recovery was generally limited to two species (*Distichlis spicata*[36] and *Salicornia* agg.), with recovery times taking 12-24 months; seedling establishment was rare. The disturbance covered a small area (2m^2 circular plots) and the author noted that large scale disturbances would result in longer recovery times due to poor seedling establishment and the greater distance required for vegetated spread.

De Leeuw et al. (1992) also considered disturbance of vegetation and sediments. Plots disturbed by digging were quickly recolonised by *Puccinellia maritima* (with *Suaeda maritima* as a co-dominate), with an increase in cover of *Aster tripolium* over time. The study found that while initially the vegetation returned to its original species composition, over time the vegetation developed into a new community type.

---

[36] *Distichlis spicata* – a rhizomatous saltmarsh grass, native to the Americas

Davy et al. (2011) showed there is a correlation between cover of bare ground and redox potential; with areas with low redox potentials frequently unvegetated. It is expected, although not recorded as part of my study, that following the installation of pipelines/cables the increase in bare ground in the long-term along the corridor may be due to low redox potentials. Vegetation regeneration in these effected areas is limited by sediment compaction, whether the saltmarsh elevation has been modified *e.g.* a small reduction in elevation can lead to more frequent tidal flooding, and the ability of that area to subsequently drain. These local changes to the saltmarsh can lead to areas with low redox potentials where vegetation recovery is poor; and consequently, you find more permanent pools of water developing.

Saltpans

Soil salinity in the lower saltmarsh is fairly constant, but in the upper saltmarsh soil salinity is often reduced due to rainfall. During drier periods, evapotranspiration can increase soil salinity, locally forming salt crust/ salt pans. These hypersaline features also have a limiting effect on vegetation growth creating areas of bare ground (Beeftink, 1977). Along the freer draining creek banks, high water velocities have a flushing affect limiting the build-up of salts. Two types of natural salt pans have been described and are summarised in Goudie (2013), primary pans which are circular and flat bottomed with gentle sloping sides; and secondary pans which are longer and may have developed from former creeks. Goudie's study used aerial images to characterise the distribution and morphology of creeks and pans across England and Wales. For pans, the study found that higher pan densities were recorded in saltmarsh systems where there was a lower rate of sea level change. It also noted that sediment size was an important factor with an increased pan density with sediment size, possibly due to vegetation finding it harder to stabilise coarse sediment and therefore being more vulnerable to high energy tidal environments. Goudie also noted that several studies (Packham and Willis, 1997, Pethick, 1974), recognised that there is an inverse relationship between creek and pan densities, *i.e.* where creek densities are low, there is often more pans and vice versa. Reed et al. (1999) noted that where creek densities are low the marsh will receive insufficient amounts of sediments to maintain marsh growth and so, waterlogging is more likely. Goudie suggests that this could be a reason for lower pan densities on clay marshes as the creek densities are higher on finer sediments. The tidal range was also recognised as important, noting that where the tidal range was more extreme the pan density was lower.

Sand Dunes

Chapter 4 Sand Dune Vegetation Recovery

4.1 Introduction

There have been a number of classic sand dune studies across the UK, focusing on sites at Braunton Burrows, the Sefton Coast, Newborough Warren, and Blakeney Point (Pearsall, 1934, Ranwell, 1960a, 1960b, 1959, Salisbury, 1922, Willis et al., 1959), as well as larger studies for example across Scotland by Gimingham (1964). These early studies helped develop the processes that govern sand dune formation and succession and formed the basis of our dune vegetation classification system widely used today (Rodwell 2000). These sites also have provided the basis for many long-term studies into vegetation change, in particular the loss of early successional habitats through over-stabilisation, which is the focus of current work in trying to reverse the trend. During the 2015 Dynamic Dunes conference (Waternet et al., 2015) many of the presentations focused on dune rejuvenation, re-profiling of frontal dunes to create artificial trough blowouts, accelerate wind flow and create sand transport corridors between the beach and inland dunes.

As with saltmarshes, sand dune restoration projects provide an insight into the likely recovery of post-construction sites in terms of time frames and direction of succession (Arens and Geelen, 2006, Grootjans et al., 2002, Pye and Blott, 2012). However, there are very few examples specifically regarding the post-construction impact of pipeline or cable installation on sand dune habitats. Much of the published work is from early pipeline projects installed in Scotland (Ritchie, 1980, Ritchie and Gimingham, 1989).

Ritchie and Gimingham (1989) published a case study considering the recovery of three sand dune sites in Aberdeenshire following the installation of six oil and gas pipelines. The pipelines were installed between 1973 and 1984 at St. Fergus, Cruden Bay and Shadwick. The case study documents the progress of restoration measures which focused on restoring landform stability. A combination of reinstatement methods were used, including planting of *Ammophila arenaria*, importing topsoil, seed sowing using a commercial seed-mixture and reinstatement of the topography. The results were of limited success in terms of producing vegetation similar to the baseline, but as Ritchie and Gimingham, conclude the aim of restoration was to achieve surface stability through rapid vegetation cover. They noted that at sites with a greater floristic interest the importing of topsoil should be avoided, and a more appropriate seed-mix used (further details are given on *page 285*).

Many lessons have been learned since these pipelines were installed in Aberdeenshire, but without widely published case studies which include both success and failures, it is difficult for these results to provide ecological benefits to future projects. The aim of this chapter is therefore to draw together the results of surveys taken at Talacre Warren, Tetney Marshes and Coatham Sands in Redcar, to help assess vegetation recovery following construction.

4.2 Hypothesis

4.2.1 Introduction

This chapter focuses on vegetation recovery of sand dune habitats following temporary development. The hypotheses all relate to the period following construction, and to effects that will become less marked or disappear over time. It provides evidence with regards to Themes 1-3 identified in *Section 1.7.* These are:

- Theme 1 centres on defining attributes of vegetation recovery in terms of vegetation structure and function for sand dune habitats.
- Theme 2 focuses on the likely time frame for recovery.
- Theme 3 focuses on the likely outcomes of recovery.

The hypotheses are sub-divided by vegetation zone *i.e.* embryo/ mobile dunes, fixed dunes, dune grassland and dune slacks (as shown in Figure 48 and Photo Plate 3). Photos of some the characteristic species are shown in Photo Plate 4. These zones are based on the definitions set out in the Common Standard Monitoring Guidelines for Sand Dunes (JNCC, 2004b). Details on the statistical analysis methods used are provided in *Section 2.4*.

4.2.2 General Hypotheses

In sand dunes disturbance caused by the installation of pipelines is likely to result in the following outcomes:

- A loss in specific plant species that are intolerant to disturbance or physical damage, and an increase in those that are more competitive/ or ruderal including non-native species;
- A change in vegetation composition. In sand dunes it is expected that there will be an initial increase in bare ground supporting open vegetation with annuals and short-lived perennials (reducing the extent of closed grassland communities *i.e.* dune grassland). Over time closed grassland communities will recover to pre-installation extents. It is expected that there may be a modification of species composition and structure of dune slacks through changes to the hydrology, and
- Time frames for recovery will be dependent on the vegetation zone, the main vegetation communities and the degree of damage from construction, but it is likely to be Medium to

Long term before the species composition and structure is similar to the Unaffected vegetation.

4.2.3 Embryo/ Mobile Dunes

35. Following construction, the cover of *Ammophila arenaria*, *Carex arenaria*, *Elytrigia juncea* and *Leymus arenarius* will increase On the pipeline in response to disturbance.
36. It is expected that cover of annual species *e.g. Cakile maritima* and *Atriplex* spp. will be higher On the pipeline compared to Off.
37. Losses or a reduction in the cover of slow-growing perennial species such as *Eryngium maritimum* and *Honckenya peploides* On the pipeline compared to Off of it.
38. Following pipeline installation there will be an increase in cover of bare ground (and inversely a decrease in vegetation cover) in the On sample area compared to the Off area.
39. It is expected that there will be an increase in species-richness On the pipeline compared to Off, at least in the Short-term. In Unaffected areas, species-richness is likely to be lower as *Ammophila arenaria*, or *Leymus arenarius* become dominant.
40. Following construction, the extent (ha) of embryo/ mobile dunes, will increase in the Short-term, but return to baseline extents in the Long-term, subject to natural change.
41. The embryo/ mobile dune vegetation is expected to quickly recover following construction in the Short-term to Medium-term (5-25 years). In the Long-term and in areas Unaffected by construction it is likely that fixed dune vegetation will develop as a result of succession.

4.2.4 Fixed Dunes

42. The cover of graminoid species typically found in this zone *e.g. Ammophila arenaria, Arrhenatherum elatius, Carex arenaria,* and *Festuca rubra* are likely to be lower On the pipeline at least in the Short-term.
43. Early successional grasses which prefer more open sand such as *Festuca arenaria, Leymus arenarius* and *Poa humilis* will have a higher cover On the pipe, at least in the Short-term.
44. Cover of typical herbs from the fixed dunes *e.g. Anthyllis vulneraria*, *Crepis capillaris, Diplotaxis tenuifolia* and *Lotus corniculatus* will be higher On the pipeline, at least in the Short-term. Cover of *Ononis repens* (a shrubby perennial) will be lower. As the grasses become more dominant, these species are likely to decrease over time.
45. Cover of scrub such as *Rubus fruticosus* agg. will be reduced On the pipeline in the Short-term.
46. Cover of key early successional mosses will not be significantly different On the pipeline, at least in the Short-term. Over time the increased dominance of the grasses and perennial herbs will mean they will decline, due to shading.

47. Following pipeline installation there will be an increase in cover of bare ground (and inversely a decrease in vegetation cover) in the On sample area compared to Off, at least in the Short-term.
48. It is expected that there will be an increase in species-richness On the pipeline compared to Off, at least in the Short-term (due to the creation of bare sand areas allowing the establishment of early successional species). In the Long-term/ Unaffected areas, species-richness is likely to be lower as *Ammophila arenaria* or *Arrhenatherum elatius* becomes dominant.
49. Following construction, the extent (ha) of fixed dune vegetation, will increase in the Short-term following the creation of new areas of bare ground. By the Long-term it is expected to return to pre-construction levels.
50. Vegetation typical of fixed dunes is expected to recover quickly following construction activities and therefore it is expected to return in the Medium-term (10-25 years). In the Long-term, where managed fixed dune vegetation will persist, but where left, succession may result in dune grassland.

4.2.5 Dune Grassland

51. Following construction, unless replanted the cover of *Ammophila arenaria* will be reduced in the On sample area compared to the Off sample area. As this species prefers dunes where there is active sand movement it is unlikely this species will re-establish itself in the dune grassland zone.
52. Other broad-leaved grasses such as *Arrhenatherum elatius, Dactylis glomerata*, *Holcus lanatus* and *Poa pratensis* will initially have a lower cover along the On sample area compared to the Off sample area. But it is expected that they will rapidly increase in cover in the Short to Medium-term.
53. Typical herbs of mesotrophic grassland swards will initially have a lower cover along the On sample area compared to the Off sample area; but would increase over time.
54. Woody shrubs such as *Ononis repens*, *Rubus caesius* and *Rubus fruticosus* agg. will be initially lower in the On area compared to the Off area, but will rapidly re-establish themselves in the Short to Medium term.
55. Cover of mosses will be lower along the pipeline (On area) compared to the Off sample area. Over time the increased dominance of the grasses and perennial herbs will mean mosses will decline.
56. Following pipeline/ cable installation there will be an increase in bare ground (and inversely a decrease in vegetation cover) in the On sample area compared to the Adjacent and Off areas.

57. It is expected that there will be an increase in species-richness On the pipeline compared to Off, at least in the Short-term (due to the reduction in cover of broad-leaved grasses and the creation of bare sand areas). In the Long-term/ Unaffected areas (where there is no management) species-richness is likely to be lower as mesotrophic grassland swards establish and *Arrhenatherum elatius* becomes dominant.
58. Following construction, the extent (ha) of dune grassland, will initially decrease as a result of disturbance, but it is expected to return to (or exceed) pre-construction levels by the Medium- to Long-term.
59. Following construction, in the dune grassland it is expected that vegetation recovery will be relatively quick (*i.e.* Short-term by 10 years) where impacts are greater, recovery may take until the Medium-term (10-25 years). In the Long-term, where managed dune grassland will persist, but where left, succession may result in mesotrophic grassland or scrub.

4.2.6 Dune Slacks

60. Dune slacks are sensitive to changes in the water-table and compaction. If as a result of construction, there is a lowering of the water-table (and the dunes become drier) along the pipeline this will result in the loss of typical wetland graminoids and herbs.
61. Where the water-table is lowered, it is expected that typical wetland graminoids and herbs will be replaced by graminoids/ herbs that are more tolerant to drier conditions.
62. Following pipeline/ cable installation there will be an increase in bare ground (and inversely a decrease in vegetation cover) in the On sample area compared to the Off areas.
63. It is expected that species-richness will be highest in the Unaffected and Off sample areas, although there may be an increase in species-richness On the pipeline at least in the Short-term (due to disturbance restricting the cover of dominant species and creating areas of bare ground).
64. The extent (ha) of dune slacks is likely to decrease On and Adjacent to the pipeline following construction, unless specific post-construction restoration measures are used to create new areas of this sensitive habitat type.
65. Predicting habitat change of dune slacks vegetation following construction is difficult, and very much dependent on the depth of the resulting water-table. There are opportunities to increase this vegetation type if post-construction restoration is taken, but there is also a chance that this sensitive habitat is lost. Where the pipeline/cable has influenced the water-table making it locally wetter, there will be an increase in dune slack communities, but where it becomes drier dune grassland or fixed dunes may develop. Vegetation recovery in the dune slacks is expected in the Long-term (25-40 years).

Figure 48 - An illustration showing the key sand dune vegetation zones (JNCC, 2004b) and National Vegetation Classification communities (Rodwell, 2000) as recorded at my study sites. Embryo/ mobile dunes types SD2 *Honckenya peploides-Cakile maritima* strandline community, SD4 *Elymus farctus* ssp. *boreali-atlanticus* foredune community, SD5 *Leymus arenarius* mobile dune community, and SD6 *Ammophila arenaria* mobile dune community. **Fixed dune types** SD7 *Ammophila arenaria-Festuca rubra* semi-fixed dune community and SD8 *Festuca rubra-Galium verum* fixed dune grassland. **Dune grassland** types SD9 *Ammophila arenaria-Arrhenatherum elatius* dune grassland and MG1 *Arrhenatherum elatius* grassland. **Dune slacks** SD16 *Salix repens-Holcus lanatus* dune-slack community SD17 *Potentilla anserina - Carex nigra* dune-slack community. Other communities S4 *Phragmites australis* swamp and reed-beds, S19 *Eleocharis palustris* swamp, S20 *Scirpus lacustris* ssp. *tabernaemontani* swamp and SD18 *Hippophae rhamnoides* dune scrub.

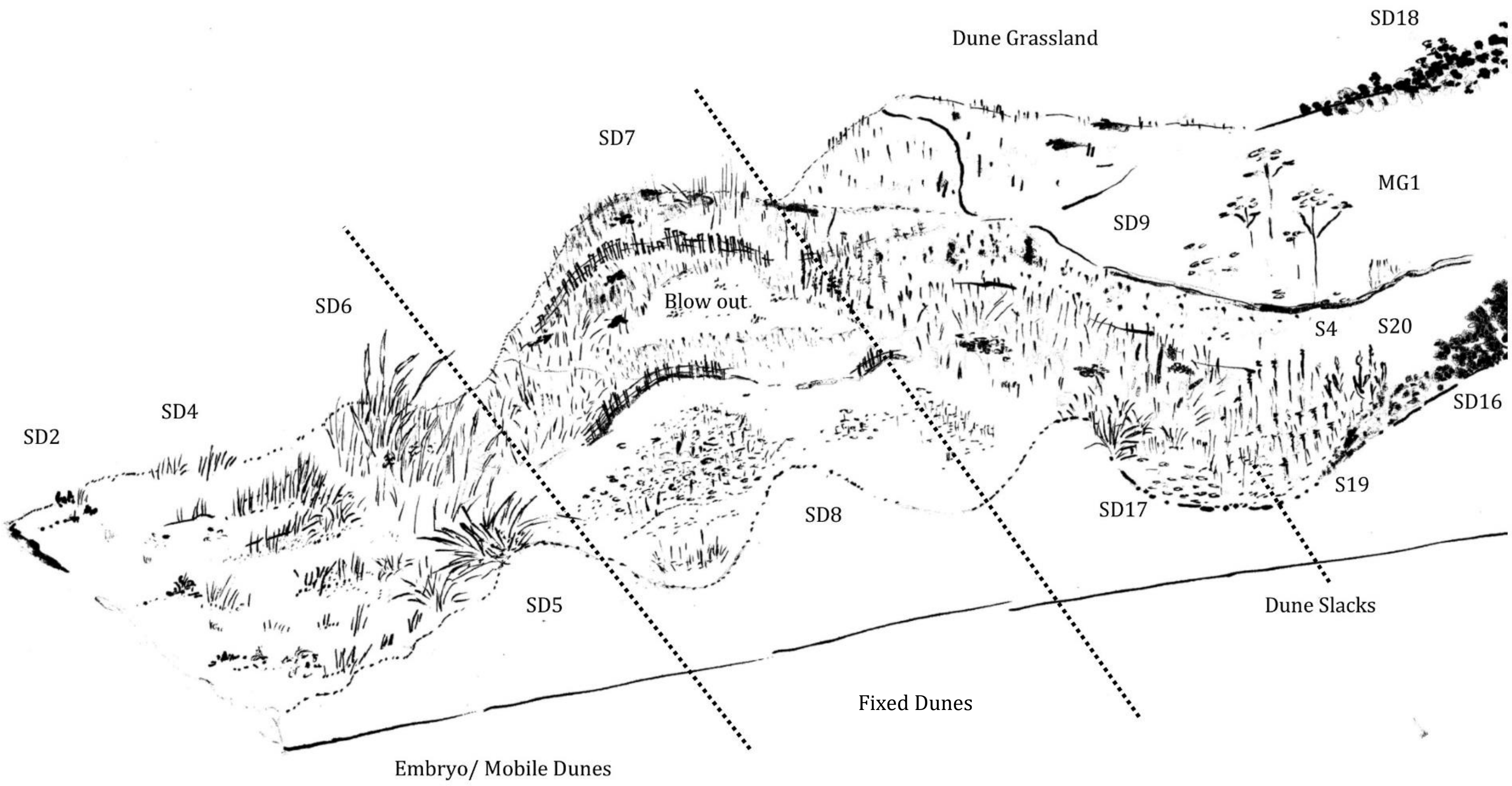


Photo Plate 3 – Examples of sand dune vegetation zones taken at study sites.


Mobile dunes at Tetney Marshes


Mobile dunes at Project Breagh, Coatham Common


Fixed dunes within the working width of Project Breagh, Coatham Common


Dunes grassland looking along the working width (towards sea) at Project Breagh, Coatham Common


Dune slacks adjacent to working width at Project Breagh, Coatham Common

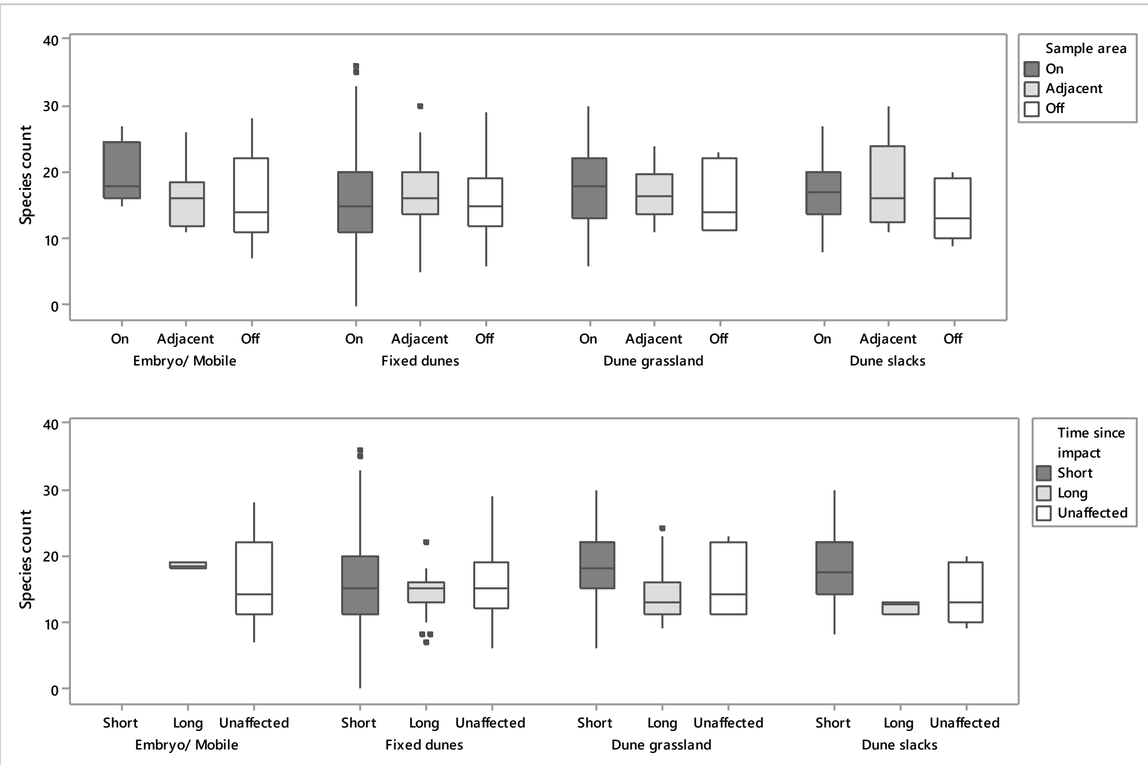
4.3 Results – All Vegetation Zones

4.3.1 Boxplots

The entire dataset for sand dunes was initially reviewed using a series of boxplots and descriptive statistics. These focused on the differences between the vegetation zones with sample area and time since impact.

As with the saltmarsh zones, there was little difference between the average number of species per quadrat recorded in each vegetation zone with either the sample area or time since impact (Figure 49). This was supported when analysed a General Linear Model (GLM). It should be noted there is insufficient data for the embryo/ mobile dunes in the Short-term to enable comparison.

Figure 49 - Boxplots showing species numbers with vegetation zones (embryo/mobile dunes, fixed dunes, dune grassland and dune slacks), and sample area (On, Adjacent and Off) [top] and time since impact (Short-term, Long-term and Unaffected) [bottom]. The boxplot shows the quantitative variables[37] with their ranges.



The cover of bare ground showed differences between the vegetation zones when considered with sample area. The greatest difference in the cover of bare ground was noted in the fixed dunes between the On sample area when compared to the Adjacent and Off sample areas. There was also a difference between the On and Off sample area in the embryo/mobile dune data. These findings were supported by significant values when analysed using a GLM. The difference between the dune grassland data was not significant with sample area (with a GLM), although the

[37] Quantitative variables - minimum, first quartile, median, third quartile, maximum, and outliers

On sample area showed a greater variation in the cover of bare ground than in the undisturbed Adjacent and Off data. In the dune slacks the cover of bare ground is seen to be greater in the Off sample area compared to the On sample area (and this difference was significant with GLM). Similar patterns were recorded with time since impact, with the fixed dunes showing significant differences between the Short and Long, and Unaffected periods (Figure 50).

Figure 50 - Boxplots showing cover of bare ground with vegetation zones (embryo/mobile dunes, fixed dunes, dune grassland and dune slacks), and sample area (On, Adjacent and Off) [top] and time since impact (Short-term, Long-term and Unaffected) [bottom].

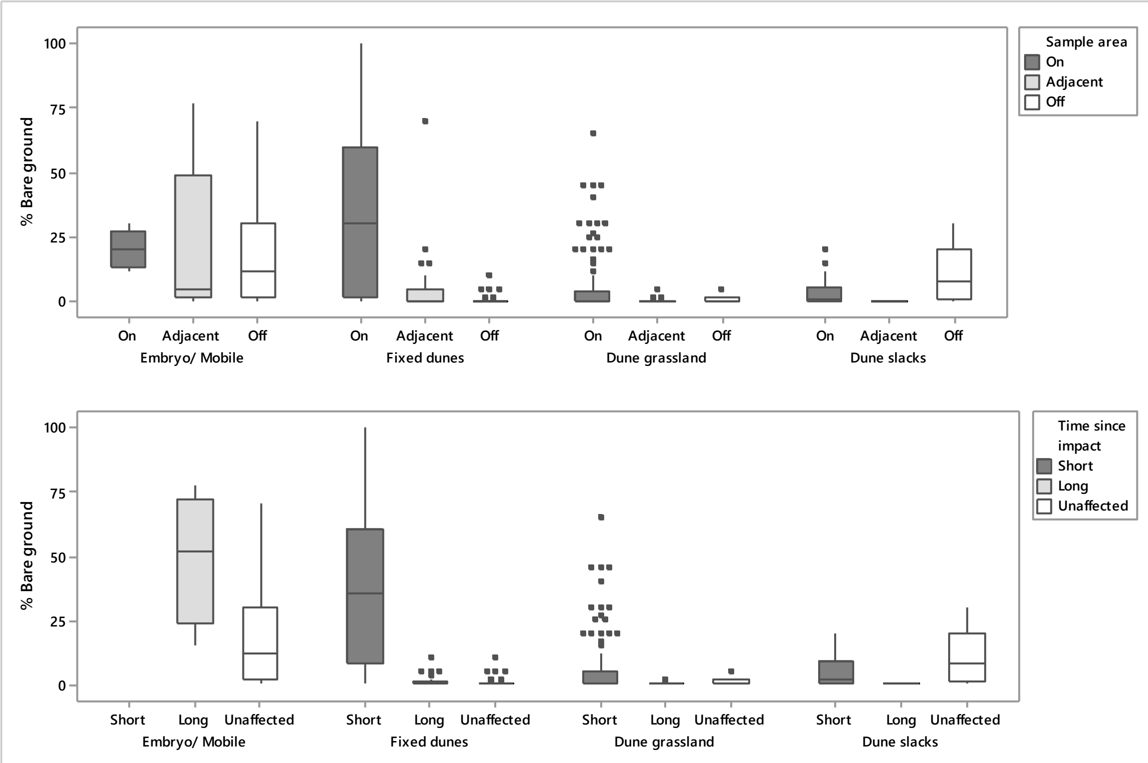
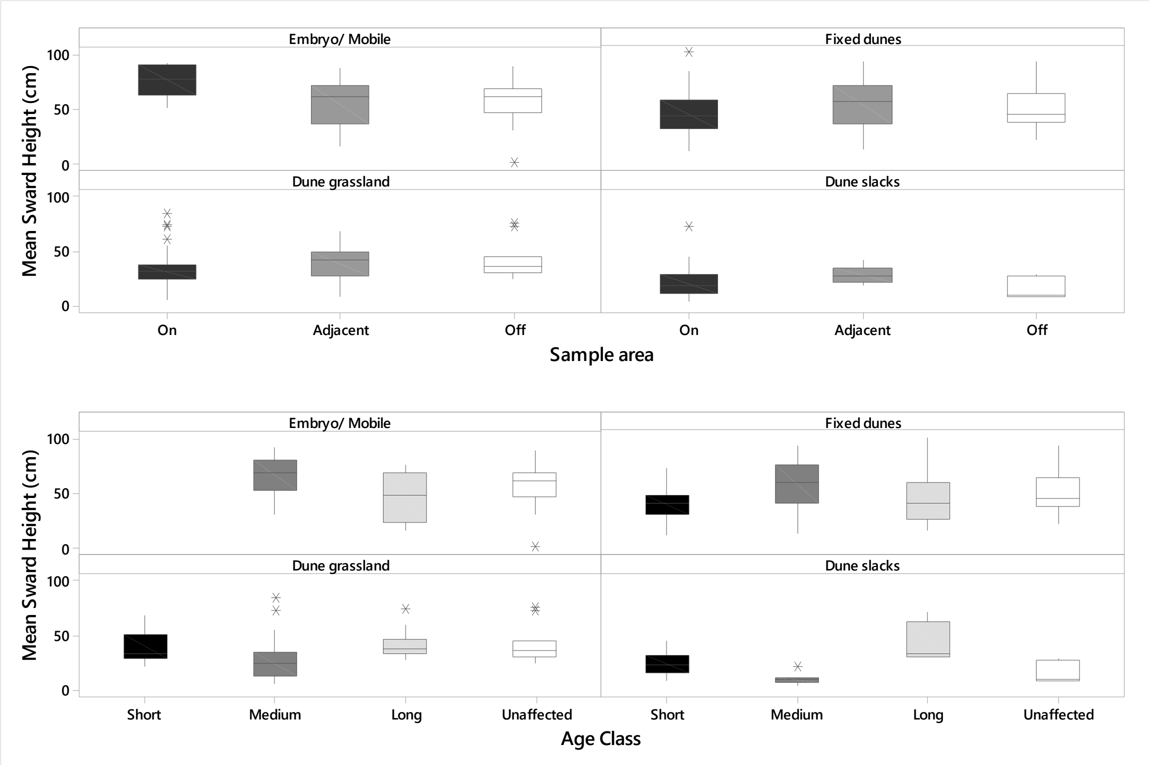


Figure 51 - Boxplots showing mean sward height with vegetation zones (embryo/mobile dunes, fixed dunes, dune grassland and dune slacks), and sample area (On, Adjacent and Off) [top] and time since impact (Short-term, Medium-term, Long-term and Unaffected) [bottom].

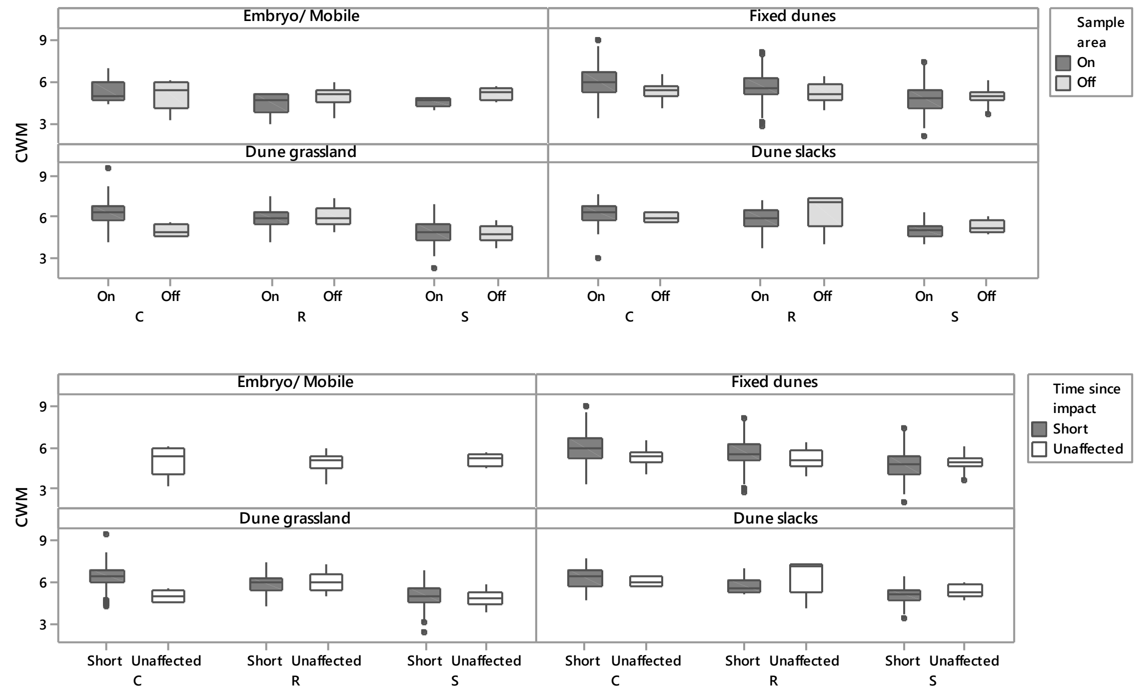


The average sward height of the vegetation showed little difference between the zones for either sample area or time since impact (Figure 51).

The proportion of competitive, ruderal and stress-tolerant species (based on Grime's CSR strategy (Grime et al., 1988) showed little difference between the three zones (embryo/ mobile, dune grassland and dune slacks). In the fixed dunes there was greater variation in the strategies between the On and Off sample areas and over time (Figure 52).

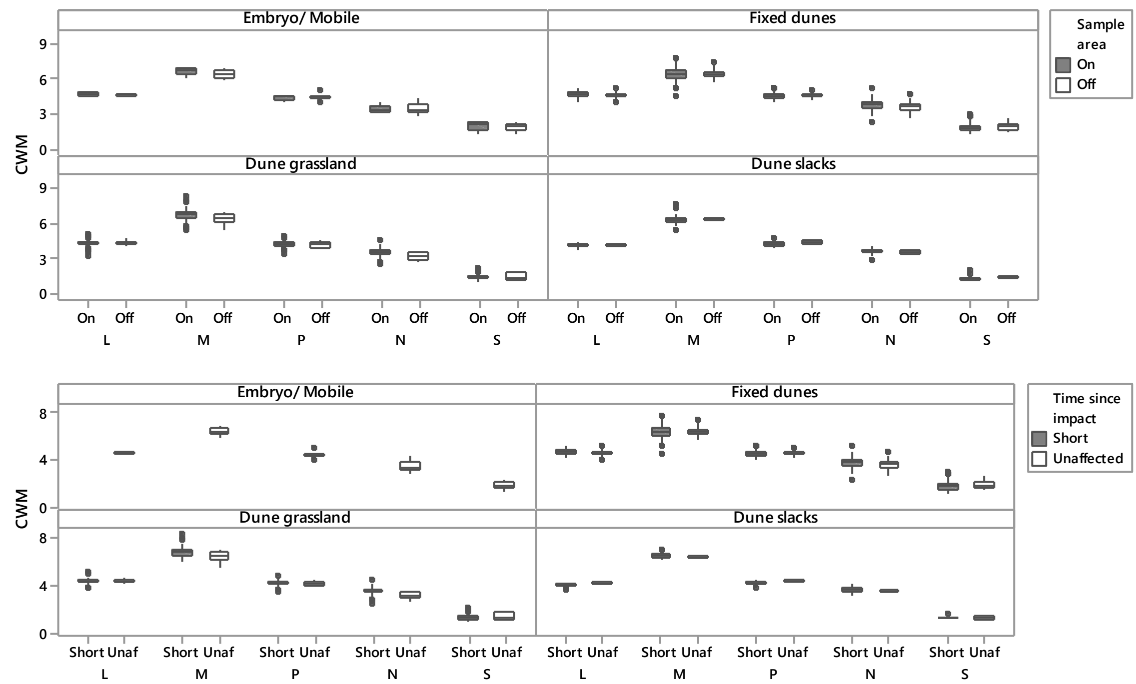
The differences in the community weighted means of quadrats with four key Ellenberg indicators (species requirement for light, moisture, pH, nutrient and tolerance to salinity) (Hill et al., 1999) is shown in Figure 53. Values for moisture showed greater variation across the fixed dunes, dune grassland and dune slacks between the On and Off sample area and between the Short-term and Unaffected vegetation. This does provide an indication that the pipeline/cable installation influences the hydrology of the dunes.

Figure 52 -Boxplots showing Community Weighed Means (CWM) of CSR strategies (Grime et al., 1988) with vegetation zones (embryo/mobile dunes, fixed dunes, dune grassland and dune slacks), and sample area (On and Off) [top] and time since impact (Short-term and Unaffected) [bottom].



Community Weighted Means (CWM) (i.e. plot-level trait values weighted by species abundances) generated in CANOCO 5 for CSR strategies. C=Competitor, R=Ruderal, S=Stress-tolerator (Grime et al., 1988)

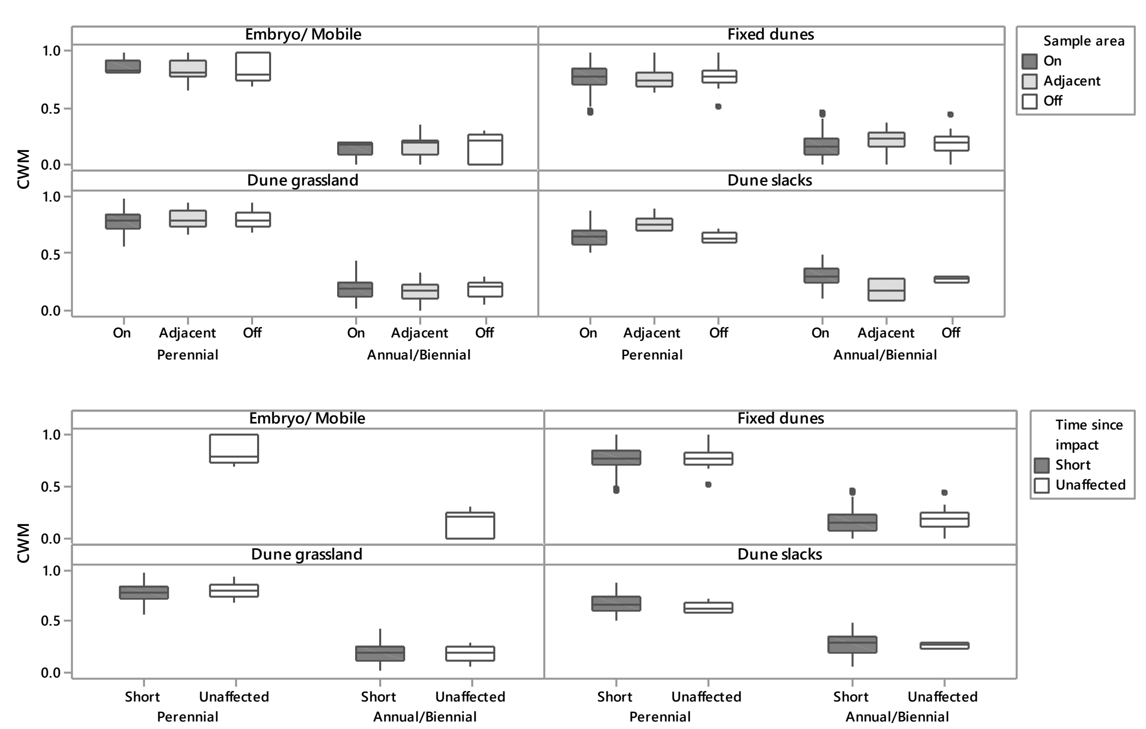
Figure 53 - Boxplots showing Community Weighed Means (CWM) of Ellenberg values (Hill et al., 1999) with vegetation zones (embryo/mobile dunes, fixed dunes, dune grassland and dune slacks), and sample area (On and Off) [top] and time since impact (Short-term and Unaffected) [bottom].



Community Weighted Means (CWM) (i.e. plot-level trait values weighted by species abundances) generated in CANOCO 5 for Ellenberg values. L=Light, M=Moisture, P= pH, N=Nitrogen (in effect a general indicator of soil fertility), S=Salinity (Hill et al., 1999)

The differences in the community weighted means of quadrats when considering plant life cycles *i.e.* perennial versus annual or biennial life cycles appeared to show no differences between the zones. However, when considered with a GLM, the fixed dunes showed significant differences in the cover of perennials and annuals and biennials between the On and Off sample area (Figure 54).

Figure 54 - Boxplots showing Community Weighed Means (CWM) of plant life cycle (perennial, annual, biennial) with vegetation zones (embryo/mobile dunes, fixed dunes, dune grassland and dune slacks), and sample area (On and Off) [top] and time since impact (Short-term and Unaffected) [bottom].



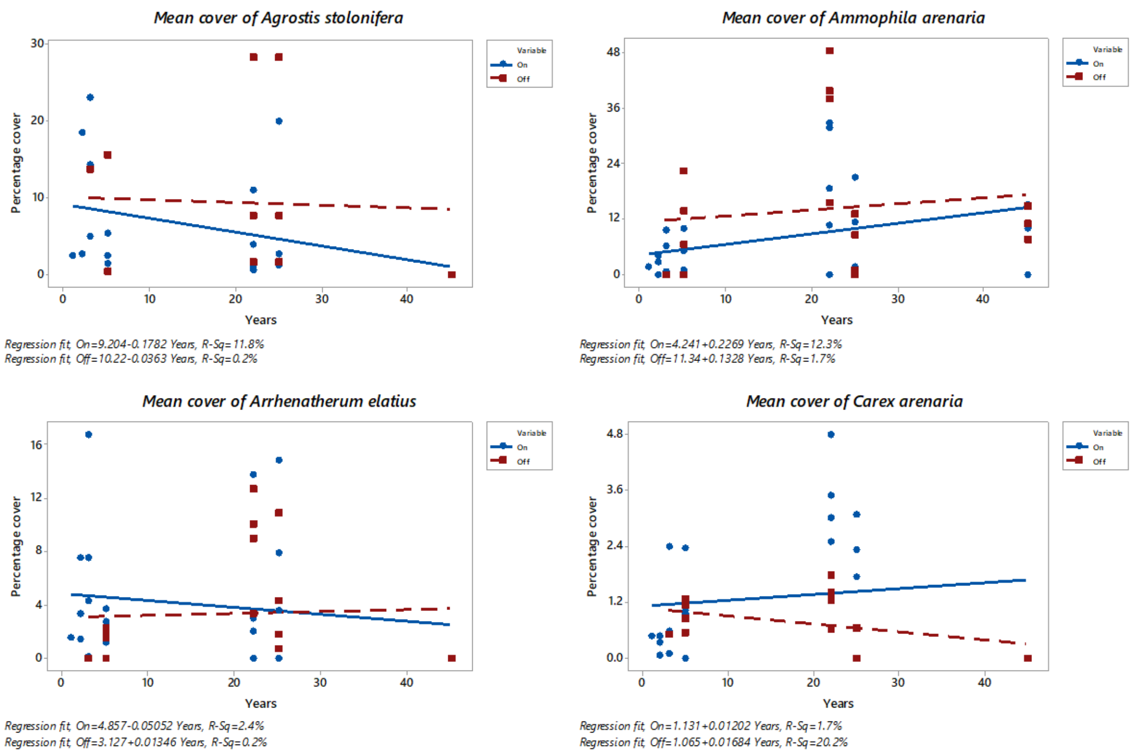
Community Weighted Means (CWM) (i.e. plot-level trait values weighted by species abundances) generated in CANOCO 5 for plant life strategies.

4.3.2 Scatterplot Recovery Trends

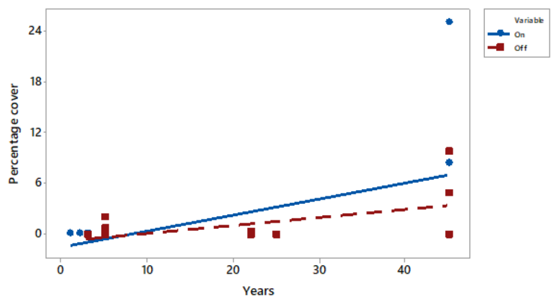
The mean cover for key individual species representative of each zone, with the On and Off sample area separated, were analysed using scatterplots with a regression line of best fit applied. This includes the graminoids *Agrostis stolonifera*, *Ammophila arenaria*, *Arrhenatherum elatius*, *Carex arenaria, Elytrigia juncea*, *Festuca arenaria*, *Festuca rubra* and *Leymus arenarius* and the forbs *Anthyllis vulneraria*, *Equisetum arvense*, *Lotus corniculatus*, and *Ononis repens*. The graphs are shown in Figure 55. A general trend showing the direction and recovery times of each species can be implied (although as the data combines species values from each zone there is often considerable variation within the data). For many of the species the trend for the Off value (*i.e.* unaffected vegetation) shows little change in cover over time *e.g.* the graminoids *Agrostis stolonifera*, *Ammophila arenaria*, *Arrhenatherum elatius*, *Festuca arenaria*, *Festuca rubra*, and forbs *Anthyllis vulneraria, Equisetum arvense*, *Lotus corniculatus* and *Ononis repens.* The regression fit for these species shows that the R-Sq values are *c.* 4%. These species are typical of closed swards (with the exception of *Festuca arenaria*). The greatest change over time with species in the Off sample area was recorded in *Elytrigia juncea* and *Leymus arenarius* which increased over time; and in *Carex arenaria* and *Syntrichia ruralis* subsp. *ruraliformis* which showed a decrease with time. These species are all characteristic of early successional vegetation and their cover would be expected to change over time even in unaffected vegetation. The R-Sq values for the regression lines varied from *c.* 10% to 45%.

The On sample trend was typically more significant for all of the species. Species that showed a decreasing trend over time included *Agrostis stolonifera*, *Anthyllis vulneraria*, *Equisetum arvense*, *Lotus corniculatus* and *Ononis repens*. These species typically either produce stolons or runners or produce large quantities of seed and are able to colonise areas of bare sand quickly but are out-competed by other species with time. In contrast *Ammophila arenaria*, *Elytrigia juncea*, *Festuca rubra* and *Leymus arenarius* all showed an increase over time, taking longer to become established, but once established increasing in dominance. *Arrhenatherum elatius* perhaps surprisingly showed a weak downward trend (R-Sq=2.4%) On the pipeline over time, suggesting that disturbance caused by cable installation may help restrict its dominance. Both *Carex arenaria* and *Syntrichia ruralis* subsp. *ruraliformis* showed a weak response in terms of a change in cover over time On the pipeline, which was unexpected as both species are typical of open mobile dunes and these conditions would be expected to occur after pipeline installation.

Figure 55 – Scatterplots with a regression line of best fit, showing the mean cover of key sand dune species for On (shown in blue) and Off (shown in red) the pipeline.

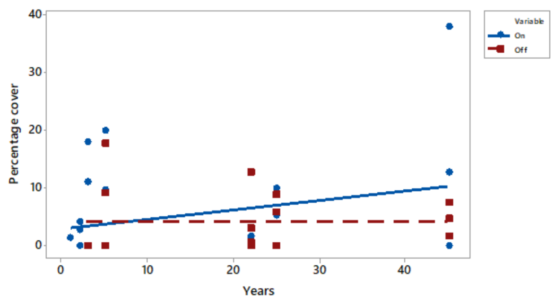


Mean cover of *Elytrigia juncea*



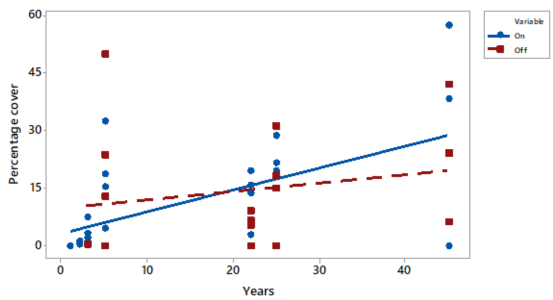
Regression fit On=-1.52+0.1876 Years, R-Sq=28.3%
Regression fit Off=-0.855+0.09373 Years, R-Sq=28.4%

Mean over of *Festuca arenaria*



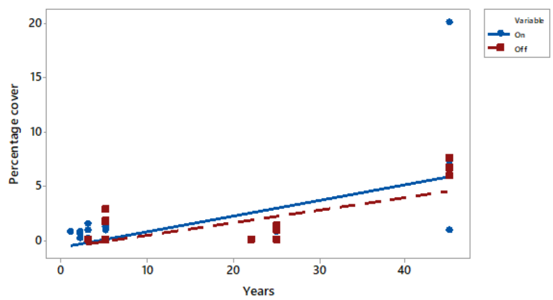
Regression fit On=2.926+0.1664 Years, R-Sq=7.5%
Regression fit Off=4.133+0.00252 Years, R-Sq=0.0%

Mean cover of *Festuca rubra*



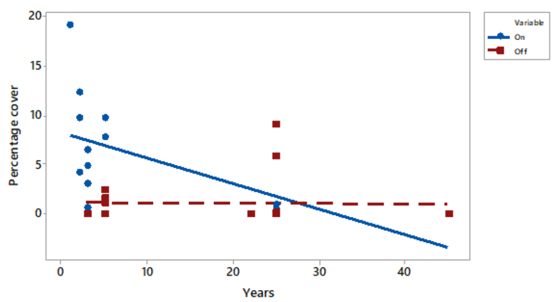
Regression fit On=3.476+0.5603 Years, R-Sq=30.9%
Regression fit Off=10.05+0.2105 Years, R-Sq=4.1%

Mean cover of *Leymus arenarius*



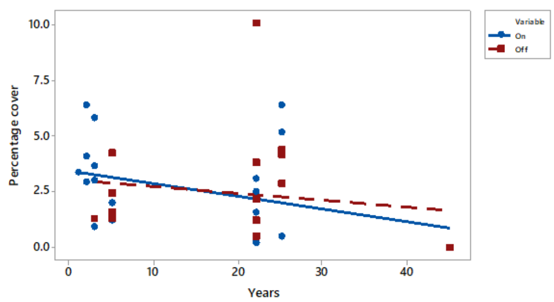
Regression fit On=0.615+0.1442 Years, R-Sq=27.0%
Regression fit Off=-0.6947+0.1173 Years, R-Sq=45.2%

Mean cover of *Anthyllis vulneraria*



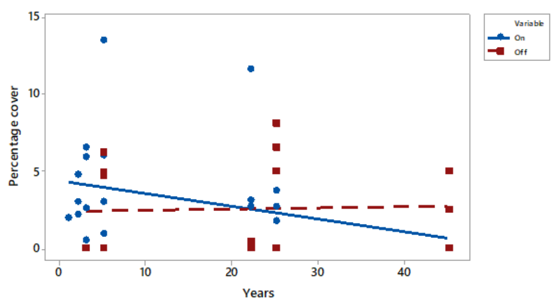
Regression fit On= 8.341-0.2606 Years, R-Sq=41.5%
Regression fit Off=1.276+0.00401 Years, R-Sq=0.1%

Mean cover *Equisetum arvense*



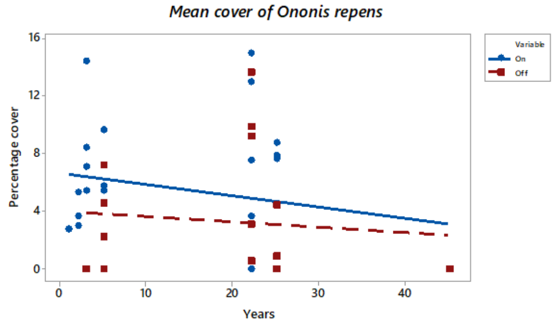
Regression fit On= 3.435-0.0574 Years, R-Sq=17.8%
Regression fit Off= 3.027-0.0307 Years, R-Sq=3.4%

Mean cover of *Lotus corniculatus*



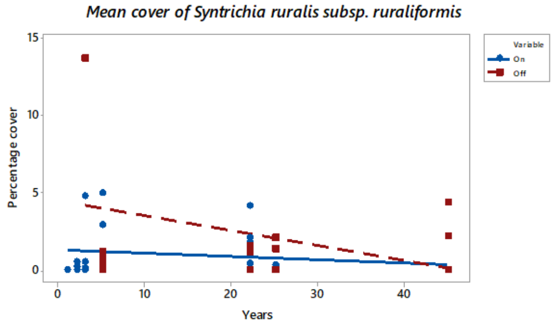
Regression fit On= 4.433-0.08354 Years, R-Sq=12.7%
Regression fit Off= 2.388+0.00811 Years, R-Sq=0.2%

Mean cover of *Ononis repens*



Regression fit On= 6.0667-0.07728 Years, R-Sq=6.4%
Regression fit Off= 4.024-0.03735 Years, R-Sq=1.6%

Mean cover of *Syntrichia ruralis subsp. ruraliformis*

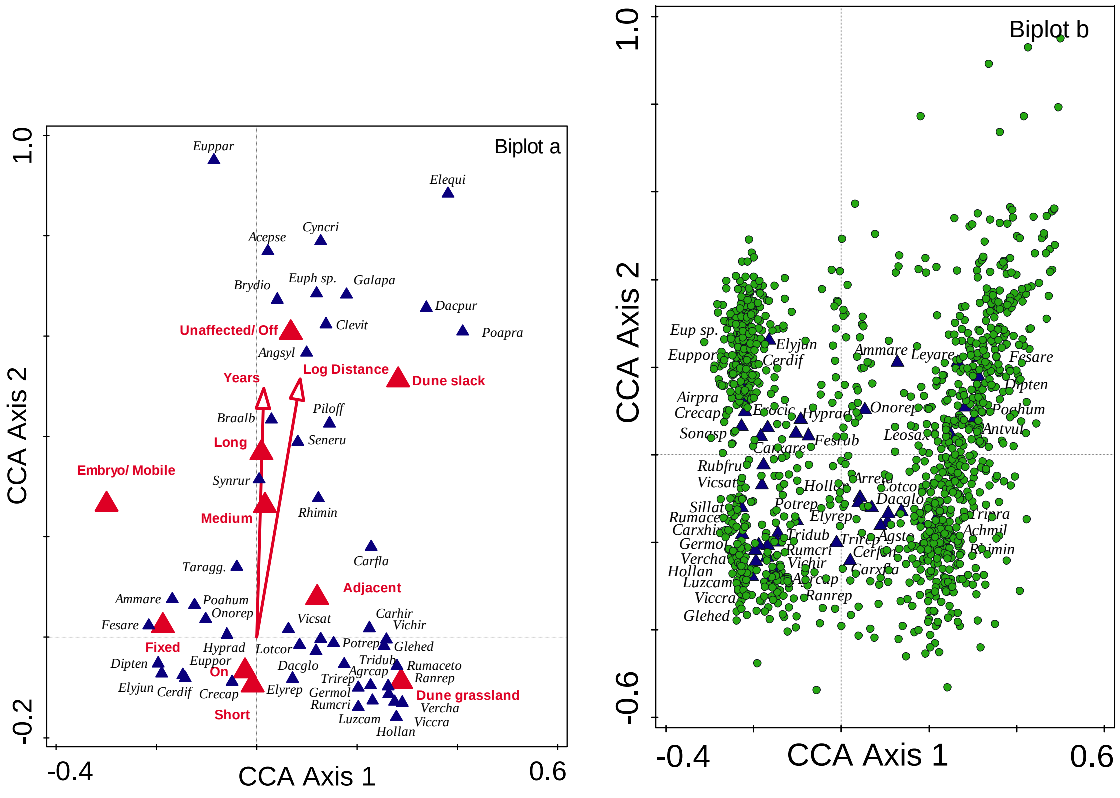


Regression fit On= 1.330-0.02203 Years, R-Sq=4.3%
Regression fit Off= 4.541-0.09643 Years, R-Sq=10.6%

4.3.3 Canonical Correspondence Analysis

A constrained ordination (CCA) of all data was undertaken to test the significance of the environmental explanatory variables in explaining the variation in species composition. The distance of a species symbol and the symbols of environmental variable classes shows the relative preference of that species for individual environmental variable classes. The species is predicted to occur with the highest relative frequency (or with the highest probability) in classes with their symbols close to that species' point. In addition, dummy variables for vegetation zone was included. The data shows separation of the early successional vegetation types *i.e.* fixed dune with the On and Short-term factors. These are associated with dune forming grasses such as *Ammophila arenaria*, *Elytrigia juncea* along with *Crepis capillaris*, *Diplotaxis tenuifolia*, *Euphorbia portlandica*, *Poa humilis* which all colonise open sand. The generalist grassland species such as *Agrostis capillaris*, *Dactylis glomerata* and *Holcus lanatus*, as well as *Ranunculus repens*, *Vicia cracca* and *Trifolium repens* are associated with the dune grassland. The dune slacks are more closely associated with the Unaffected/ Off sample area and increased years/ distance. Few typical dune slack species are shown, but this is due to the biplot being restricted to the top 50 species by fit. Species such as *Dactylorhiza purpurella* and *Eleocharis quinqueflora* indicate an increased moisture content. The Unaffected/ Off sample area is also associated with a woody element with the presence of *Acer pseudoplatanus*, *Bryonia dioica* and *Clematis vitalba*.

Figure 56 - Species-environmental variable biplot (a) and species-quadrats biplot (b) using CCA (of the first two axes) with environmental variables selected by forward selection procedure. Total variation is 5.24, explanatory variables account for 12.4% (adjusted explained variation is 11.68%); 1st Axis pseudo-F=5.5, p=0.002; All Axes pseudo-F=16.5, p=0.0002. The species (shown as blue triangles) are labelled by the first three letters of the generic name and the first three letters of the specific name. Species are limited to the top 50 by fit. Quadrats are shown as green circles with the quadrat number.



4.4 Results – Embryo/ Mobile Dunes

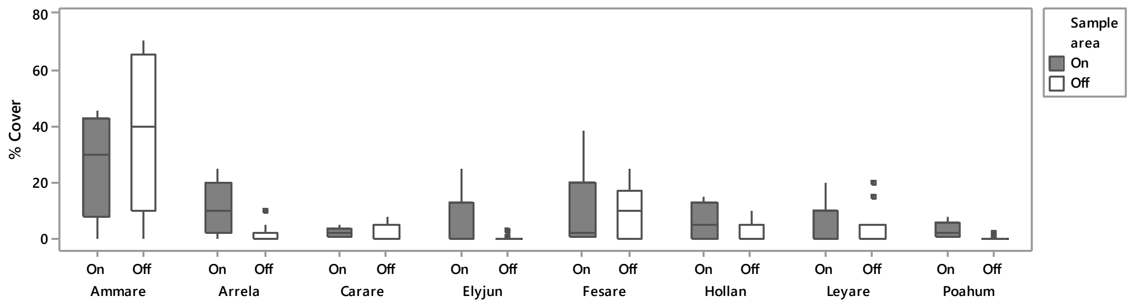
4.4.1 Vegetation Composition and Structure

In the embryo/ mobile dunes only 29 quadrats were sampled, which resulted in insufficient quadrats for the statistical analysis, especially with the GLM which groups quadrats by the relevant sample area and time since impact. Further details are provided on *page 216*.

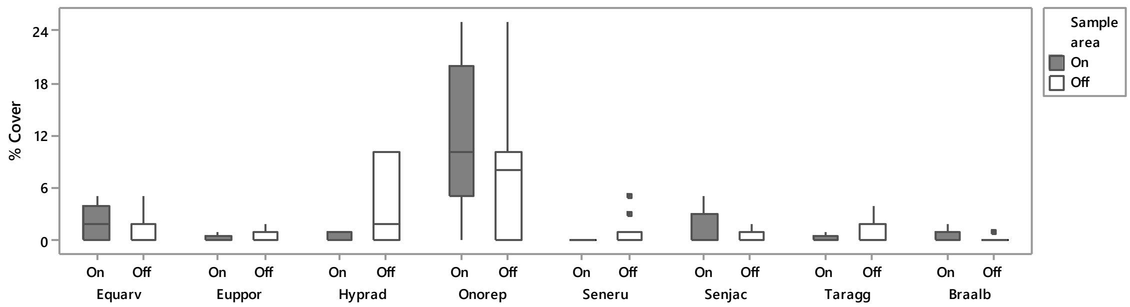
Across the study sites, vegetation in the embryo/ mobile dunes was generally species-poor in comparison to the other sand dune vegetation zones. In total 38 vascular plant and six moss species were recorded. The mean number of species recorded On the pipeline was higher (but not significantly so), than the Adjacent/Off sample area (On = 19.8 species; and Adj/Off = 15.8 species). Due to the lack of samples. no data was available for the Short-term making comparison of recovery over time in this zone difficult and subject to increased extrapolation of the data. The most species in an individual quadrat in this zone was 28.

The embryo/ mobile dunes are frequently dominated by *Ammophila arenaria* (which was recorded in 82% of the quadrats). Locally *Elytrigia juncea* and *Leymus arenarius* were also dominant. The boxplots showed that the Off sample area had a higher cover of *Ammophila arenaria* (although not significantly so with a GLM). Whereas *Arrhenatherum elatius*, *Elytrigia juncea*, *Festuca arenaria* and *Holcus lanatus* all had a higher cover On the pipeline (not significantly). *Ononis repens* was the most abundant forb, which had a higher cover On the pipeline. In contrast *Hypochaeris radicata* appeared to prefer the Off sample area where it had a higher cover. Boxplots showing cover of key species in this zone by sample area and time since impact are given in Figures 57-58.

Figure 57 - Boxplots showing the cover of key embryo/ mobile dune species with sample area (On and Off). Typical graminoids are shown [top] and other herbs/ bryophytes [bottom].

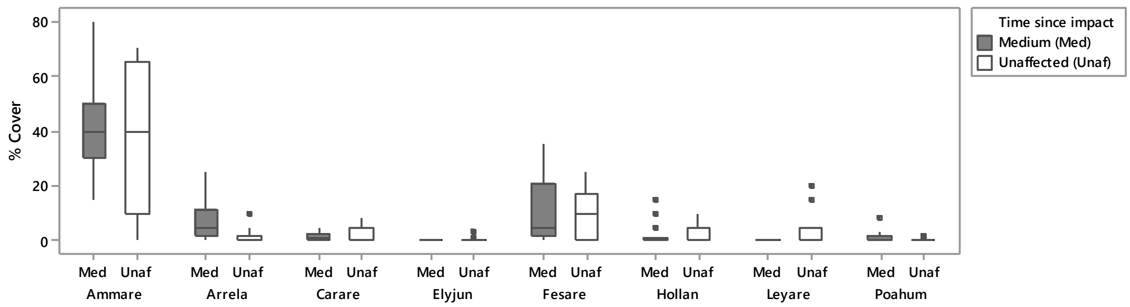


Species – Ammophila arenaria (Ammare); Arrhenatherum elatius (Arrela); Carex arenaria (Carare); Elytrigia juncea (Elyjun); Festuca arenaria (Fesare); Holcus lanatus (Hollan); Leymus arenarius (Leyare); Poa humilis (Poahum)

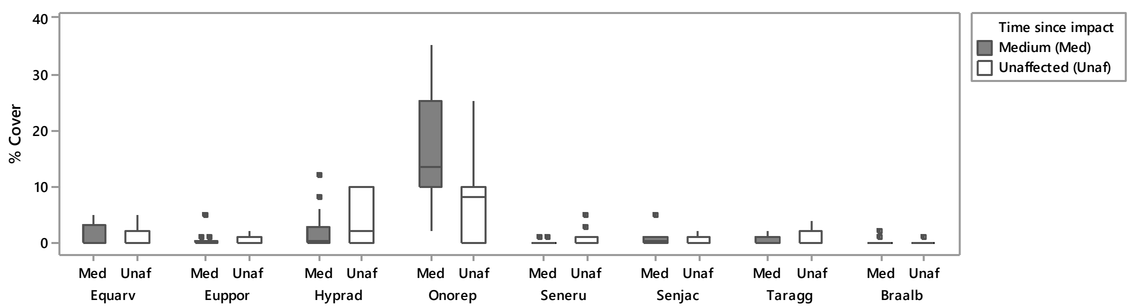


Species – Equisetum arvense (Equarv); Euphorbia portlandica (Euppor); Hypochaeris radicata (Hyprad); Ononis repens (Onorep); Senecio erucifolius (Seneru); Senecio jacobaea (Senjac); Taraxacum agg. (Taragg), Brachythecium albicans (Braalb)

Figure 58 - Boxplots showing the cover of key embryo/ mobile dune species with time since impact (Medium-term and Unaffected). Typical graminoids are shown [top] and other herbs/ bryophytes [bottom].



Note no Short-term data available. Species – Ammophila arenaria (Ammare); Arrhenatherum elatius (Arrela); Carex arenaria (Carare); Elytrigia juncea (Elyjun); Festuca arenaria (Fesare); Holcus lanatus (Hollan); Leymus arenarius (Leyare); Poa humilis (Poahum)



Note no Short-term data available. Species – Equisetum arvense (Equarv); Euphorbia portlandica (Euppor); Hypochaeris radicata (Hyprad); Ononis repens (Onorep); Senecio erucifolius (Seneru); Senecio jacobaea (Senjac);

General Linear Model and Tukey Pairwise Comparison Test

Hypotheses 35 – [Cover of the main graminoid species will be higher On the pipeline]. This was expected as growth of *Ammophila arenaria*, *Carex arenaria*, *Elytrigia juncea* and *Leymus arenarius* are stimulated by sand burial. However, *Ammophila arenaria* showed no statistical difference between cover in the On and the Off sample areas (df=2; F=1.74; p=0.196), although its mean was higher (37.9 On/ 26.0 Adj/Off). Similarly, the cover of *Carex arenaria, Elytrigia juncea* and *Leymus arenarius* were not statistically significant – disproving the hypothesis. The data for change in cover over time is more difficult to interpret due to the lack of quadrats (and no sites with data from the Short-term). When considering change in vegetation cover between the Medium-term and Unaffected vegetation, none of the four species were significant. These results indicate that all four species show recovery in the embryo/ mobile dunes reaching similar vegetation cover On the pipeline by or before the Medium-term.

Hypotheses 36 - [Cover of annual species will be higher On the pipeline]. An increase in annual species was considered likely due to increased areas of bare sand in the On sample areas. In actual fact, very few annual species were recorded in this zone and those present were only recorded in a small number of quadrats (less than 4). Therefore, it is not possible to prove or disprove this hypothesis.

Hypotheses 37 – [Cover of perennial species will be lower On the pipeline]. Considering the main perennial species frequently recorded in this zone, the differences in the mean cover were not significantly different when GLM and sample area or time since impact were considered - disproving the hypothesis. This may be due to the sparsity of the quadrat data; or perhaps that pipeline installation mimics natural disturbance episodes which the species have evolved to deal with.

Hypothesis 38 – [Following pipeline installation bare ground will be higher On the pipeline at least in the Short-term]. No difference in the mean cover of bare ground between the On and Off sample area was noted or with time since impact - disproving the hypothesis. This is supported by the GLM and Tukey Pairwise Comparison test (df=2; T=0.41; p=0.671). The cover of herbs was slightly higher On the pipeline (but not statistically significant), and inversely graminoid and moss cover was slightly lower On the pipe (but not statistically significant).

A full summary of the results of the GLM and Tukey Pairwise Comparison for embryo/ mobile dune vegetation is given in Appendix 4 Tables 31-33.

Canonical Correspondence Analysis

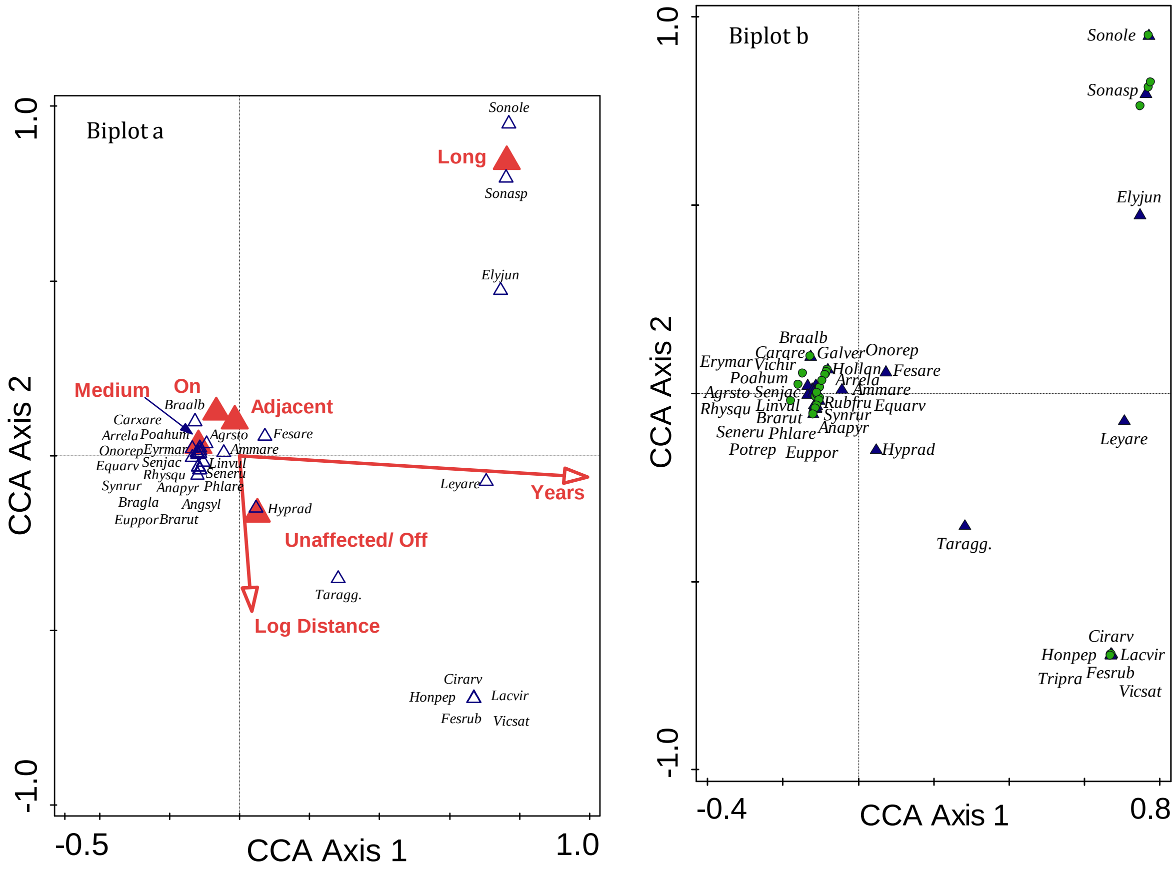
In CCA and forward selection of environmental variables with the embryo/ mobile dunes data the years factor explains the greatest amount of variation and is statistically significant. The Long-term factor and Adjacent sample area were also significant. This is set out in Table 19.

Table 19 - Explanatory value of environmental variables considered in CCA analysis for embryo and mobile dunes. Significant effects are given in bold.

Environmental Variable	Explains %	Contribution %	Pseudo-F	P-value	P(adj)
Years	**18.6**	**51.8**	**6.2**	**0.0002**	**0.0016**
Time since impact - Long	**8.3**	**22.9**	**2.9**	**0.0008**	**0.0032**
Sample area - Adjacent	4	11.2	1.5	0.0656	0.17493
Log distance	3.6	10	1.3	0.1436	0.2872
Time since impact - Unaffected	1.5	4.1	0.5	0.9652	0.9678

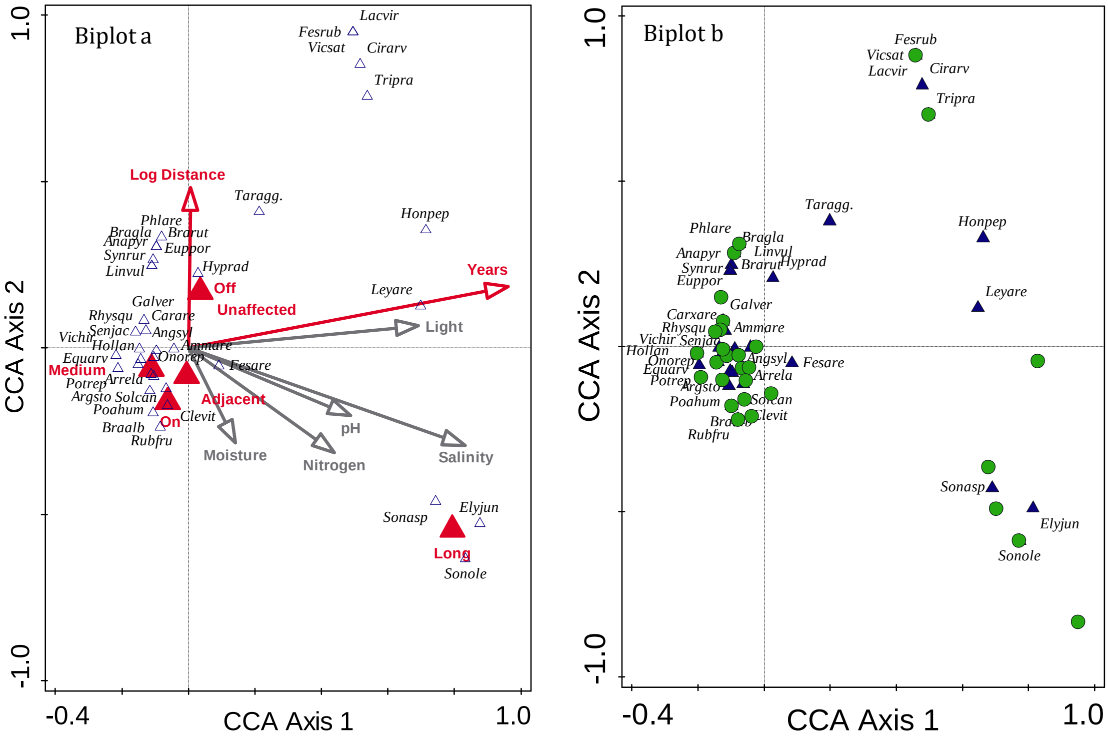
The CCA plot shows that there is little separation between the On, Adjacent and Medium-term factors (Figure 59). These factors are associated with species typical of mobile dunes (SD6d) where the sand has become somewhat stabilised; with *Ammophila arenaria*, *Carex arenaria*, *Euphorbia portlandica*, *Festuca arenaria*, *Linaria vulgaris*, *Phleum arenarium* and *Poa humilis*. Over time it appears that *Elytrigia juncea* vegetation (SD4) develops in the Long-term which is perhaps surprising considering this vegetation community tends to develop as fore dunes fronting the other dune communities. A similar situation was noted with *Leymus arenarius* which increased with years.

Figure 59 – Species-environmental variable biplot (a) and species-quadrats biplot (b) using CCA (of the first two axes) with environmental variables selected by forward selection procedure. Total variation is 3.10, explanatory variables account for 36.0% (adjusted explained variation is 22.1%); 1st Axis pseudo- F=5.3, P=0.0002; All Axes pseudo- F=2.6, P=0.0002. The species (shown as blue triangles) are labelled by the first three letters of the generic name and the first three letters of the specific name. Quadrats are shown as green circles with the quadrat number.



The inclusion of Ellenberg values (Hill et al., 1999) as additional explanatory variables in the CCA analysis increased the percentage variation explained by the environmental variables from 36% to 55.7%, and the forward selection process identified moisture and salinity as being significant. Of these, moisture was the most significant explaining 7.5% of the variation (Figure 60).

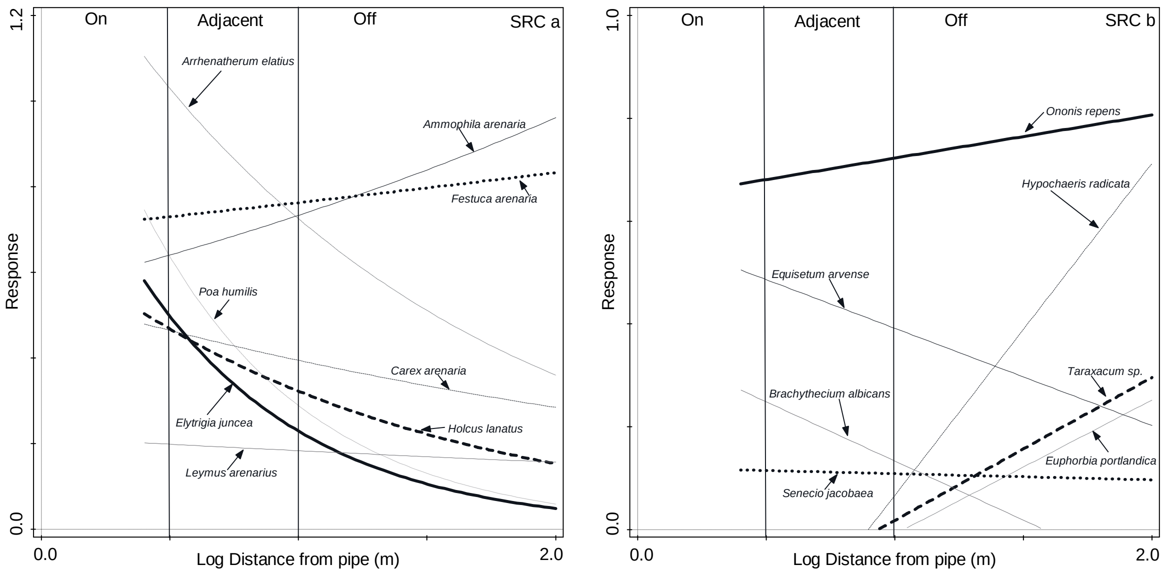
Figure 60 - Species-environmental variable biplot (a) and species-quadrats biplot (b) using CCA (of the first two axes) with environmental variables selected by forward selection procedure. The biplot includes Ellenberg values for moisture, nitrogen requirement, light and salinity as additional explanatory variables. Total variation is 3.10, explanatory variables account for 55.7% (adjusted explained variation is 31.7%); 1st Axis pseudo- F=4.4, P=0.0002; All Axes pseudo- F=2.3, P=0.0002. The species (shown as blue triangles) are labelled by the first three letters of the generic name and the first three letters of the specific name. Quadrats are shown as green circles with the quadrat number.



Species Response Curves Distance and Time

Species Response Curves with distance were produced for the embryo/ mobile dunes (Figure 61a&b). Due to a lack of data in particularly On the pipeline, only broad trends can be determined for this zone. The data shows that *Ammophila arenaria* increases with distance from the pipeline. This is expected as the pipeline installation process would result in its initial loss in the construction area. It is often then replanted as part of reinstatement works but can be slow to establish and bulk up in terms of its cover where there is a lack of sand movement. The coarse grasses *Arrhenatherum elatius* and *Holcus lanatus* both show a decrease in cover with distance indicating that in this zone they are less able to compete in undisturbed area. There is also a reduction with distance away from the pipeline of the species associated with more open conditions and mobile sands *i.e. Poa humilis*, *Carex arenaria*, *Elytrigia juncea* and *Leymus arenarius*, although *Festuca arenaria* increases in cover with distance. The forbs *Euphorbia portlandica*, *Hypochaeris radicata* and *Taraxacum* agg. show a clear preference for the undisturbed zone increase in cover with distance. This is perhaps surprising for the *Taraxacum* agg. as it generally considered to be a species of disturbance. However, in dunes it may well be a species of one of the less vigorous Sections of *Taraxacum i.e. Erythrosperma.* Members of the Section *Erythrosperma* tend to be smaller more delicate plants with dissected leaves, and are poor competitors, rarely behaving as ruderals or weeds (Rich, 2012). The moss *Brachythecium albicans* shows that it prefers more open conditions, decreasing with distance from the pipeline. It is one of the first colonisers of the dunes. Due to the lack of data from the embryo/ mobile dunes (in particular from the Short-term) a Species Response Curve plot showing the species data with years was not possible.

Figure 61 - Species Response Curves (SRC) of log distance from the pipeline (a & b) with typical embryo/ mobile dune species. Limited data for this zone was available due in part because pipeline installation typically avoids this vegetation zone, consequently the larger presence/ absence dataset was used and data from On the pipeline is absent. The plot uses a poisson response distribution and a linear predictor. The response value indicates species abundance. An indication of the sample area (On, Adjacent and Off) has been given.

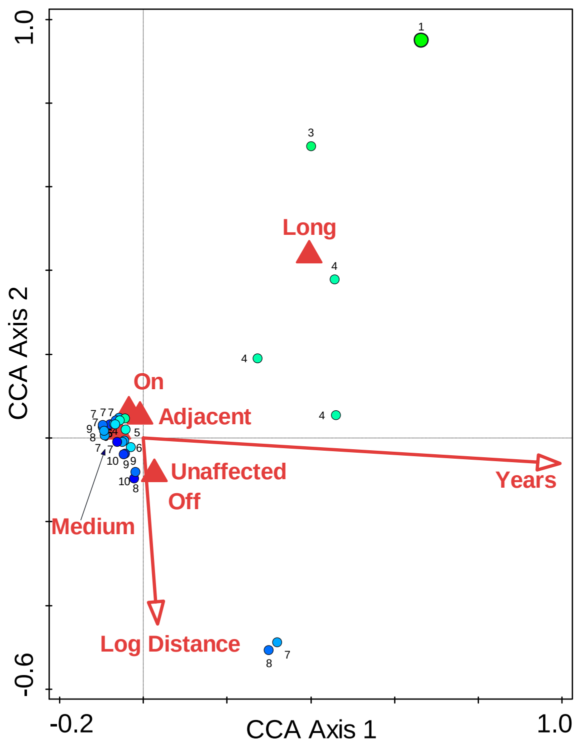


Species Diversity

Hypotheses 39 - [Species-richness will be highest On the pipeline at least in the Short-term. In Unaffected areas species-richness is likely to be lower as *Ammophila arenaria* or *Leymus arenarius* becomes dominant]. The species diversity diagram (Figure 62) when considered with the CCA biplot (Figure 59) shows that in general the most species-poor quadrats (with 3-4 species) are associated with the Long-term (*Elytrigia juncea* dominated vegetation), which probably indicates there has been natural disturbance in this zone. The On, Adjacent and Medium-term factors have 5-7 species and are typically associated with a more closed sward, often with taller mesotrophic grasses such as *Arrhenatherum elatius* and *Holcus lanatus*. In contrast, the Off/ Unaffected factors support the most species-rich quadrats (8-10 species). This factor is associated with more typical mobile dune species such as the graminoids *Ammophila arenaria*, *Carex arenaria, Festuca rubra*, and herbs *Anacamptis pyramidalis*, *Euphorbia portlandica*, *Linaria vulgaris*, and *Hypochaeris radicata.* This indicates that the hypothesis is disproven.

No nationally rare species were recorded in this zone. One nationally scarce grass *Festuca arenaria* was recorded in 23 quadrats (and appears to have no preference for sample area). Two species listed as Near Threatened (Stroh et al., 2014) were recorded, namely *Eryngium maritimum* (recorded in one quadrat Adjacent to the pipe) and *Phleum arenarium* (recorded in one quadrat Off the pipe). One non-native plant species *Solidago canadensis* was recorded in the Adjacent sample area.

Figure 62 - Species diversity diagram showing species number per quadrat in the driftline. Green circles indicate low species-richness, while blue indicate high-species richness within the zone; numbers are the actual number of species in the quadrat.



4.4.2 Ecosystem Function

The Common Standards Monitoring guidelines (JNCC, 2004b) notes "*Extent is the most important attribute and must always be assessed. Extent will be subject to natural change, as dune systems are dynamic. The requirement is that net extent of all designated habitats should be maintained, but not at the expense of other designated categories*'". Pipeline/ cable installation is likely to result in a change in the extent of the sand dune zones, with some vegetation types expanding in areas, while others decrease.

Strandline/ Embryo/ Mobile Dune Resource

Within my study sites, strandline vegetation was very much restricted in extent, with scattered plants typical of the NVC type SD2 *Honckenya peploides* - *Cakile maritima* strandline community.

No individual quadrats were sampled, and as a result no information is available on the likely impacts of pipeline installation on this vegetation zone.

Embryo dunes form just above the High Water Mark of Ordinary Spring Tides, through the accumulation of tidal litter and strandline plants (Ranwell, 1972). The embryo and mobile dunes described here include the shifting dunes represented by the NVC types SD4 *Elymus farctus*[38] ssp. *boreali-atlanticus* foredune community and SD5 *Leymus arenarius* mobile dune community; and the mobile dunes referable to the NVC type SD6 *Ammophila arenaria* mobile dune community.

Examples of embryo/ mobile dune vegetation was recorded at three sites; Talacre Warren, Redcar and at Tetney Marshes. The extent of this dune type is very much restricted at all three, but particularly at Talacre Warren where much of the fore dunes were lost during recent winter storms. At Redcar, the fore dune habitats were avoided during construction of the three projects by undertaking Horizontal Directional Drilling (HDD *Section 5.2.3*), so it is found in the Adjacent and Off sample areas but not On the pipeline. The extent of embryo/ mobile dune vegetation at each of the study sites in 2015-16 is given in Table 20. Due to differences in the size of the working width (*i.e.* On sample area) and the length of pipeline, the habitat areas (ha) are not directly comparable between sites, therefore the habitat resource is also provided as a percentage of the total site area.

Table 20 - Extent (ha and % of the total area) of the fore dune habitats (strandline, embryo, and mobile dunes) across study sites in 2015-16.

Site	Area (ha) in 2015-16	% of survey area
Redcar	0.9	5
Talacre Warren	0.3	6
Tetney Marshes	0.2	1
Total habitat area surveyed in 2015-16 (ha)		**1.4**
Proportion of total survey area (%)		**3.6**

Hypothesis 40 – [Following construction, the extent (ha) of embryo/ mobile dunes will increase in the Short-term but will return to baseline extents in the Long-term].

Talacre Warren

A detailed NVC report of Talacre Warren (with accompanying maps and data) was completed in 1991, two years prior to pipeline installation, by Ashall et al. (1991). This survey was completed as part of the wider sand dune survey of Great Britain (Dargie, 1995). The availability of the 1991 survey allows the change in vegetation zonation over time, following construction, to be documented, and for the purposes of this assessment forms the pre-construction baseline survey. Following construction, annual vegetation surveys were carried out between 1994 and 1999 by Dr Richard Carter (Carter Ecological Limited, 2000, 1999) as part of the monitoring scheme; and

[38] Now Elytrigia juncea

in 2000 a NVC survey of Talacre Warren was completed to inform ongoing habitat management of the designated site (Carter Ecological Limited, 2001). This survey included the area along the pipeline which provides an intermediate recovery stage in this assessment. The 2015-16 botanical surveys completed as part of this PhD provide the most recent information as to habitat recovery. Table 21 shows the extent (ha) of bare sand (excluding the beach), strandline, and mobile dune vegetation and as a percentage of the total for each sample area *i.e.* On, Adjacent and Off the pipeline. Figures 63-64 show the main vegetation types and the NVC communities recorded at Talacre Warren between 1991 and 2016.

Table 21 - The extent (ha and % of total habitat resource) of bare sand, strandline, mobile dune and fixed dune vegetation at Talacre Warren over 25 years following the installation of a pipeline.

	1991 (Ashall et al., 1991)			2000 (Carter Ecological Limited, 2001)			2015-16		
Habitat extent (ha)	**On**	**Adj**	**Off**	**On**	**Adj**	**Off**	**On**	**Adj**	**Off**
Bare sand (excluding beach)	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Strandline	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Mobile dunes	0.3	0.6	0.5	0.1	0.2	0.2	0.0	0.1	0.1
Fixed dunes	0.0	0.1	0.2	0.7	1.1	1.1	0.6	0.7	0.8
Habitat extent (%)	**On**	**Adj**	**Off**	**On**	**Adj**	**Off**	**On**	**Adj**	**Off**
Bare sand (excluding beach)	0	3	1	0	0	0	0	1	0
Strandline	0	0	0	0	0	0	0	1	0
Mobile dunes	44	37	29	17	14	10	4	8	6
Fixed dunes	6	5	9	83	75	62	69	45	40

The strandline vegetation at Talacre Warren is very much restricted in area, with small scattered patches of SD2[39] (approximately 50cm wide) recorded along the top of the beach. It was not recorded in previous years, but this is probably due to the scale of survey mapping and scarcity of the habitat, rather than its absence. No embryo dune vegetation was recorded at Talacre Warren in the vicinity of the pipe.

The extent of the mobile dune vegetation has changed dramatically. In 1991, 44% of the On sample area was classified as mobile dunes (SD6[40] with three sub-communities represented - SD6a[41], SD6d[42] and SD6e[43]). The 2000 survey (Carter Ecological Limited, 2001), classified most of the dunes in the vicinity of the pipeline (rather broadly) as SD6/SD7[44]. The accompanying annual monitoring data however, separated the seaward ridge from the landward ridge; with the data indicating the seaward ridge was probably SD6d or SD6e (a mobile dune community) and the landward ridge was probably SD7c (a fixed dune community). For the purpose of this assessment,

[39] SD2 Honckenya peploides-Cakile maritima strandline community
[40] SD6 *Ammophila arenaria* mobile dune community
[41] SD6a *Ammophila arenaria* mobile dune community, *Elymus farctus* sub-community
[42] SD6d *Ammophila arenaria* mobile dune community, *Ammophila arenaria* sub-community
[43] SD6e *Ammophila arenaria* mobile dune community, *Festuca rubra* sub-community
[44] SD7 *Ammophila arenaria - Festuca rubra* semi-fixed dune community

the habitat areas use a combination of the 2000 survey map and associated data, which shows this mobile dune habitat comprising of 17% of the On sample area. Over the subsequent 16 years much of the mobile dunes have been succeeded to fixed dunes, so that it now only represents 4% of the On sample area and is restricted to the very front of the dune system. At Talacre Warren therefore, hypothesis 40 is disproven (probably as a result of the natural dynamic nature of sand dunes).

It should be noted that some of the change in the extent of the mobile dune habitat at Talacre Warren, may be due to the scale of the vegetation survey mapping. In both 1991 and 2000 the whole dune system was surveyed at a scale of approximately 1:10,000. In contrast, the 2015-2016 survey of the pipeline corridor used 1:2500 field maps. Therefore, the earlier surveys while covering a much large area, were less detailed in the vicinity of the pipeline (as this was not the focus of the survey effort). Although some caution is therefore needed in interpreting the habitat areas given in Table 21, it is clear there has been ongoing succession from a mobile dune vegetation to fixed dunes On and Off the pipeline.

Coatham Sands, Redcar

In the vicinity of the two pipelines at Coatham Sands, Redcar, embryo and mobile dune habitat is restricted in area (Table 22). The area of embryo dunes has changed little since 2009 (0.3ha compared to 0.4ha in 2016) - disproving hypothesis 40, with the entire resource recorded in the Off sample area The extent of mobile dunes has increased slightly over the same period in all three sample areas, but this change is due to differences in mapping area (with the 2009 survey not including the entire construction area) Figures 65-68 show the main vegetation types and the NVC communities recorded at Coatham Common between 2009 and 2016.

Table 22 - The extent (ha and % of total habitat resource) of embryo and mobile dunes at Coatham Sands SSSI in the vicinity of the pipeline over 7 years following the installation of a pipeline.

	2009	**2009**	**2009**	**2016**	**2016**	**2016**
Habitat	**On**	**Adj**	**Off**	**On**	**Adj**	**Off**
Mobile dunes (ha)	0.00	0.02	0.22	0.06	0.37	0.43
Mobile dunes (%)	0.0	0.2	3.6	0.9	6.0	6.9

Figure 63 - Comparison of vegetation zones at Talacre Warren based on the 1991 (pre-construction) vegetation survey (Ashall et al., 1991), 2000 (post-construction survey (Carter Ecological Limited, 2000) and the 2016 vegetation survey undertaken to determine the current vegetation condition as part of this thesis. The pipeline is given as a red dotted line.

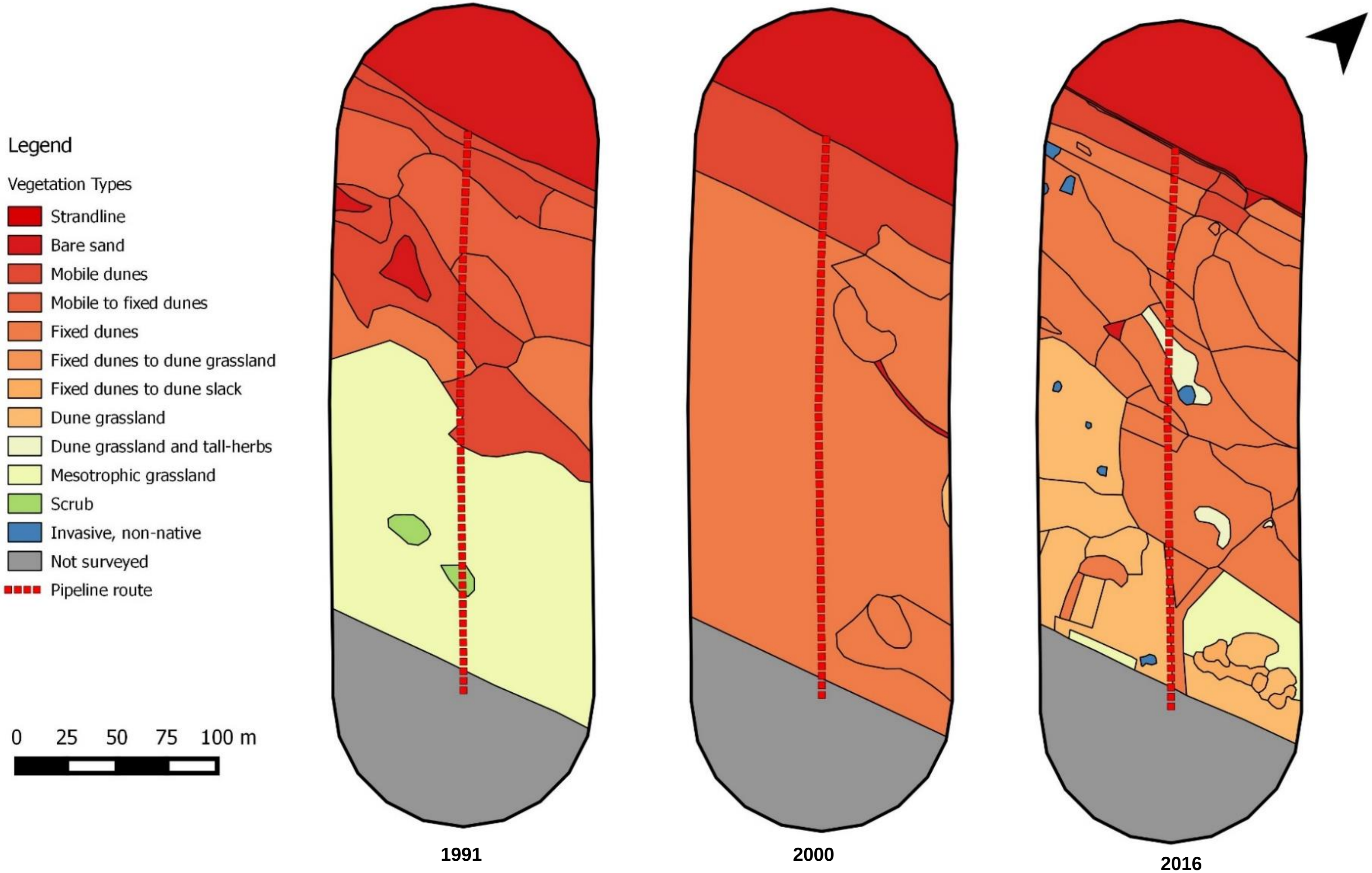


Figure 64 - National Vegetation Classification maps at Talacre Warren based on the 1991 (pre-construction) vegetation survey (Ashall et al., 1991), 2000 (post-construction survey (Carter Ecological Limited, 2000) and the 2016 vegetation survey undertaken to determine the current vegetation condition as part of this thesis. The pipeline is given as a red dotted line.

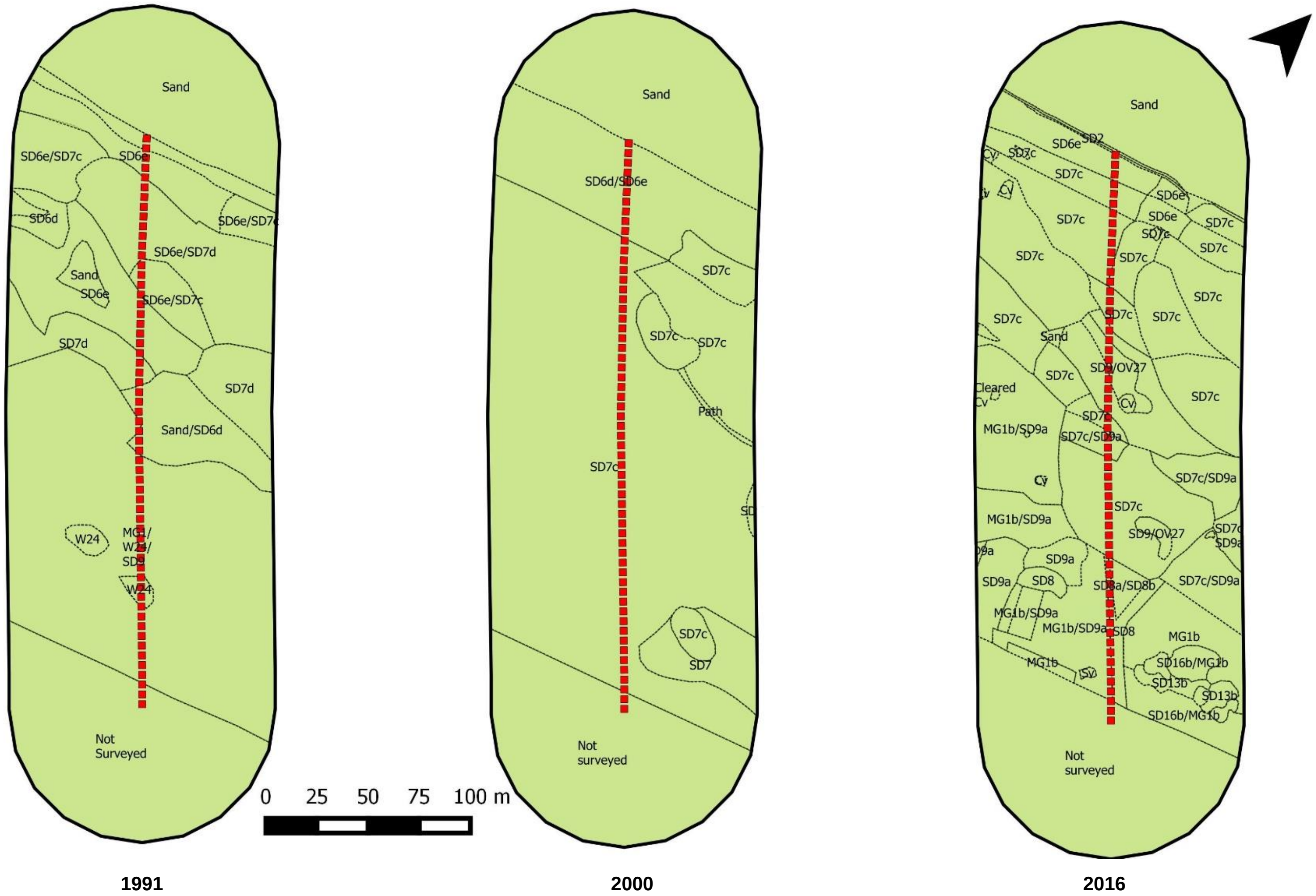


Figure 65 - Comparison of vegetation zones at Coatham Common in 2009. The pipeline is given as a red dotted line.

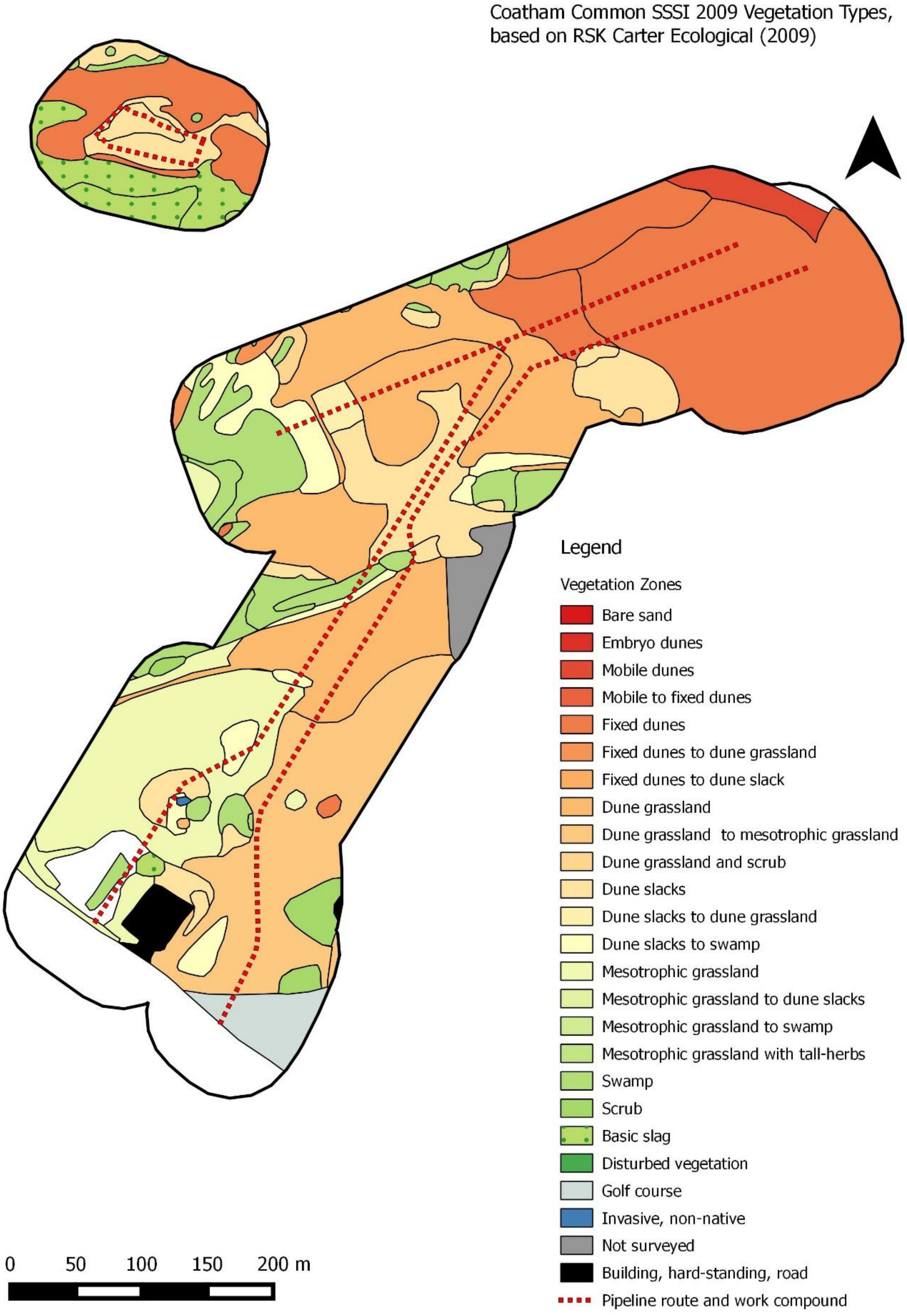


Figure 66 - Comparison of vegetation zones at Coatham Common in 2016. The pipeline is given as a red dotted line.

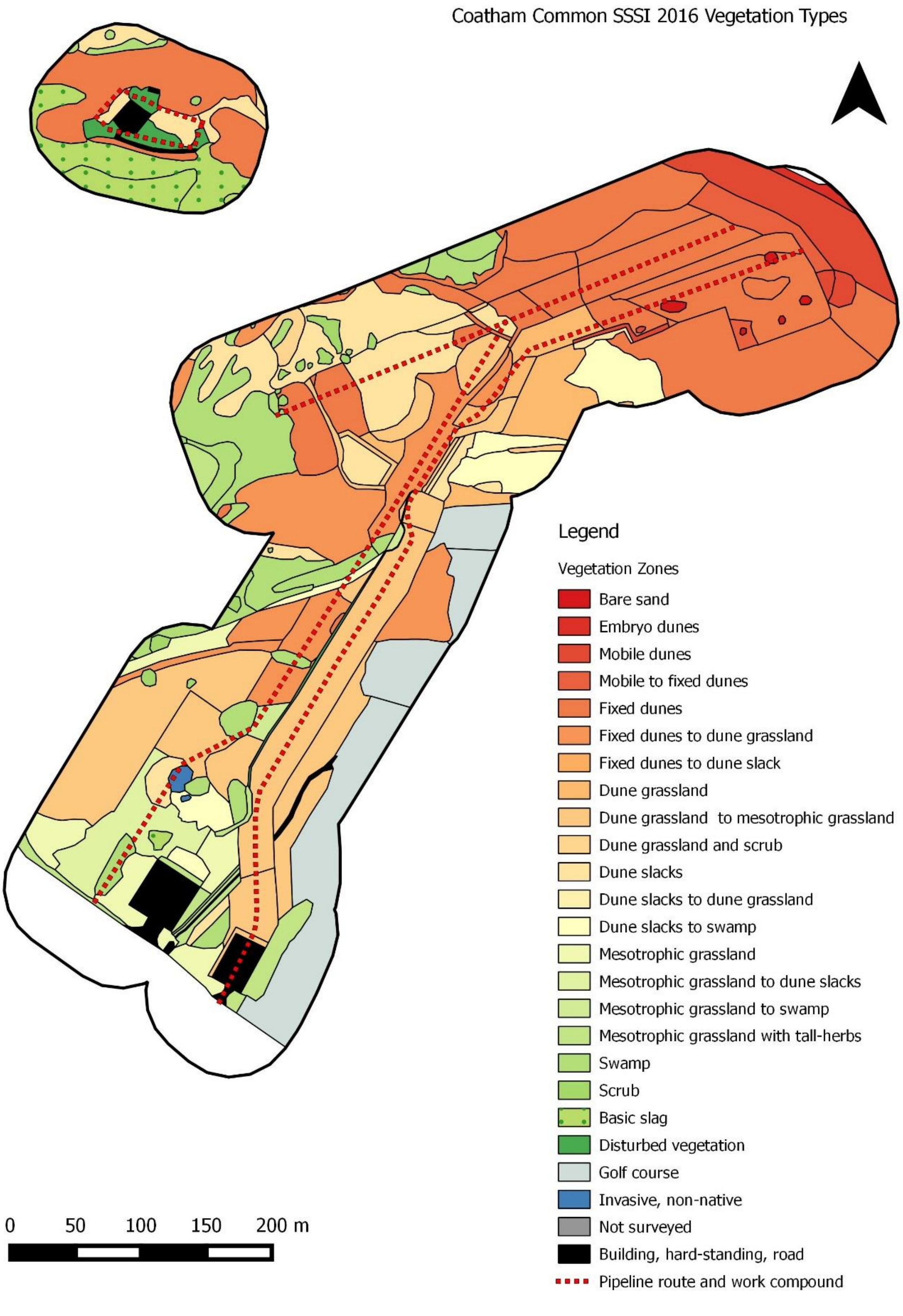


Figure 67 - National Vegetation Classification map at Coatham Common 2009. The pipeline is given as a red dotted line.

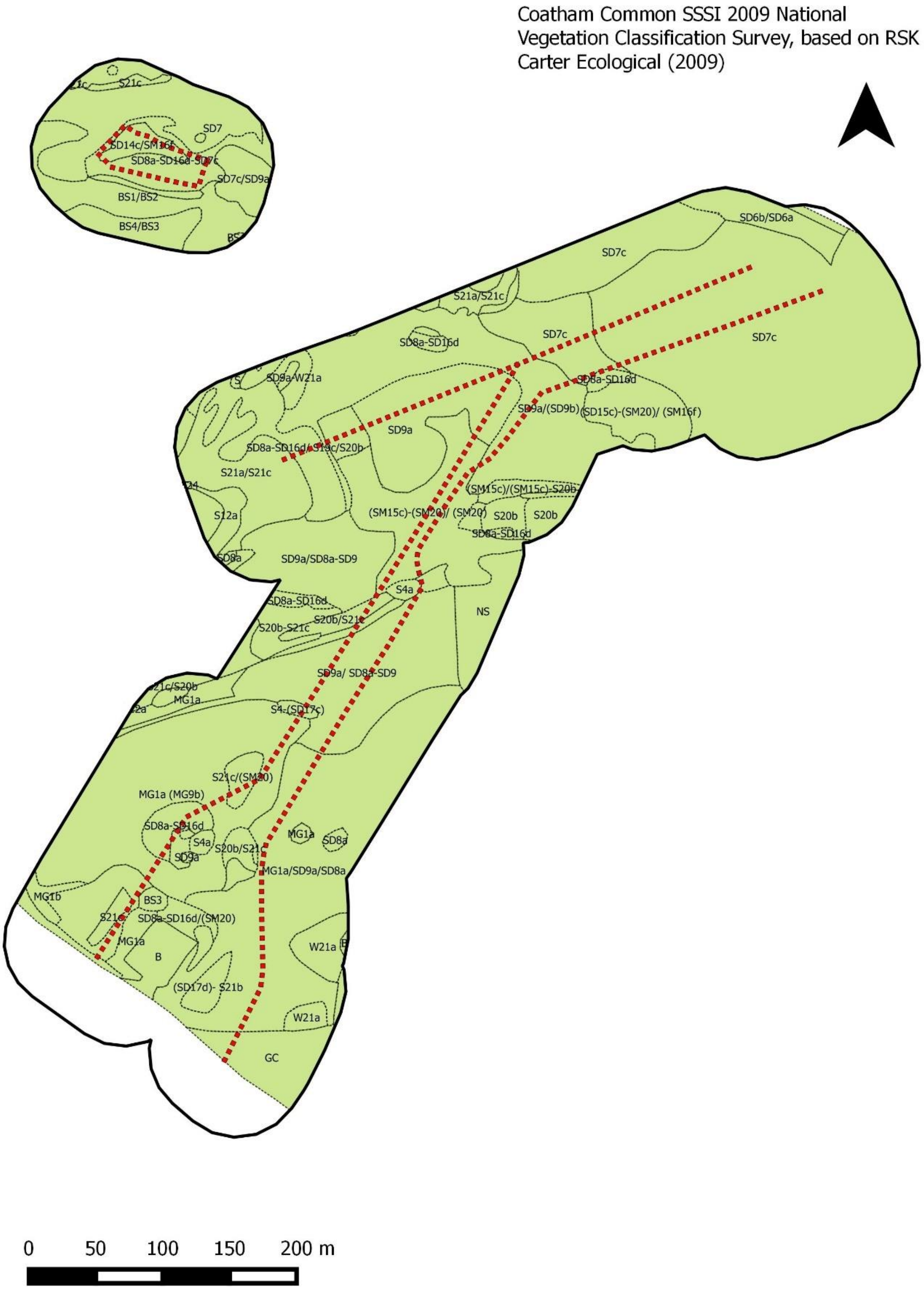
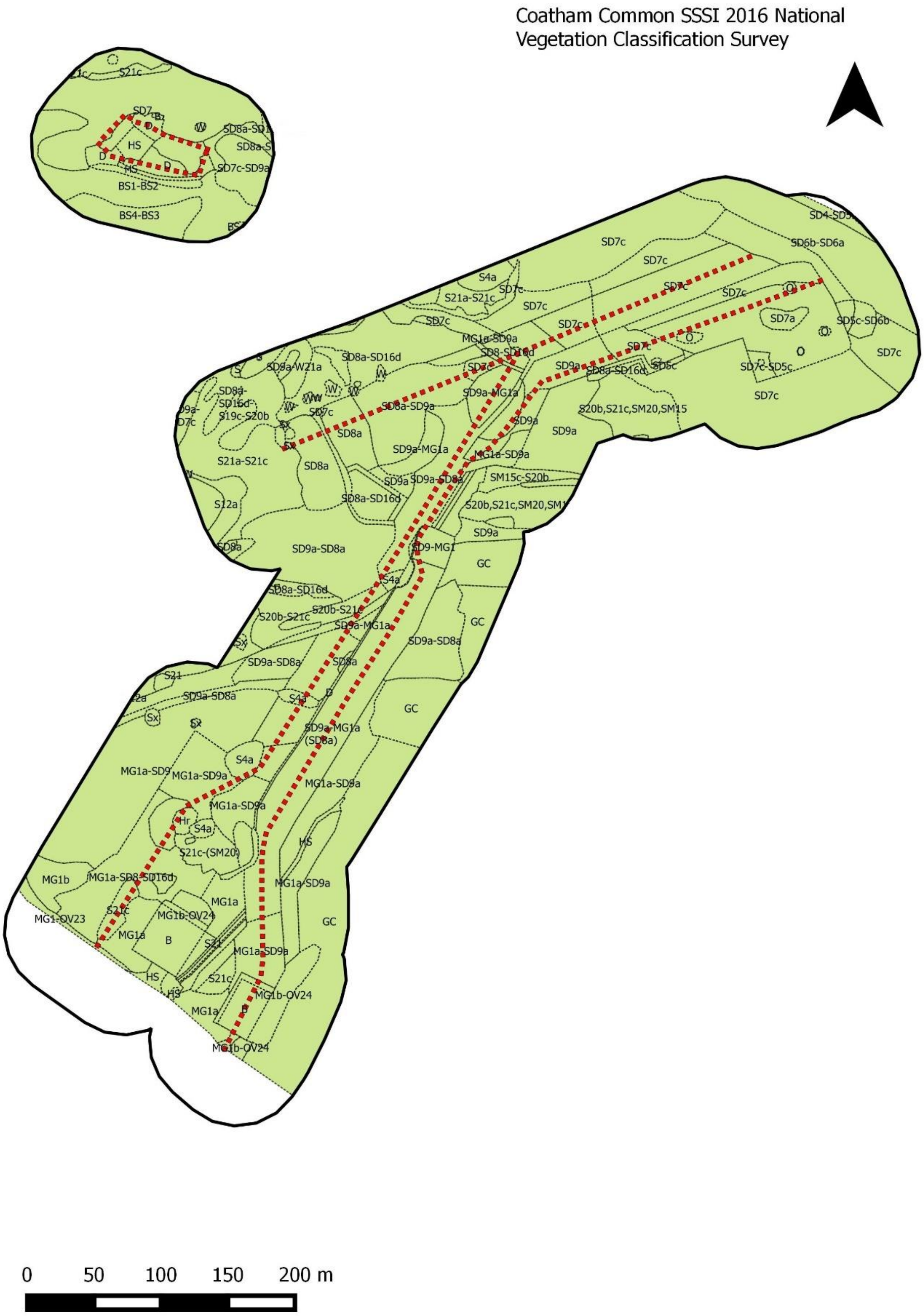


Figure 68 - National Vegetation Classification map at Coatham Common 2016. The pipeline is given as a red dotted line.



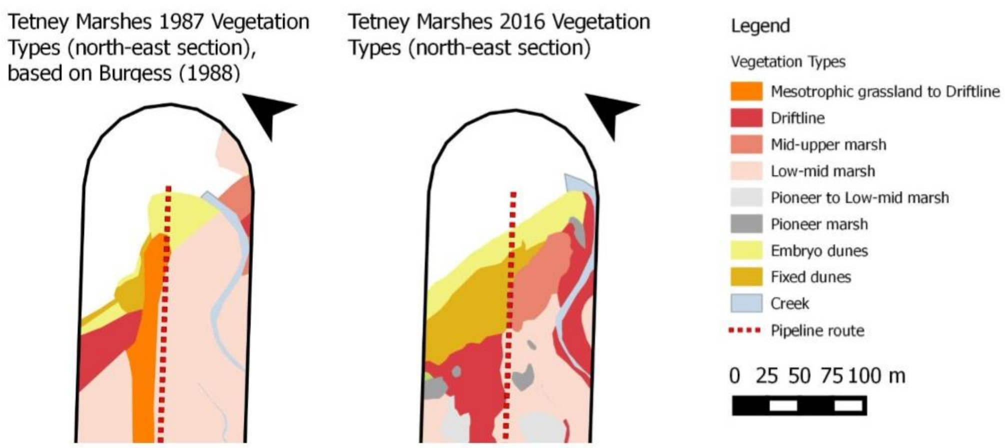
Tetney Marshes

From the vegetation maps (Figure 69) and habitat extents (Table 23) it is clear that the area of sand dunes has increased since 1987 in the vicinity of the pipeline and causeway. The data shows that the extent of embryo/ mobile dunes has remained fairly constant over time (disproving hypothesis 40). With much of the increase in dune vegetation due to an inland spread of fixed dunes across areas which were previously classified as driftline vegetation (SM24).

Table 23 - The extent (ha and % of total habitat resource) of embryo and fixed dune vegetation at Tetney Marshes over 29 years.

Habitat extent (ha)	1987	1991	2001	2016
Embryo/ mobile dunes	0.2	0.3	0.4	0.2
Fixed dunes	0.1	0.0	0.0	0.4

Figure 69 – Expansion of sand dune habitat at Tetney Marshes.

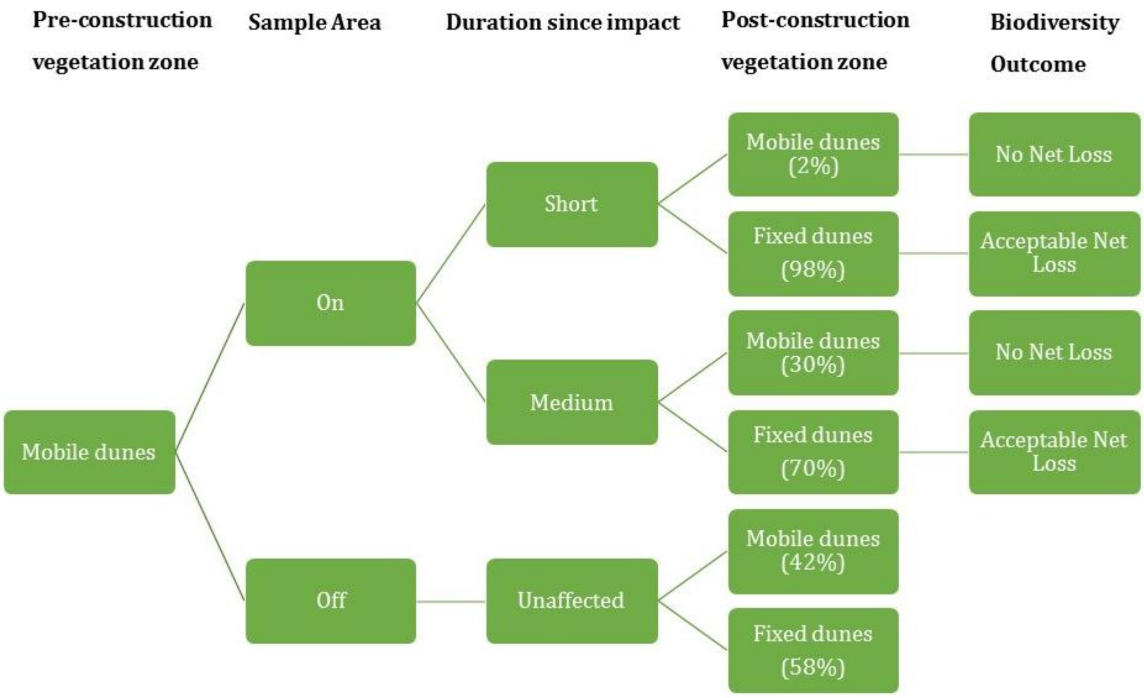


4.4.3 Outcomes of Recovery

By comparing the pre-construction vegetation types identified in the historical survey data against the current vegetation assessment, the likely direction of succession following construction both On and Off the pipeline can be determined over time.

Hypotheses 41– [In the embryo/ mobile dunes, where impacts are minor it is expected that the vegetation will recover quickly *i.e.* in the Short-term. Where impacts are greater, recovery may take until the Medium-term. In the Long-term/ Unaffected vegetation, it is likely that fixed dune vegetation will develop]. The recovery outcome of 165 quadrats classified as mobile dunes prior to construction is shown in Figure 70. In the Short-term, after construction most quadrats (98%) were classified as supporting fixed dune vegetation. It is probably that this reflects the small sample size, and the fact that typically direct impacts on this vegetation zone are avoided (*i.e.* through using HDD). Therefore, it is likely that the change from embryo/ mobile dunes to fixed dunes is due to natural succession. However, comparing On and Off areas, where left undisturbed 42% of the quadrats remained as mobile dunes and 58% succeeded to fixed dunes. This suggests that succession may be accelerated by construction, for example the compaction of the sand could allow the establishment of species such as *Ammophila arenaria.*

Figure 70 - Likely vegetation outcomes of mobile dunes following construction, based on a comparison of pre-construction vegetation types with current vegetation condition. Percentage values given represent the proportion of quadrats within each sample area and time since impact that result in each given post-construction vegetation type. The biodiversity outcome is based on those outlined in Theme 3 *Section 1.7.3.*



As described in *Section 1.6.5,* there are four possible outcome scenarios - No Net Loss, Acceptable Net Loss, Net Positive Impact and Unacceptable Net Loss. Considering the outcome pathway, a change of mobile dune vegetation to fixed dunes would be an Acceptable Net Loss as this change is probably due to ongoing succession. Although it would be hoped that new areas of embryo or mobile dunes would form allowing the retention of early dune species. Only one site surveyed as part of this project, Tetney Marshes, showed formation of new dunes over time. Retention of mobile dunes would be a No Net Loss scenario.

4.5 Results – Fixed Dunes

4.5.1 Vegetation Composition and Structure

The surveys in the fixed dunes recorded 175 species, of which 160 were vascular plants and 15 were bryophytes. Mean species numbers On and Off the pipe appeared similar for the sample areas (On = 10.6 species; and Off = 13.8 species). However, when analysed using a GLM the Off sample area had a statistically significantly higher number of species than the On sample area (df=2; T=3.27; p=0.003). Mean species numbers for time since impact also appeared similar (Short =10.6 species; Medium = 8.5 species; Long = 13.3; and Unaffected = 13.8 species), and this was supported by the GLM which was not significant. The most species recorded in an individual quadrat was 36.

The most frequent species, *Ononis repens* was recorded in 70.5% of the quadrats. The boxplots showed clear differences between the On and Off sample areas for several of the key species *i.e. Ammophila arenaria* (which had a higher cover for the Off sample area), and to a lesser extend *Arrhenatherum elatius* and *Festuca rubra*. In contrast *Anthyllis vulneraria*, *Carex arenaria* and *Festuca arenaria* showed greater cover On the pipeline (Figure 71). Similar patterns were recorded over time with *Ammophila arenaria*, *Arrhenatherum elatius* and *Festuca rubra* having a higher cover in Unaffected areas, while *Anthyllis vulneraria*, *Carex arenaria* and *Festuca arenaria* showed greater cover in the Short-term (Figure 72).

Figure 71 - Boxplots showing the cover of key fixed dune species with sample area (On and Off). Typical graminoids are shown [top] and other herbs/ bryophytes [bottom].

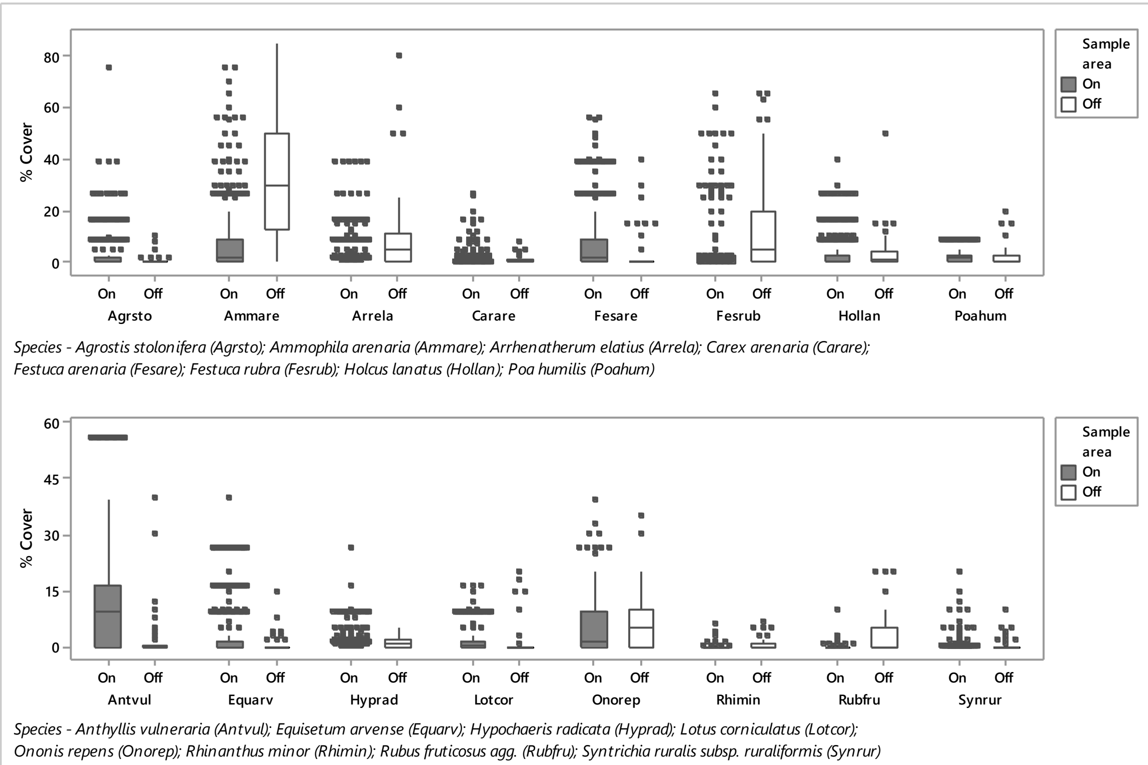
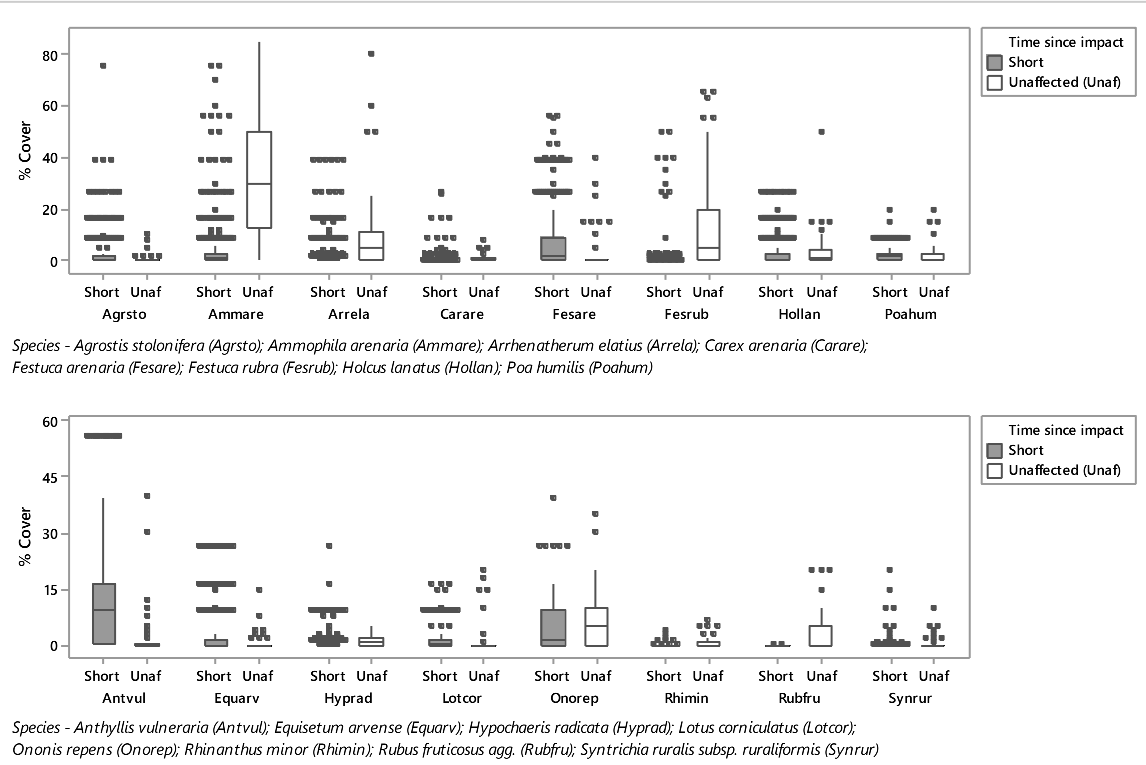


Figure 72 - Boxplots showing the cover of key fixed dune species with time since impact (short-term and unaffected). Typical graminoids are shown [top] and other herbs/ bryophytes [bottom].



General Linear Model and Tukey Pairwise Comparison Test

Hypothesis 42– [Cover of typical grasses of this zone will be lower On the pipeline, at least in the Short-term]. All four species (*Ammophila arenaria, Arrhenatherum elatius, Carex arenaria,* and *Festuca rubra*) had a significantly reduced cover On the pipeline[45]. And all four species had significantly less cover when considering time since impact, between the Short-term and Unaffected vegetation[46] - supporting the hypothesis. However, by the Medium-term the cover of *Ammophila arenaria*, *Carex arenaria* and *Festuca rubra* was not significantly different indicating that these species were back to pre-construction levels. The cover of *Arrhenatherum elatius* remained significantly lower in the Medium-term (df=3; T=-4.38; p=0.000) and Long-term (df=3; T=-4.06; p=0.000) showing a Long-term (positive) effect from the pipeline installation.

Hypothesis 43– [Early successional dune grasses which prefer more open sand will have a higher cover On the pipe at least in the Short-term]. The cover of *Festuca arenaria* and *Leymus arenarius*[47] was significantly higher On the pipeline and in the Short-term compared to the Unaffected vegetation[48] (supporting the hypothesis for these species). However, cover of *Phleum arenarium*

[45] *Ammophila arenaria* = df=2; T=5.34; p=0.000; *Arrhenatherum elatius* = df=2; T=8.37; p=0.000; *Carex arenaria* = df=2; T=3.77; p=0.000; *Festuca rubra* = df=2; T=8.64; p=0.000
[46] *Ammophila arenaria* = df=3; T=5.46; p=0.000; *Arrhenatherum elatius* = df=3; T=4.38; p=0.000; *Carex arenaria* = df=3; T=4.48; p=0.000; *Festuca rubra* = df=3; T=9.07; p=0.000
[47] *Festuca arenaria* = df=2; T=-5.61; p=0.000; *Leymus arenarius* = df=2; T=-5.45; p=0.000
[48] *Festuca arenaria* = df=3; T=-5.44; p=0.000; *Leymus arenarius* = df=3; T=-5.02; p=0.000

and *Poa humilis* was not statistically significant for sample area or time since impact (disproving the hypothesis for these species).

Hypothesis 44 – [Typical herbs of this zone will quickly establish themselves along the pipeline following construction, resulting in a higher cover On the pipe]. Cover of *Anthyllis vulneraria*, *Crepis capillaris,* and *Diplotaxis tenuifolia* were statistically higher On the pipeline[49] supporting the hypothesis for these species; while cover of *Lotus corniculatus* was not statistically significant (disproving the hypothesis). The shrubby perennial (*Ononis repens*) responded with lower cover On the pipeline and in the Short-term compared to the undisturbed vegetation. Significant results were also obtained with time since impact when considering species cover in the Short-term compared to the Unaffected vegetation for *Anthyllis vulneraria*, and *Diplotaxis tenuifolia*[50] - supporting the hypothesis for these species. Cover of both, *Crepis capillaris* and *Lotus corniculatus* was not significant over time (disproving the hypothesis for these species).

Hypothesis 45 – [Cover of scrub will be lower On the pipeline at least in the Short-term]. The main scrub species in this zone, *Rubus fruticosus* agg. showed significant differences (lower cover) between the On and Off sample areas[51] and between the Short-term and Unaffected vegetation[52] - supporting this hypothesis.

Hypothesis 46 – [Cover of mosses will not be significantly different On the pipeline at least in the Short-term]. In actual fact, the total moss cover (when all moss species were combined) was significantly higher On the pipeline (df=2; T=-10.43; p=0.000), and in the Short-term (df=3; T=-11.13; p=0.000) – disproving this hypothesis. This is presumably due to less competition from taller species, allowing early successional species such as *Brachythecium albicans* and *Syntrichia ruralis* subsp. *ruraliformis* (both individually not significant) to establish. Two species, *Ceratodon purpureus*, and *Oxyrrhynchium hians* had a significantly lower cover On the pipeline, in the Short-term.

Hypothesis 47 – [Cover of bare ground will be higher On the pipeline, at least in the Short-term]. There was a significant increase in bare ground On the pipeline (df=2; T=-7.86; p=0.000) and for the Short-term compared to Unaffected vegetation (df=3; T=-6.89; p=0.000) – supporting the hypothesis. By the Medium-term the difference in the cover of bare ground was not significant indicating the sward had closed after 10 years. In the Short-term, the total cover or graminoids and herbs were significantly lower On the pipeline.

---

[49] *Anthyllis vulneraria* = df=2; T=-6.14; p=0.000; *Crepis capillaris* = df=2; T=-3.00; p=0.000; *Diplotaxis tenuifolia* = df=2; T=-6.89; p=0.000
[50] *Anthyllis vulneraria* = df=3; T=-5.87; p=0.000; *Diplotaxis tenuifolia* = df=2; T=-5.99; p=0.000
[51] *Ononis repens* = df=2; T=4.45; p=0.000; *Rubus fruticosus* agg. = df=2; T=8.27; p=0.000
[52] *Ononis repens* = df=3; T=4.15; p=0.000; *Rubus fruticosus* agg. = df=3; T=7.29; p=0.000

A full summary of the results of the GLM and Tukey Pairwise Comparison for fixed dune vegetation is given in Appendix 4 Tables 34-37.

Canonical Correspondence Analysis

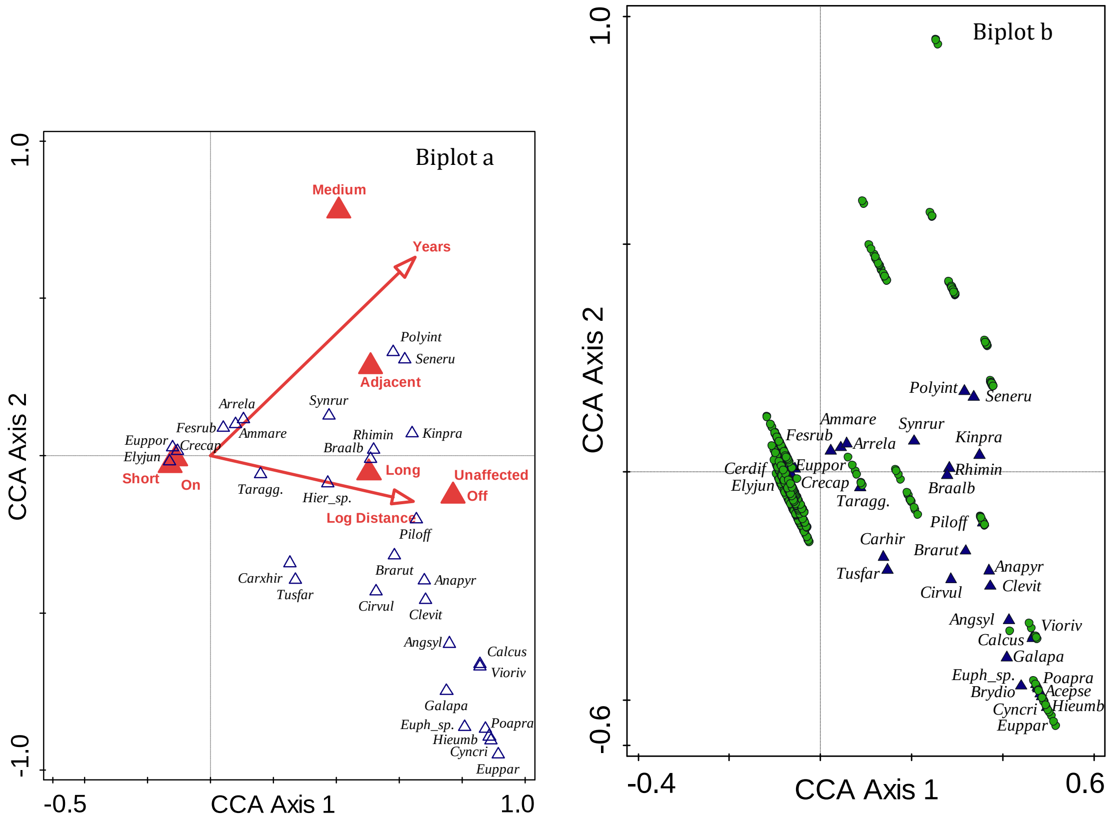
In CCA and forward selection of environmental variables with the fixed dunes data the Short-term factor explains the greatest amount of variation in the data. In addition, all of the time since impact factors were significant along with years and log distance. Interestingly, the Adjacent sample area is also significant, indicating that impacts in the fixed dune samples may have extended beyond the documented working width. This is set out in Table 24.

Table 24 - Explanatory value of environmental variables considered in CCA analysis for fixed dunes. Significant effects are given in bold.

Environmental Variable	Explains %	Contribution %	Pseudo-F	P-value	P(adj)
Time since impact - Short	**3.2**	**39.5**	**25.1**	**0.0002**	**0.00045**
Years	**1.5**	**18.7**	**12.1**	**0.0002**	**0.00036**
Log distance	**1.3**	**15.8**	**10.3**	**0.0002**	**0.0003**
Time since impact - Long	**1.1**	**13.5**	**8.9**	**0.0002**	**0.00026**
Time since impact - Unaffected	**0.6**	**7.2**	**4.8**	**0.0002**	**0.00023**
Time since impact - Medium	**0.6**	**7.2**	**4.8**	**0.0002**	**0.00023**
Sample area - Adjacent	**0.4**	**5.2**	**3.5**	**0.0002**	**0.00023**

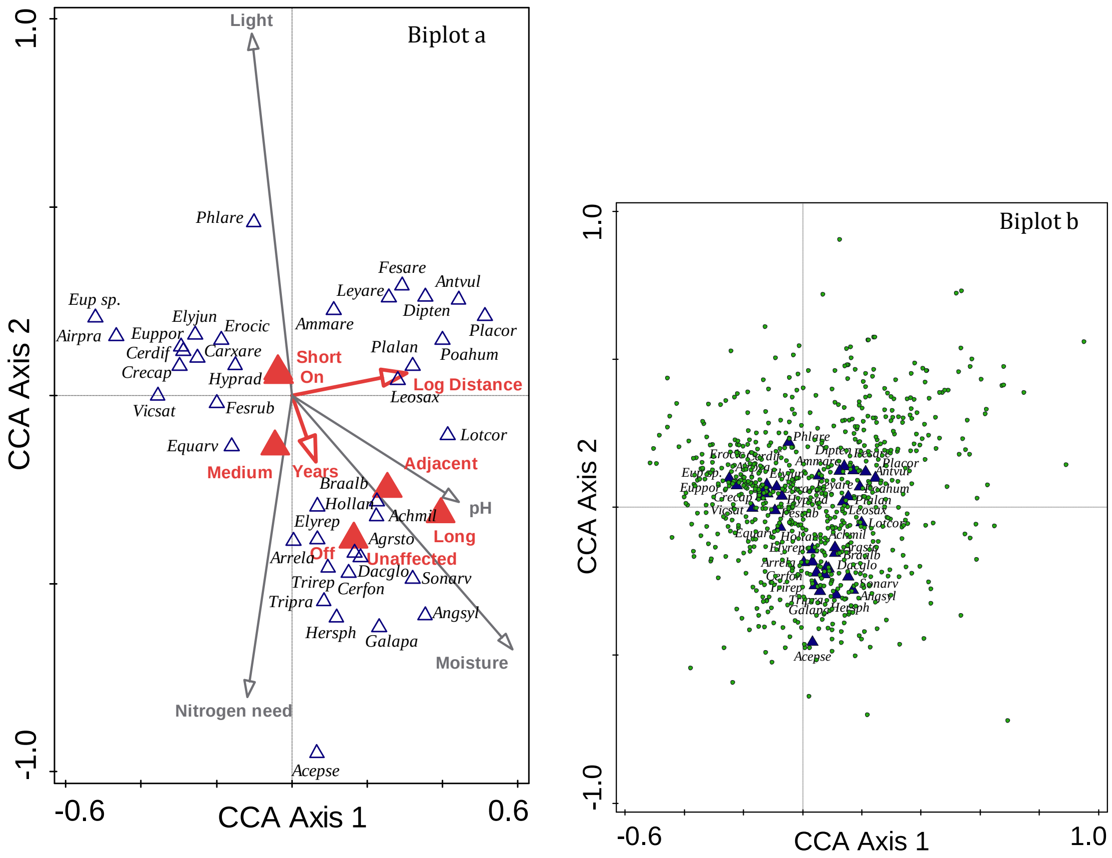
The CCA plot (Figure 73a&b) for the fixed dunes shows that the Short-term and On factors are closely associated together with species typical of open dunes *i.e. Elytrigia juncea*, *Euphorbia portlandica*, *Crepis capillaris* and *Festuca rubra*. In contrast the Long-term, Unaffected and Off factors are associated the more diverse sward with species such as *Anacamptis pyramidalis, Euphrasia* agg., *Pilosella officinarum*, *Viola riviniana*. There is also an increased number of mosses *e.g. Brachythecium albicans*, *Brachythecium rutabulum*, *Calliergon cuspidatum* and *Kindbergia praelonga*.

Figure 73 - Species-environmental variable biplot (a) and species-quadrats biplot (b) using CCA (of the first two axes) with environmental variables selected by forward selection procedure. Total variation is 4.22, explanatory variables account for 8.0% (adjusted explained variation is 7.3%); 1st Axis pseudo- F=27.1, P=0.0002; All Axes pseudo- F=11.1, P=0.0002. The species (shown as blue triangles) are labelled by the first three letters of the generic name and the first three letters of the specific name. Quadrats are shown as green circles with the quadrat number.



The inclusion of the main Ellenberg values (Hill et al., 1999) as additional explanatory variables in the CCA analysis (Figure 74a&b) helped further separate the factors, and increased the percentage variation explained by the environmental variables from 8.0% to 19.7%. The forward selection process identified all five variables as being significant. An increased moisture gradient (which was the most significant factor explaining 4.9% of the variation) showed close proximity to the Adjacent, Off, Long-term and Unaffected factors, while the On and Short-term factors were situated at the lower end of the gradient providing an indication that hydrology may be altered through pipeline installation.

Figure 74 - Species-environmental variable biplot (a) and species-quadrats biplot (b) using CCA (of the first two axes) with environmental variables selected by forward selection procedure. The biplot includes Ellenberg values for light, moisture, nitrogen requirement and pH as additional explanatory variables. Total variation is 4.22, explanatory variables account for 20.7% (adjusted explained variation is 19.7%); 1st Axis pseudo- F=55.5, P=0.0002; All Axes pseudo- F=19.8, P=0.0002. The species (shown as blue triangles) are labelled by the first three letters of the generic name and the first three letters of the specific name. Quadrats are shown as green circles with the quadrat number.



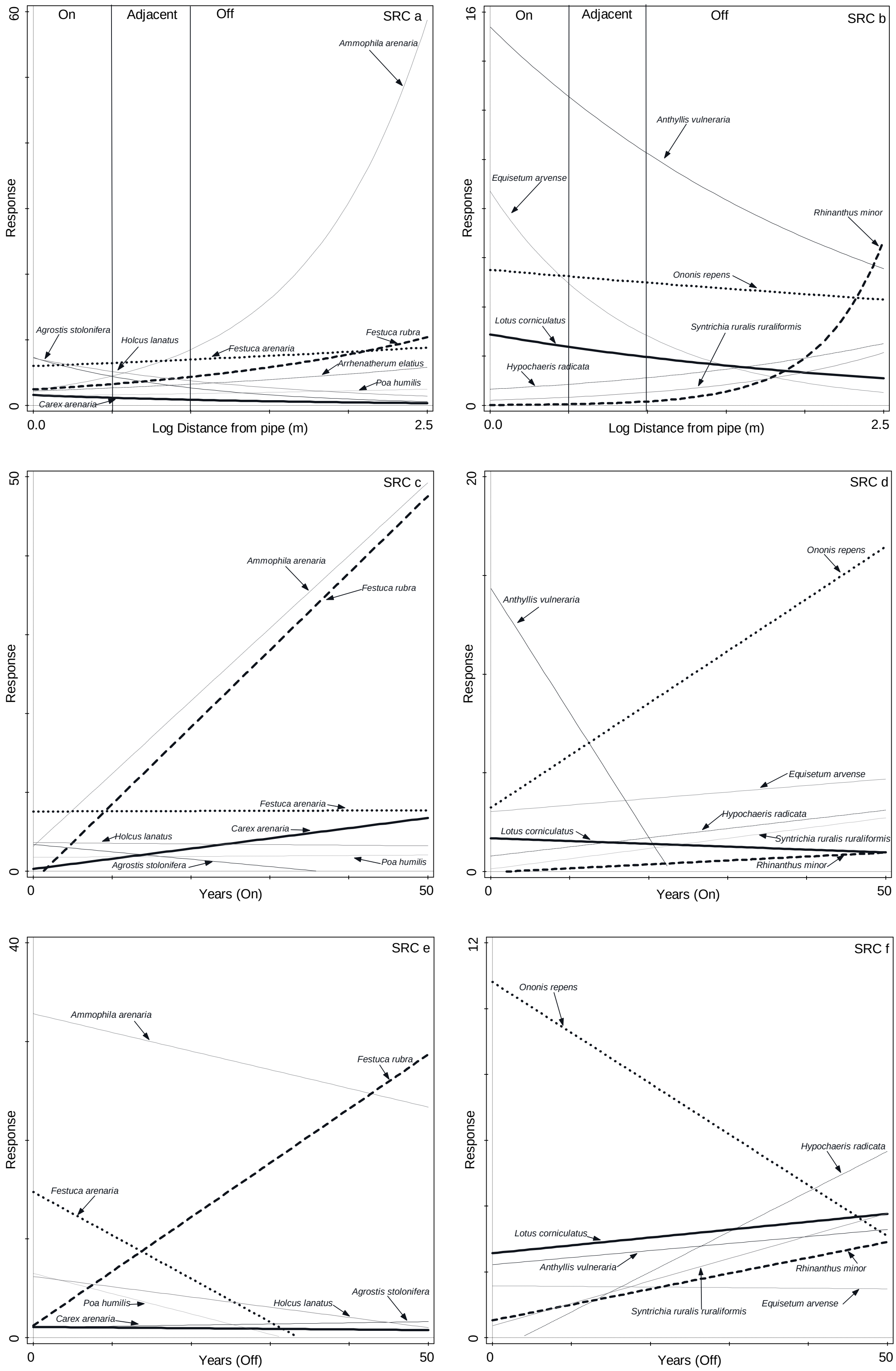
Species Response Curve Distance and Time

The Species Response Curve for the fixed dunes uses a Generalised Linear Model, with species cover plotted against the log distance (Figure 75a&b). The plot shows that *Ammophila arenaria* increases sharply in the Off sample area, increasing in cover from *c.* 4% (On) to 60% (Off). There is also an increase in *Arrhenatherum elatius* and *Festuca rubra* although this is not strong *e.g. Festuca rubra* increases from *c.* 4% to 10% with distance. The other grasses *i.e. Agrostis stolonifera*, *Holcus lanatus* show a gradual decrease in cover, while the cover of *Carex arenaria*, *Festuca arenaria*, and *Poa humilis* is more less constant with distance. In terms of the forbs, *Anthyllis vulneraria* and *Equisetum arvense* (and to a lesser extent *Lotus corniculatus* and *Ononis repens*) show a reduction in cover with distance (*e.g.* the cover of *Anthyllis vulneraria* On the pipeline is *c.* 15% compared to 6% Off the pipe). The cover of *Rhinanthus minor* shows an increase in cover with distance clearly preferring the Off sample.

On the pipeline *Ammophila arenaria* and *Festuca rubra* both showed a strong positive relationship in terms of increased cover with time. After installation cover of *Ammophila arenaria* was around 4% increasing to *c.* 12% by 10 years, 22% by 20 years and 30% by 30 years. In the Off sample area, *Ammophila arenaria* showed a gradual decline in cover from *c.* 33% to 25% over the 50 year period. It appears, that recovery of *Ammophila arenaria* in this zone (so that it achieves a similar vegetation cover to the Unaffected area) would take between 20 and 30 years. With *Festuca rubra* On the pipeline there was a slight time delay after construction before it re-established itself, after which it increased from 0% cover to 10% in 10 years, 18% by 20 years and 28% by 30 years. In the Off sample area *Festuca rubra* also showed an increase, which is likely to represent succession from mobile dunes to fixed dune communities. The other graminoids showed a less significant change with time On the pipeline, with the exception of *Carex arenaria* which increased slightly over time from 0% after installation to *c.* 5% by 20 years. In the Off sample area it showed little change. In the Off sample area *Festuca arenaria* was shown to be lost from the sward (by around 30 years), this change is due to ongoing succession, as it is a species that prefers more open conditions.

On the pipeline *Anthyllis vulneraria* decreases rapidly in cover with time (from *c.*14% after installation to being lost from the sward by *c.* 20 years). In contrast Off the pipeline this species shows a gradual increase in cover over time. *Ononis repens* showed a strong response On the pipeline increasing in cover from *c.* 3% after installation to *c.* 6% by 10 years, 8% by 20 years and 25% by 30 years. In the Off sample area its cover fell over time from *c.* 11% to 3%. The other forbs (and moss) all showed a gradual increase in cover both On and Off the pipeline, with the exception of *Lotus corniculatus* which decreased On the pipe but increased Off of it. On the pipeline there was a delay in the recovery time (by *c.* 2 years) of *Rhinanthus minor* after installation. It is a hemi-parasitic and therefore it requires a sufficient amount of its host species (in this case grasses) to be present before it can become established.

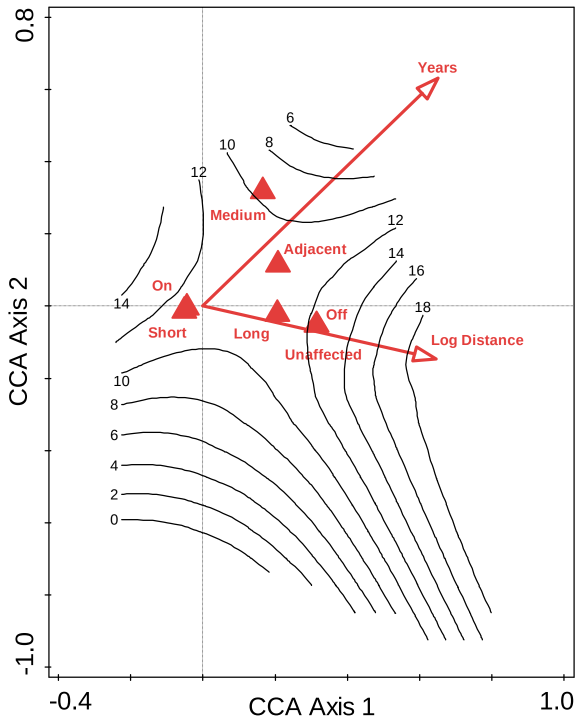
Figure 75 - Species Response Curves (SRC) of log distance from the pipeline (a & b), years On the pipeline (b & d), years Off the pipeline (e & f) with typical fixed dune species. The plot uses a poisson response distribution and a linear predictor. The response value indicates species abundance. For log distance an indication of the sample area (On, Adjacent and Off) has been given.



Species Diversity

Hypotheses 48 - [Species-richness will be highest On the pipeline at least in the Short-term. In the Long-term/ Unaffected areas, species-richness is likely to be lower as *Ammophila arenaria* or *Arrhenatherum elatius* becomes dominant]. A contour plot summarising species numbers as areas of similarity for the fixed dunes is shown in Figure 76. The plot shows that there is little difference in species numbers between the factors. For example, the On, Adjacent, Short- and Long-term factors have 10-12 species, while the Medium-term appears to have slightly less (8-10 species). The Unaffected/ Off factors are the most species-rich with 12-14 species – disproving the hypothesis.

Figure 76 - Species diversity diagram using a contour plot showing species number in the fixed dunes.



No nationally rare species were recorded in this zone. Two nationally scarce species were recorded in the fixed dunes quadrats, *Festuca arenaria* was recorded in 241 quadrats and *Vulpia fasciculata* was recorded in 6 quadrats from this zone. The record of *Vulpia fasciculata* was from Talacre Warren in Wales and was recorded as part of the post-construction monitoring between 1996 and 1999 by Dr Richard Carter. This species was not rediscovered in the 2015 and 2016 surveys.

At Redcar, one species, *Astragalus danicus* listed as Endangered (Stroh et al., 2014) was recorded in 2 quadrats[53] in the fixed dunes (both On the pipeline). Walker et al. (2017) notes that this

[53] Although it was found as a locally frequent component On the pipeline in the fixed dunes

species is a poor competitor restricted to short swards and sites with low fertility. It is typically associated with the NVC type SD8 *Festuca rubra*-*Galium verum* fixed dune grassland (as noted at Redcar). *Astragalus danicus* was one of the key species translocated (as plants and seeds) prior to construction; and it appears that it has not only survived but prefers the shorter, herb-rich swards that have developed following installation.

Silene gallica was recorded in 2016 at Coatham Sands, Redcar (but not in a quadrat), this species is nationally scarce and appears to be a new record for the 10km square. For the English sites (Redcar and Tetney Marshes) two species listed as Near Threatened (Stroh et al., 2014) were recorded; namely *Carlina vulgaris* (recorded in one quadrat Adjacent to the pipe at Tetney Marshes) and *Phleum arenarium* (recorded in 30 quadrats at Coatham Sands, 29 of which were On the pipe in the Short-term). No plant species listed from Talacre Warren were listed on the Vascular Plant Red Data List for Wales (Dines, 2008).

Four non-native plant species were recorded in this zone, *Acer pseudoplatanus*, *Oenothera glazioviana*, *Senecio squalidus* and *Solidago canadensis*. Of these the shading effect of *Acer pseudoplatanus* and the rhizomatous spread of *Solidago canadensis* mean these species are a threat to native sand dune species. Both *Acer pseudoplatanus* and *Solidago canadensis* were recorded at Talacre Warren (Off the pipeline) and are currently being controlled by cutting and a targeted herbicide treatment.

4.5.2 Ecosystem Function

Fixed Dunes

Actively growing or mobile dunes often have significant areas which are unvegetated with exposed sand and are accordingly called yellow dunes. As *Ammophila arenaria* becomes more dominant, wind erosion at the surface decreases and sand is stabilised allowing the colonisation of bare areas by smaller plants, increasing species diversity. In addition, with the development of new embryo and yellow dunes to the seaward side, wind erosion is less severe, consequently the dunes here are referred to as semi-fixed or fixed.

Examples of fixed dunes were found at the three study sites. The best examples of this vegetation type were recorded at Redcar and Talacre Warren. At Redcar, in 2016 it extended roughly 360m along the most recent pipeline and 185m along the oldest pipeline. It was also recorded at Talacre Warren extending for 185m. The extent of fixed dune habitat (including fixed dune habitat transitional to dune grassland) at each of the study sites in 2015-16 is given in Table 25. Due to differences in the size of the working width (*i.e.* On sample area) and length of pipeline, the habitat areas (ha) are not directly comparable between sites, therefore the habitat resource is also provided as a percentage of the total site area.

Table 25 - Extent (ha and % of the total area) of the fixed dunes across study sites in 2015-16.

Site	Area (ha) in 2015-16	% of survey area
Redcar	6.4	34
Talacre Warren	2.1	48
Tetney Marshes	0.4	2
Total habitat area surveyed in 2015-16 (ha)		**8.9**
Proportion of total survey area (%)		**22.1**

Hypothesis 49 – [The extent (ha) of fixed dune vegetation, will increase in the Short-term; by the Long-term it is expected to return to pre-construction levels].

Talacre Warren

Table 26 shows the extent (ha) of fixed dune vegetation and as a percentage of the total for each sample area *i.e.* On, Adjacent and Off the pipeline at Talacre Warren. In 1991, the area of fixed dunes habitat (SD7c[54] and SD7e[55]) was similar in the On and Adjacent sample areas (*c.* 5%). In 2000 (Short-term), fixed dune habitat (SD7c) represented the main vegetation type On the pipeline (*c.* 83%), and in the Adjacent and Off sample areas – supporting the hypothesis. This increased in fixed dune vegetation in the Adjacent and Off sample areas may represent either a wider impact area (*i.e.* construction extending beyond the documented working width) or may be an artefact of the scale of 2000 vegetation mapping. By 2016, fixed dune habitat showed a decrease in extent in all sample areas as a result of ongoing succession. Here the vegetation is referable to the NVC type SD7c with transitions to SD9a[56].

Table 26 - The extent (ha and % of total habitat resource) of fixed dune vegetation at Talacre Warren over 25 years following the installation of a pipeline as recorded in 1991 by (Ashall et al.), 2000 by (Carter Ecological Limited) and as part of this study in 2015-16.

	1991			2000			2015-16		
Habitat extent (ha)	**On**	**Adj**	**Off**	**On**	**Adj**	**Off**	**On**	**Adj**	**Off**
Fixed dunes	0.0	0.1	0.2	0.7	1.1	1.1	0.6	0.7	0.8
Habitat extent (%)	**On**	**Adj**	**Off**	**On**	**Adj**	**Off**	**On**	**Adj**	**Off**
Fixed dunes	6	5	9	83	75	62	69	45	40

Coatham Sands, Redcar

The available habitat survey maps from Redcar can also be used to document the extent of fixed dunes. A detailed habitat survey was completed in 2009 (RSK Carter Ecological, 2009) as part of the Project Breagh pipeline pre-construction EIA. The survey extended over much of the dunes at South Gare & Coatham Sands SSSI, to help determine the best route for construction, and therefore included the AMCO CATS pipeline corridor which was installed in 1990-91 and the construction

[54] SD7c *Ammophila arenaria - Festuca rubra* semi-fixed dune community, *Ononis repens* sub-community
[55] SD7e Ammophila arenaria-Festuca rubra semi-fixed dune community, Elymus pycnanthus sub-community
[56] SD9a *Ammophila arenaria-Arrhenatherum elatius* dune grassland, typical sub-community

compound of the Teesside OWF installed subsequently in 2012-13. Table 27 shows the extent (ha) of fixed dune vegetation and as a percentage of the total for each sample area *i.e.* On, Adjacent and Off the pipeline. In 2009, fixed dune habitat was roughly equal across the three sample areas. In 2016, cover of fixed dunes vegetation in the On sample area was very slightly higher increasing from 1.5ha to 1.7ha while in the Adjacent and Off sample areas it had decreased very slightly. In 2016, there was also transitional vegetation SD7 to SD9 which appears more prominent on the pipeline compared to the Off sample area. The initial increase of fixed dunes and transitional habitat after construction of the Project Breagh pipeline in the On sample area supports hypothesis 49.

Table 27 - The extent (ha and % of total habitat resource) of fixed dune vegetation at Redcar since 2009 following the installation of the Project Breagh pipeline and construction compound for the Teesside OWF.

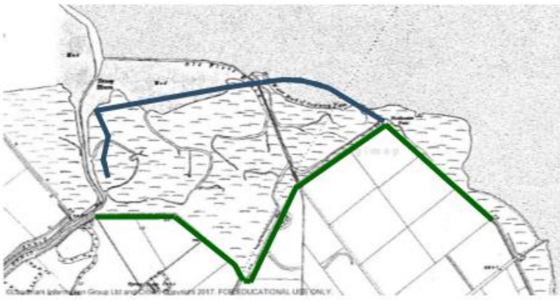
	2009			2016		
Habitat extent (ha)	**On**	**Adj**	**Off**	**On**	**Adj**	**Off**
Fixed dunes	1.5	1.6	1.6	1.7	1.5	1.5
Fixed dunes to dune grassland	0.0	0.0	0.1	0.7	0.6	0.5
Habitat extent (%)	**On**	**Adj**	**Off**	**On**	**Adj**	**Off**
Fixed dunes	23	26	26	26	23	24
Fixed dunes to dune grassland	0	0	1	12	9	7

Tetney Marshes

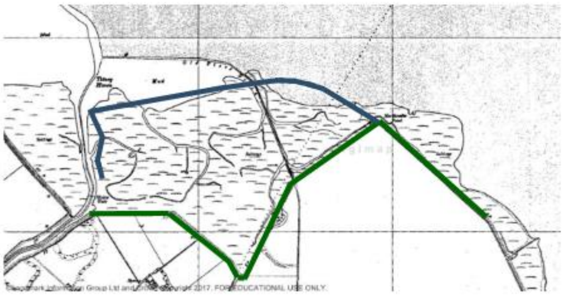
As discussed in the embryo/ mobile dune section, the area of fixed dunes at Tetney Marshes has increased over time since 1987 from 0.1ha to 0.4ha in 2016 (Figure 69 and Table 23).

Whether the change from saltmarsh to sand dunes has occurred as a result of the pipeline/ causeway installation or natural change is difficult to determine. It is hypothesised that the construction of the causeway (which was left in-situ) reduced the frequency of tidal inundation behind the beach, which allowed the increased dominance of *Elytrigia atherica.* This was followed by the subsequent spread of sand from the beach inland, creating dunes across the driftline vegetation. However, care is required in interpreting habitat change at Tetney Marshes as there is no pre-construction baseline vegetation mapping, and the 1987 survey was completed 17 years after construction. The OS historical maps for the area (from the 1900s to 1970s (Figure 77)) show significant changes in the vicinity of the pipeline, including land reclamation with the construction of a sea wall at some point after 1970. The pipeline and causeway construction resulted in the loss of one of the main creeks, and it separated the remaining creeks from the area where dunes have subsequently developed. Across the whole saltmarsh system many creeks were severed, and new creeks developed.

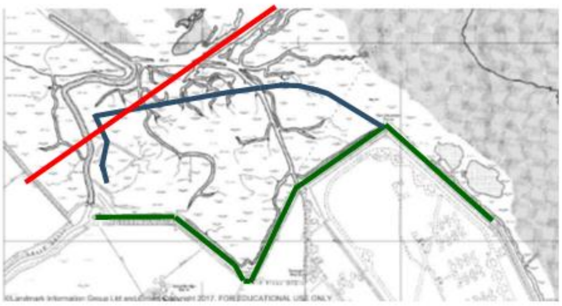
Figure 77 - Tetney Marshes historical Ordnance Survey maps produced by Digimap®.



Section of the 1900s Ordnance Survey historical map at Tetney Marshes produced by Digimap®



Section of the 1950s Ordnance Survey historical map at Tetney Marshes produced by Digimap®



Section of the 1970s Ordnance Survey historical map at Tetney Marshes produced by Digimap®

Alignment of contemporary sea defence

Historical sea defence (shown on 1880s OS Map)

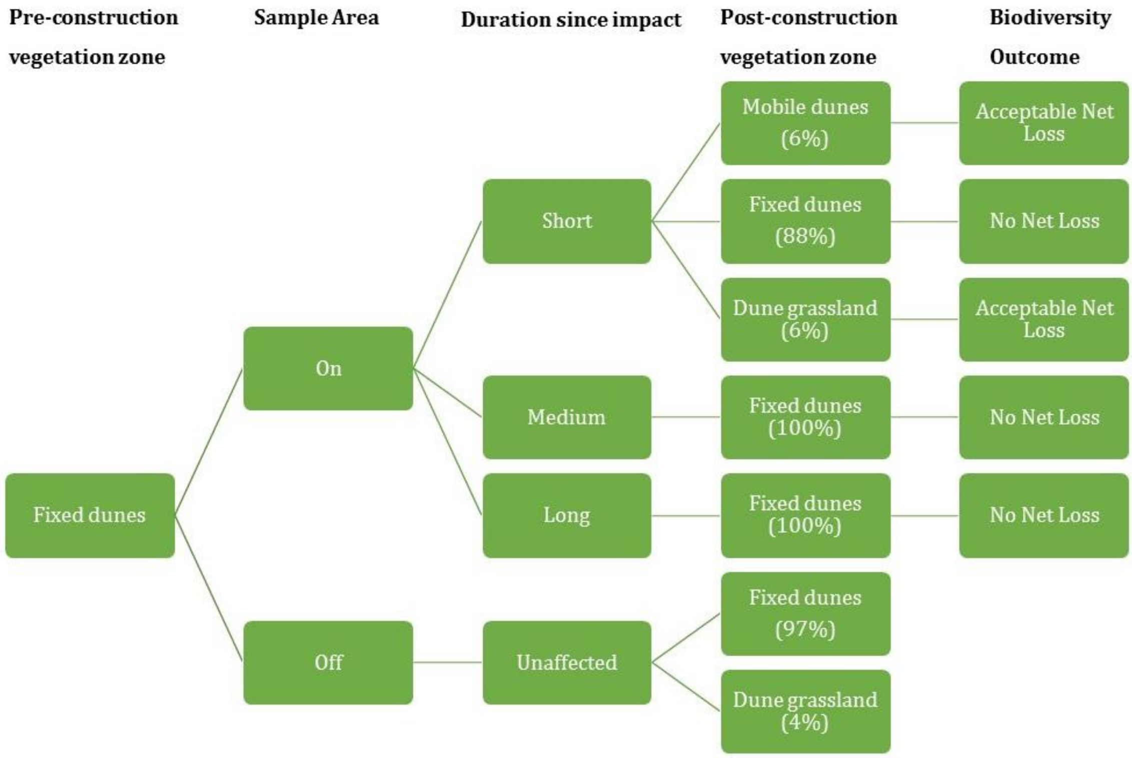
Pipeline and causeway installed in 1969

4.5.3 Outcomes of Recovery

Hypotheses 50 – [In the fixed dunes, it is expected that the vegetation will recover quickly with vegetation typical of fixed dune swards developing in the Short-term. Where impacts are greater recovery may take until the Medium-term. In the Long-term where managed, fixed dune vegetation will persist, but where left, succession may result in dune grassland]. The recovery outcome of 419 quadrats classified as fixed dunes prior to construction is shown in Figure 78. In the Short-term, On the pipeline the majority (88%) of quadrats remained as fixed dune vegetation, which continued to remain the dominant vegetation type On the pipeline in the Medium and Long-term. There were a few instances (20 quadrats) where mobile dune vegetation was established. These tended to be small areas associated with poor establishment of *Ammophila arenaria* where there was a high cover of bare ground. A few quadrats (21) also showed ongoing succession to dune grassland with an increase in *Arrhenatherum elatius.* In the Off sample area under natural conditions fixed dune grassland was retained in 97% of the quadrats.

Figure 78 - Likely vegetation outcomes of fixed dunes following construction, based on a comparison of pre-construction vegetation types with current vegetation condition. Percentage values given represent the proportion of quadrats within each sample area and time since impact that result in

each given post-construction vegetation type. The biodiversity outcome is based on those outlined in Theme 3 *Section 1.7.3.*



In the fixed dunes, in the Short-term retention of fixed dune habitat is considered to be a No Net Loss scenario. The creation of mobile dunes (especially where bare sand is colonised by early successional species) would be a Net Positive Impact. While a change to dune grassland would be an Acceptable Net Loss where this occurred at a low level.

4.6 Results – Dune Grassland

4.6.1 Vegetation Composition and Structure

The surveys in the dune grassland identified 170 species, of which 160 were vascular plants and 10 were bryophytes. The mean number of species On the pipe appeared higher than Off (On = 17.7 species; and Off = 12.1 species), however this was not statistically significant. Mean species numbers for time since impact were similar, especially comparing the Short-term with the Unaffected vegetation (Short = 12.1 species; Medium = 8.7 species; Long = 13.4; and Unaffected = 12.1 species), this was not statistically significant. The most species recorded in an individual quadrat in this zone was 30.

The most frequent species, *Holcus lanatus* was recorded in 85.4% of the quadrats in this zone. *Ammophila arenaria* showed a clear preference in terms of having a higher cover Off the pipeline (and in the Unaffected vegetation for time), while *Agrostis stolonifera* and *Dactylis glomerata* appear to have a higher cover On it (and in the Short-term). Cover of the other graminoids appear (from the boxplots) to be less significant, although with greater variation. In the dune grassland members of the plant family Fabaceae appeared to have a higher cover On the pipeline than Off of it (and in the Short-term compared to Unaffected vegetation). Most species of this family are able to fix nitrogen in their roots and this probably means that they are at an advantage over other species in the disturbed construction area (Figures 79-80).

Figure 79 - Boxplots showing the cover of key dune grassland species with sample area (On and Off). Typical graminoids are shown [top] and other herbs [bottom].

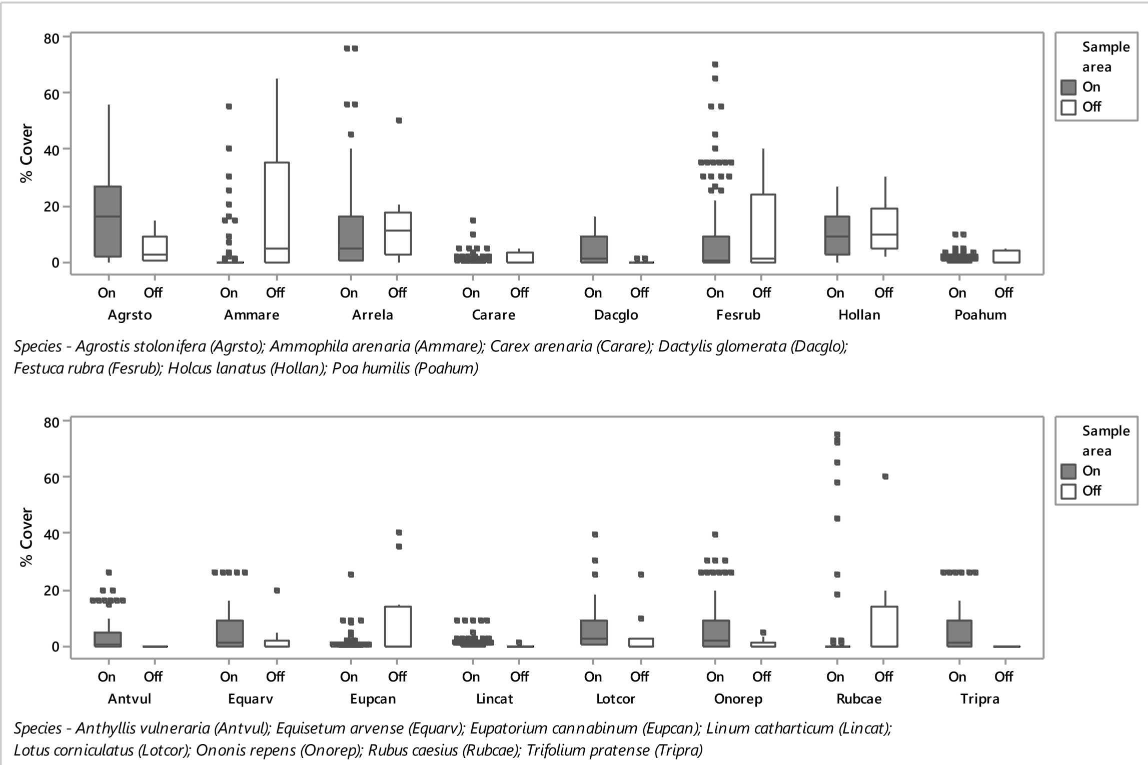
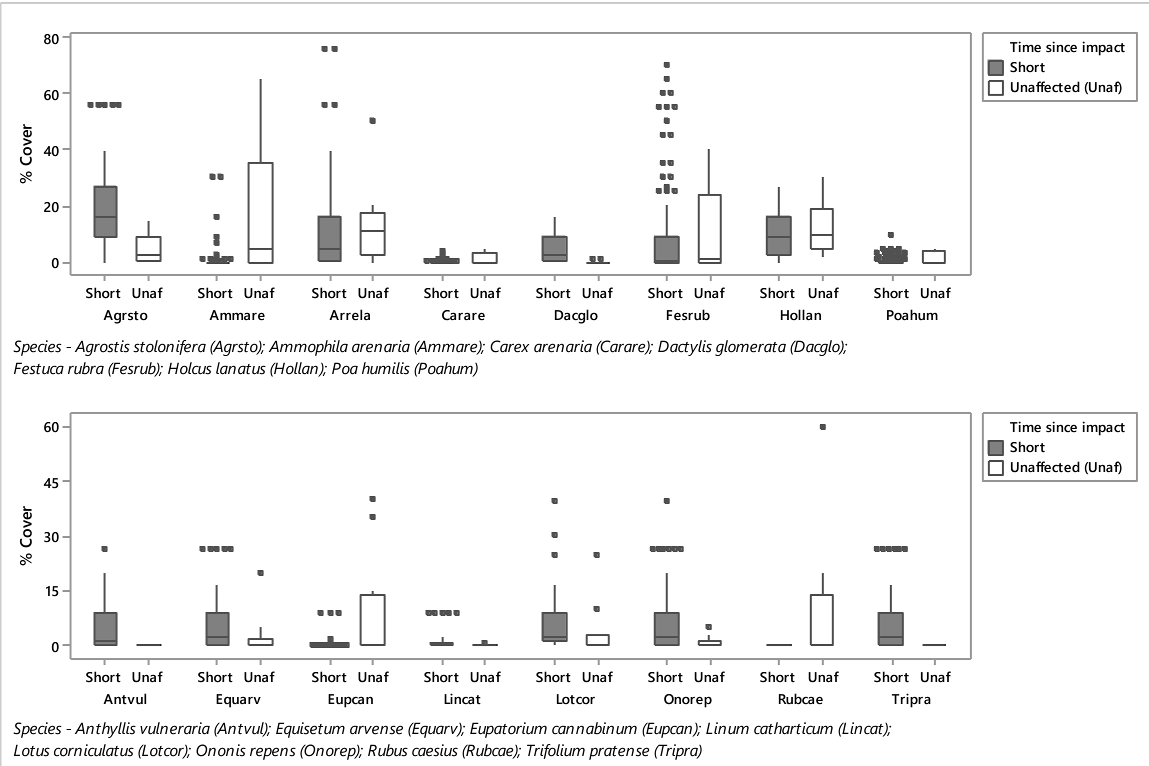


Figure 80 - Boxplots showing the cover of key dune grassland species with time since impact (Short-term and Unaffected). Typical graminoids are shown [top] and other herbs/ bryophytes [bottom].



General Linear Model and Tukey Pairwise Comparison Test

Hypothesis 51– [Cover of *Ammophila arenaria,* will be reduced or absent On the pipeline]. The data showed that *Ammophila arenaria* had a significantly reduced cover On the pipeline[57], and in the Short- and Medium-term compared to the Unaffected vegetation[58] - supporting this hypothesis.

Hypothesis 52– [Broad-leaved grasses typical of mesotrophic grassland swards would initially have a lower cover along the pipeline, at least in the Short-term]. Cover of *Arrhenatherum elatius, Dactylis glomerata*, *Holcus lanatus* and *Poa pratensis* were not significantly different between the sample area or over time – disproving this hypothesis. This indicates that these species quickly recover to pre-construction levels. In contrast, the finer-leaved graminoids typical of open swards such as *Bromus hordeaceus* and *Luzula campestris* had a significantly higher cover On the pipe, and *Festuca rubra* had a significantly higher cover in the Short-term compared to the Unaffected vegetation.

Hypothesis 53– [Typical herbs of mesotrophic grassland swards will initially have a lower cover On the pipeline; at least in the Short-term]. Most of the typical species showed no significant differences in cover between the On and Off sample areas (indicating that they recover quickly to

[57] *Ammophila arenaria* = df=2; T=-2.94; p=0.006;
[58] *Ammophila arenaria* (unaffected v. short-term) = df=2; T=3.79; p=0.001; (unaffected v. medium-term) = df=2; T=2.76; p=0.017

pre-construction levels) – disproving this hypothesis. The cover of *Centaurea nigra* was significantly higher On the pipeline. Comparing cover between the Short-term and Unaffected vegetation, *Equisetum arvense* had a significantly lower cover, but the other species tested were not significant.

Hypothesis 54 – [Woody sub-shrubs will have a lower cover On the pipeline, at least in the Short-term]. The analysis showed that cover of *Ononis repens*, *Rubus caesius* and *Rubus fruticosus* agg. was not statistically significant for sample area or time since impact – disproving this hypothesis. One species, *Clematis vitalba* had significantly lower cover On the pipeline, although this is probably due to ongoing herbicide treatment being taken by site managers at Talacre Warren, where this species was most frequent.

Hypothesis 55 – [Cover of mosses will be significantly lower On the pipeline]. In actual fact, the total moss cover (when all moss species were combined) was significantly higher On the pipeline, and in the Short-term (df=2; T=-4.13; p=0.000) – disproving this hypothesis. One moss *Kindbergia praelonga* had a significantly lower cover On the pipeline, and *Ceratodon purpureus* had a significantly lower cover in the Short-term.

Hypothesis 56 – [Cover of bare ground will be higher On the pipeline, at least in the Short-term]. There was not a significant increase in bare ground by sample area or over time – disproving this hypothesis. Although the total cover of herbs and graminoids appears to be higher On the pipe, neither are statistically significant when considered using a GLM.

A full summary of the results of the GLM and Tukey Pairwise Comparison for the dune grassland is given in Appendix 4 Table 38-41.

Canonical Correspondence Analysis

In CCA and forward selection of environmental variables with the dune grassland data the Unaffected factor explains the greatest amount of variation in the data. The other time factors *i.e.* years, Short and Medium-term were also significant as well as the factors for On and Adjacent sample areas and log distance. This is set out in Table 28.

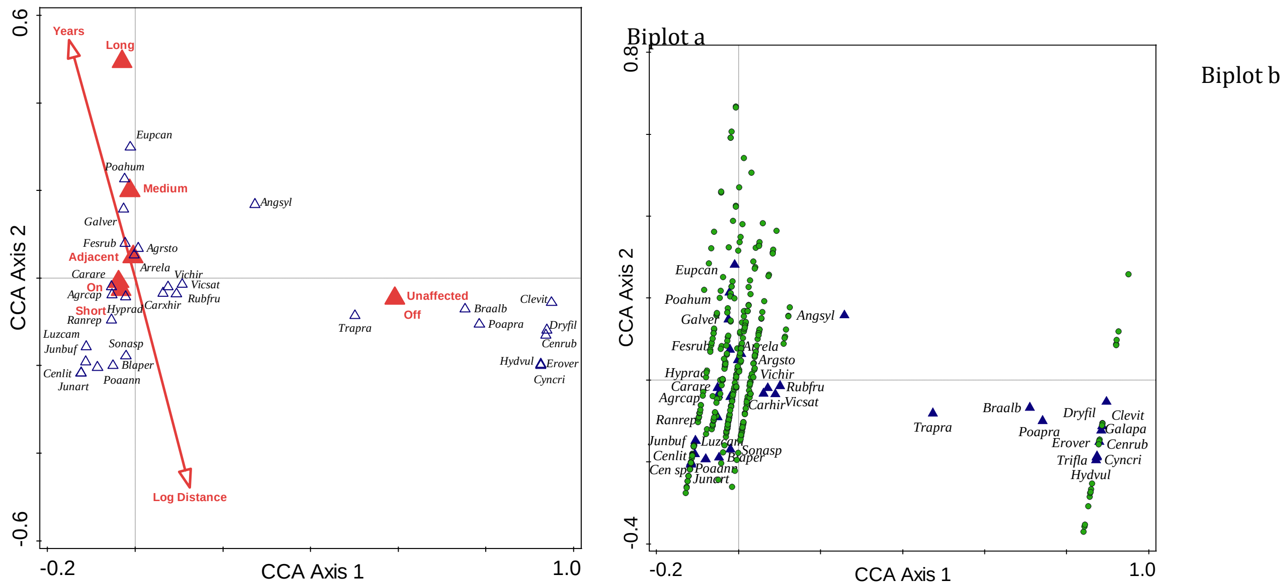
Table 28 - Explanatory value of environmental variables considered in CCA analysis for fixed dunes. Significant effects are given in bold.

Environmental Variable	Explains %	Contribution %	Pseudo-F	P-value	P(adj)
Time since impact - Unaffected	**4**	**27.4**	**13.7**	**0.0002**	**0.00045**
Years	**3.3**	**22.1**	**11.4**	**0.0002**	**0.00036**
Log distance	**2.2**	**15**	**7.9**	**0.0002**	**0.0003**
Sample area - On	**1.9**	**13**	**7**	**0.0002**	**0.00026**
Sample area - Adjacent	**1.9**	**13**	**7**	**0.0002**	**0.00026**
Time since impact -Short	**1.9**	**12.6**	**6.9**	**0.0002**	**0.00023**

Time since impact -Medium	**1.5**	**10**	**5.5**	**0.0002**	**0.00023**

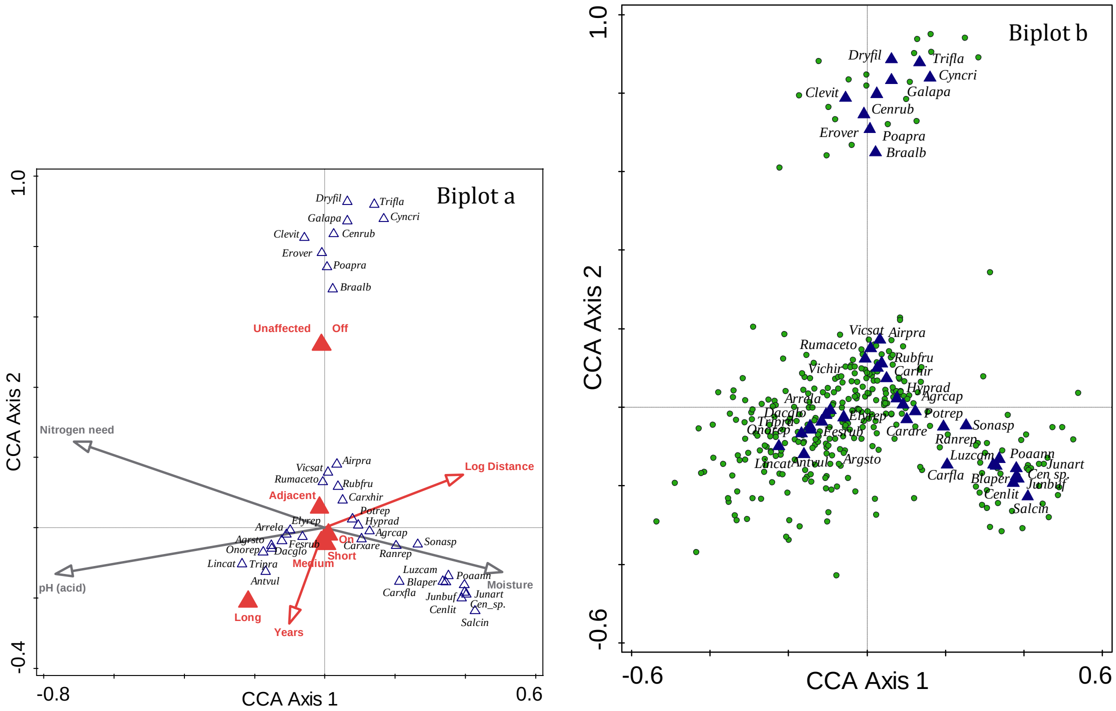
The CCA plot (Figure 81) for the dune grassland shows a clear separation of the explanatory variables of Unaffected and Off which are associated with a mixture of species and shows a possible succession to scrub with the presence of *Clematis vitalba*. The On and Short-term factors are associated with species typical of tall, dune grassland (*i.e.* SD9) with *Arrhenatherum elatius*, *Carex arenaria*, *Festuca rubra*, and *Hypochaeris radicata etc*., although *Ammophila arenaria* is absent. Towards the Adjacent and Medium-term factors, species characteristic of shorter species-rich turf *i.e.* SD8 with *Festuca rubra*, *Galium verum*, *Agrostis capillaris*, *Blackstonia perfoliata*, *Luzula campestris* was noted. The factors for the impacted dune grassland therefore indicate that succession towards a more rank mesotrophic grassland type is at least slowed after construction, and that it can provide opportunities to increase species-richness if the dominance of broad-leaved grasses can be restricted. The loss of *Ammophila arenaria* from the dune grassland is expected, as it is not generally planted in this zone (as part of restoration efforts) and would not naturally grow where sand burial is not frequent).

Figure 81 - Species-environmental variable biplot (a) and species-quadrats biplot (b) using CCA (of the first two axes) with environmental variables selected by forward selection procedure. Total variation is 3.39, explanatory variables account for 11.4% (adjusted explained variation is 10.3%); 1st Axis pseudo- F=14.6, P=0.0002; All Axes pseudo- F=10.4, P=0.0002. The species (shown as blue triangles) are labelled by the first three letters of the generic name and the first three letters of the specific name. Quadrats are shown as green circles with the quadrat number.



The inclusion of Ellenberg values (Hill et al., 1999) as additional explanatory variables in the CCA analysis increased the percentage variation explained by the environmental variables from 11.4% to 30.0%, and the forward selection process identified all five variables as being significant. Of these, pH was the most significant explaining 6.7% of the variation, followed by moisture (4.3%) and nitrogen need (4.4%) (Figure 82).

Figure 82 - Species-environmental variable biplot (a) and species-quadrats biplot (b) using CCA (of the first two axes) with environmental variables selected by forward selection procedure. The biplot includes Ellenberg values for moisture, nitrogen requirement and pH as additional explanatory variables. Total variation is 3.39, explanatory variables account for 26.9% (adjusted explained variation is 24.9%); 1st Axis pseudo- F=30.4, P=0.0002; All Axes pseudo- F=13.0, P=0.0002. The species (shown as blue triangles) are labelled by the first three letters of the generic name and the first three letters of the specific name. Quadrats are shown as green circles with the quadrat number.

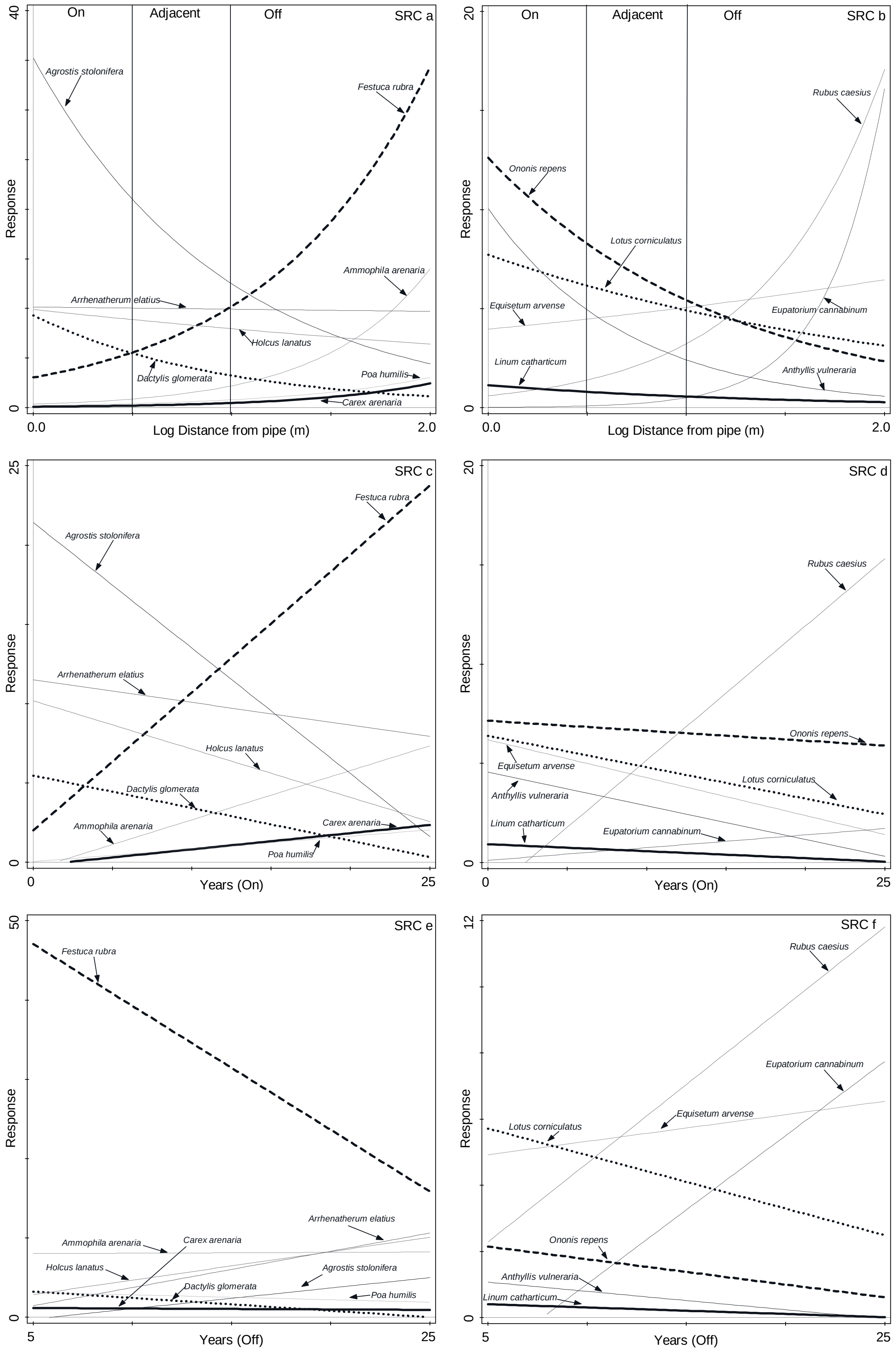


Species Response Curves Distance and Time

The Species Response Curves for the dune grassland uses a Generalised Linear Model (Figure 83). *Ammophila arenaria* is almost absent from On (and Adjacent) to the pipeline and increasing to around 15% in the Off sample area. The loss of *Ammophila arenaria* from the dune grassland On the pipeline is expected, as it is not generally planted in this zone (as part of restoration efforts) and would not naturally grow very vigorously where sand burial is not frequent. The SRC showed that *Agrostis stolonifera* (which was found at *c.* 35% On the pipeline) was replaced by *Festuca rubra* which strongly increased with distance from the pipe. The cover of *Arrhenatherum elatius* remained fairly constant with distance. Both *Dactylis glomerata* and *Holcus lanatus* showed a slight decrease in cover with distance for example cover of *Dactylis glomerata* fell from 10% to 2%. As with the fixed dunes the pipeline construction area supported a higher cover of species from the plant family Fabaceae. *Anthyllis vulneraria* and *Ononis repens* both had a strong response with their cover falling from around 10-12% On the pipeline to 1-3% Off of it. There was also an increase in the cover of woody species (as represented by *Rubus caesius*). This species showed a strong increase in cover with distance with the disturbed pipe having a low cover around 1-2% compared to *c.* 17% Off of it. There was also an increase in cover of tall-herbs *i.e. Eupatorium cannabinum* which is absent from On the pipeline increasing in cover to *c.* 16% Off of the pipeline.

On the pipeline *Festuca rubra* showed a rapid increase in cover with years, from *c.* 2% after installation increasing to 6% by 5 years, 11% by 10 years, 15% by 15 years and 25% by 25 years. Off the pipeline the trend for cover showed *Festuca rubra* decreased over time. In contrast *Agrostis stolonifera* showed a rapid decrease in cover On the pipeline from *c.* 21% to 3% over the 25 year sample period. Off the pipeline this species showed a gradual increase with a maximum cover of 5%. *Arrhenatherum elatius*, *Dactylis glomerata* and *Holcus lanatus* all showed a decrease in cover with time, although this was only by a few percent over the 25 year period so was not considered significant. In the Off sample area *Arrhenatherum elatius* and *Holcus lanatus* both showed a slight increase in cover while *Dactylis glomerata* showed a reduction. *Ammophila arenaria* showed an increase in cover reaching a maximum cover of 8% by 25 years, although there was a delay of 2-3 years before it started to re-establish itself. Most herb species in this zone showed a reduction in cover with time On the pipeline, in particular members of the plant family Fabaceae (as noted previously). One exception was *Rubus caesius* which showed a strong increase after an initial delay (2-3 years) in establishment, with its cover increasing from 2% after 5 years, 6% by 10 years, 10% by 15 years and 20% by 25 years. Off the pipeline similar trends were noted for each of the species with the exception of *Equisetum arvense* which showed a reduction in cover On the pipeline but an increase Off of it.

Figure 83 - Species Response Curves (SRC) of log distance from the pipeline (a & b), years On the pipeline (b & d), years Off the pipeline (e & f) with typical dune grassland species. The plot uses a poisson response distribution and a linear predictor. The response value indicates species abundance. For log distance an indication of the sample area (On, Adjacent and Off) has been given.

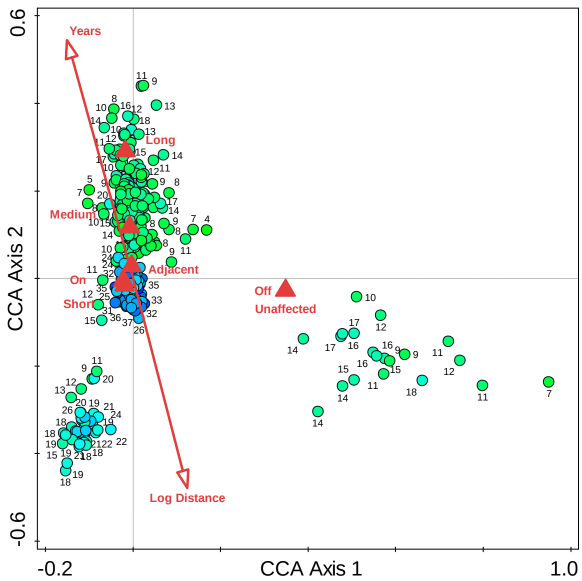


Species Diversity

Hypothesis 57 – [There will be an increase in species-richness On the pipeline, at least in the Short-term. In the Long-term/ Unaffected areas species-richness is likely to be lower].

The species diversity diagram shows that the quadrats with the greatest number of species (20-35 species) are associated with the On and Short-term factors (Figure 84) – supporting the hypothesis. The species-rich quadrats (15-22 species) shown in the bottom-left section of the plot are associated with a higher moisture content (when considered with data from the Ellenberg values). The Long-term and Unaffected/ Off factors are associated with quadrats with between 9-18 species and are typically those with dominant *Arrhenatherum elatius*.

Figure 84 - Species diversity diagram showing species number in quadrats from the dune grassland. Green circles indicate low species-richness, while blue indicate high-species richness within the zone; numbers are the actual number of species in the quadrat.



No nationally rare plant species were recorded in this zone. Two nationally scarce species *Centaurium littorale* and *Festuca arenaria* were recorded in the dune grassland. *Centaurium littorale* was recorded in 29 quadrats at Talacre Warren. These records were all from the historical data set and were recorded within 5 years of the pipeline installation. The record for *Festuca arenaria* was from a quadrat at Redcar On the pipeline in the Short-term. At Redcar, *Astragalus danicus* listed as Endangered (Stroh et al., 2014) was recorded in 5 quadrats[59] in the dune grassland (all On the pipeline). As with its occurrence in the fixed dunes it was associated with short swards in vegetation referable to the NVC type SD8 *Festuca rubra-Galium verum* fixed dune grassland. Two species listed as Near Threatened (Stroh et al., 2014) were recorded in this zone, namely *Carlina vulgaris* (recorded in one quadrat at Redcar adjacent to the pipe), and

[59] Although it was found as a locally frequent component On the pipeline in the fixed dunes

Potentilla erecta (recorded in two quadrats at Redcar On the pipe in the Short-term). No plant species listed from Talacre Warren were listed on the Vascular Plant Red Data List for Wales (Dines, 2008).

Three non-native plant species were recorded in this zone, *Aesculus hippocastanum*, *Oenothera glazioviana*, and *Senecio squalidus*. *Aesculus hippocastanum* was recorded at Talacre Warren (Off the pipeline). *Oenothera glazioviana* and *Senecio squalidus* were recorded at both sites. In addition, there is a large area of *Hippophae rhamnoides* at Redcar along the older pipeline and scattered saplings in the dune grassland along the younger pipe.

4.6.2 Ecosystem Function

Dune grassland vegetation was recorded at Talacre Warren and Coatham Common. For the purposes of this study, dune grassland, includes vegetation where *Arrhenatherum elatius* is dominant or abundant in the sward *i.e.* SD9 and sand dune variants of MG1[60]. No dune grassland was recorded at Tetney Marshes as the dunes are restricted in extent to just a narrow stretch along the shoreline (with mobile and fixed dunes), behind which is a large area of saltmarsh vegetation. The largest area of dune grassland was recorded at Redcar, where it covered approximately 25% of the survey area and extended for approximately 450m along the Project Breagh pipeline and 90m along the AMCO CATS pipe. At Talacre Warren, dune grassland vegetation types accounted for a quarter of the site. Along the pipeline it has developed in the flat area behind the dune ridges extending for approximately 70m. In the Adjacent and Off sample areas, as well as dominating the flat area, it has also developed on the north-face of the landward dune ridge.

Dune grassland and mesotrophic grassland (SD9 and MG1) at each of the study sites in 2015/2016 is given Table 29. Due to differences in the size of the working width (*i.e.* On sample area), the habitat areas (ha) are not directly comparable between sites, therefore the habitat resource is also provided as a percentage of the total site area.

Table 29 - Extent (ha and % of the total area) of the dune grassland and mesotrophic grassland across study sites in 2015-16.

Site	Area (ha) in 2015-16	% of survey area
Redcar	4.6	24.0
Talacre Warren	1.1	26.0
Tetney Marshes	0.0	0.0
Total habitat area surveyed in 2015-16 (ha)		**5.7**
Proportion of total survey area (%)		**13.9**

[60] MG1 *Arrhenatherum elatius* grassland

Hypothesis 58 – [The extent (ha) of dune grassland/ mesotrophic swards, will initially decrease as a result of disturbance, but it is expected to return to (or exceed) pre-construction levels by the Medium- to Long-term].

Talacre Warren

Analysis of the habitat maps at Talacre Warren dunes since the pre-construction survey in 1991 (Ashall et al., 1991) allows the change in area of dune grassland and mesotrophic grassland to be documented. Table 30 shows the extent (ha) of these vegetation types and as a percentage of the total for each sample area *i.e.* On, Adjacent and Off the pipeline.

Table 30 - The extent (ha and % of total habitat resource) of dune grassland and mesotrophic grassland at Talacre Warren over 25 years following the installation of a pipeline.

	1991 (Ashall et al., 1991)			2000(Carter Ecological Limited, 2000)			2015-16		
Habitat extent (ha)	**On**	**Adj**	**Off**	**On**	**Adj**	**Off**	**On**	**Adj**	**Off**
Dune grassland	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.4	0.4
Mesotrophic grassland	0.4	0.6	0.6	0.0	0.0	0.0	0.0	0.1	0.1
Habitat extent (%)	**On**	**Adj**	**Off**	**On**	**Adj**	**Off**	**On**	**Adj**	**Off**
Dune grassland	0	0	0	0	0	0	22	23	22
Mesotrophic grassland	49	43	35	0	0	0	2	6	3

In 1991 and 2000, dune grassland was absent from the survey area at Talacre Warren but had increased to 22-23% in all sample areas by 2015-16 –supporting hypothesis 58. This increase appears to be a successional change from the fixed dune vegetation which had been the dominant vegetation type in 2000. In 1991 mesotrophic grassland was recorded in the area behind the landward dune ridge and accounted for nearly half the vegetation recorded on the pipeline route, following pipeline installation in 2000, this vegetation type had been lost from the pipeline – supporting the hypothesis. This loss in this habitat type could be attributed to construction as the survey was only 5 years following the pipeline installation and it is possible that the mesotrophic grassland had not yet res-established itself. In 2016, mesotrophic grassland represented only a small proportion of the grassland on the pipeline and it is probable that the combination of the pipeline installation and ongoing habitat management (annual grass cutting) by the eni Liverpool Bay Operating Company has restricted the development of this vegetation type.

Coatham Sands, Redcar

At Redcar, it is a more complex picture. The cover of dune grassland (SD9) in all three sample areas has decreased between 2000 and 2016, with the greatest reduction noted On the pipeline (a decrease of 31%). In contrast, there has been an increase by 18% (On the pipeline) in dune grassland/ mesotrophic grassland (*i.e.* SD9/MG1) showing ongoing successional changes following pipeline installation towards a mesotrophic sward. A similar increase was also noted in the Adjacent sample area (increase of 12%), but in the Off sample area the increase was much smaller (1.1%) indicating much more stable conditions. It can therefore be summarised that the pipeline installation, when not followed by management, has increased the rate of successional change of dune grassland to mesotrophic grassland On and Adjacent to the pipeline. The decrease in dune grassland and subsequent successional change to mesotrophic grassland supports the hypothesis.

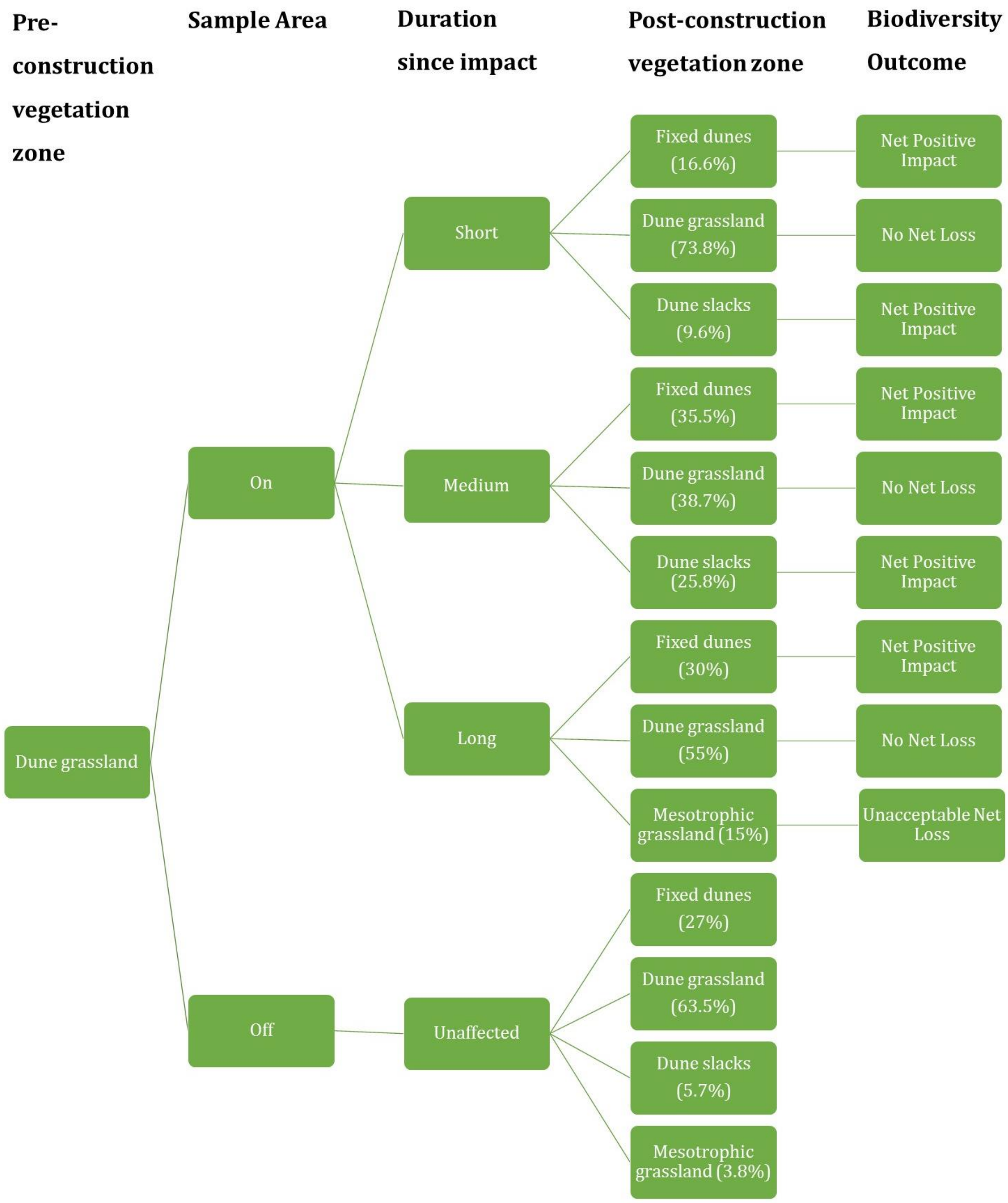
Table 31 - The extent (ha and % of total habitat resource) of dune grassland and mesotrophic grassland at Redcar since 2009 following the installation of the Project Breagh pipeline and construction compound for the Teesside OWF.

	2009			2016		
Habitat extent (ha)	**On**	**Adj**	**Off**	**On**	**Adj**	**Off**
Dune grassland	2.3	2.0	1.6	0.3	0.3	0.2
Dune grassland/ mesotrophic grassland	0.7	0.6	0.6	1.8	1.3	0.7
Habitat extent (%)	**On**	**Adj**	**Off**	**On**	**Adj**	**Off**
Dune grassland	35	32	26	4	4	3
Dune grassland/ mesotrophic grassland	11	9	10	28	21	11

4.6.3 Outcomes of Recovery

Hypotheses 59 – [In the dune grassland, vegetation recovery will quickly respond with vegetation typical of dune grassland swards developing in the Short-term. Where impacts are greater recovery may take until the Medium-term. In the Long-term, where managed, dune grassland will persist; but where left, succession may result in mesotrophic grassland or scrub]. The recovery outcome of 496 quadrats classified as dune grassland prior to construction is shown in Figure 85 and supports this hypothesis. In the Short-term, On the pipeline the majority of quadrats (74%) re-established themselves as dune grassland (No Net Loss); although more open conditions with fixed dune vegetation was noted in 11% (55) of the quadrats. The change from dune grassland is likely to be either an Acceptable Net Loss or Net Positive Impact, as fixed dunes are typically more species-rich and support a greater number of scarce and rare plants, in particular those that prefer open conditions. There were also 32 quadrats (10%) where dune slack vegetation had been established in former species-poor dune grassland/ mesotrophic grassland. This would also be considered as a Net Positive Impact. Most of these occurrences were recorded at Talacre Warren where specific post-construction restoration and subsequent management have taken place. In the Medium-term the outcome of vegetation change following construction was more evenly split with fixed dunes and dune grassland being roughly equal, and dune slack vegetation recorded in 25% of the quadrats. In the Long-term, 55% of the quadrats were classified as dune grassland, and there was evidence of succession to a more species-poor mesotrophic sward with 15% of the quadrats being defined as MG1[61]. In the Unaffected vegetation 64% of the quadrats remained as dune grassland but fixed dunes, dune slacks and mesotrophic grassland vegetation types were also recorded.

Figure 85 - Likely vegetation outcomes of dune grassland following construction, based on a comparison of pre-construction vegetation types with current vegetation condition. Percentage values given represent the proportion of quadrats within each sample area and time since impact that result in each given post-construction vegetation type. The biodiversity outcome is based on those outlined in Theme 3 *Section 1.7.3.*



[61] MG1 *Arrhenatherum elatius* grassland

4.7 Results – Dune Slacks

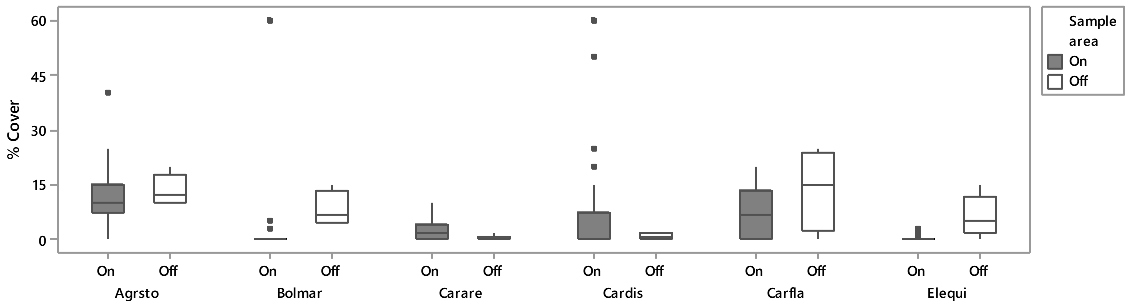
4.7.1 Vegetation Composition and Structure

The surveys in the dune slacks recorded 93 species, of which 81 were vascular plants and 12 were bryophytes. Mean species numbers On and Off the pipe were similar for the sample areas (On = 15.1 species; and Off = 16.4 species) and were not significant when analysed using a GLM with sample area. Mean species numbers for time since impact were also similar (Short = 14.6 species; Medium = 15.7 species; Long = 7.0; and Unaffected = 16.4 species) and not significant. The most species recorded in an individual quadrat in this zone was 30.

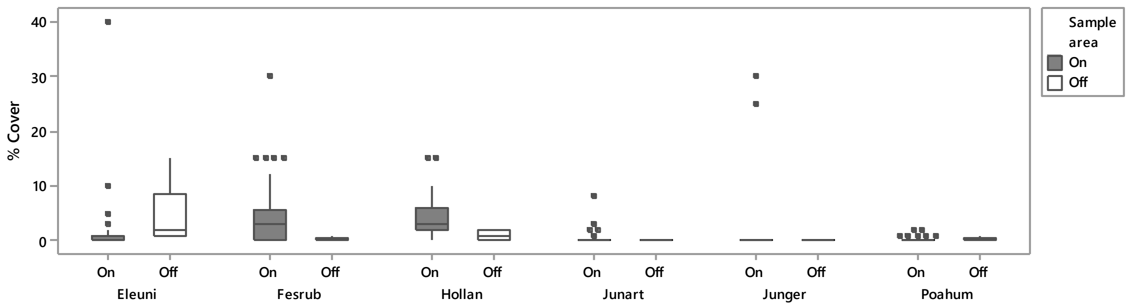
The most frequent species, *Agrostis stolonifera* was recorded in 97.8% of the quadrats in this zone. Boxplots showing cover of key species in this zone by sample area and time since impact are given in Figures 86-89. The boxplots show clear preferences (in terms of cover) for the main brackish dune slack species. *Bolboschoenus maritimus* was recorded almost entirely Off the pipeline (which was similarly to the findings in the mid-upper saltmarsh where it is also present). A similar result for the Off sample area was noted for *Eleocharis quinqueflora* and *Eleocharis uniglumis*. *Carex flacca* also showed a preference for the Off sample area although this species is tolerant of both damp and dry conditions. In contrast *Carex distans* appeared to prefer the On sample area. There also appears to be an increase in the cover of more generalist grasses *i.e. Agrostis stolonifera*, *Festuca rubra* and *Holcus lanatus* although all three species are found as typical components of dune slacks. As with the other vegetation zones members of Fabaceae appeared to show a preference to the disturbed On sample area. While the wet tolerant herbs *i.e. Hydrocotyle vulgaris* and *Glaux maritima* appeared to prefer the Off sample area. Interesting *Syntrichia ruralis* subsp. *ruraliformis* which typically prefers loose sand in unstable coastal dunes (Atherton et al., 2010) showed a preference to the undisturbed Off sample area No clear preference was noted for the orchid species *Dactylorhiza purpurella* or the moss *Calliergon cuspidatum* which is a key component of several dune slack vegetation communities (Figures 88-89).

Similar results were recorded when considering the species with time since impact. There was a clear preference for the Unaffected area by *Bolboschoenus maritimus*, *Carex flacca*, *Eleocharis quinqueflora* and *Eleocharis uniglumis*, while *Carex distans* showed a preference for the Short-term. However, the results for the other graminoids were less clear. Similarly, for the herbs, *Lotus corniculatus* and *Ononis repens* had a higher cover in the Short-term quadrats, while *Hydrocotyle vulgaris* and *Syntrichia ruralis* subsp. *ruraliformis* had a higher cover in Unaffected quadrats (Figures 88-89).

Figure 86 - Boxplots showing the cover of key graminoid dune slack species with sample area (On and Off).

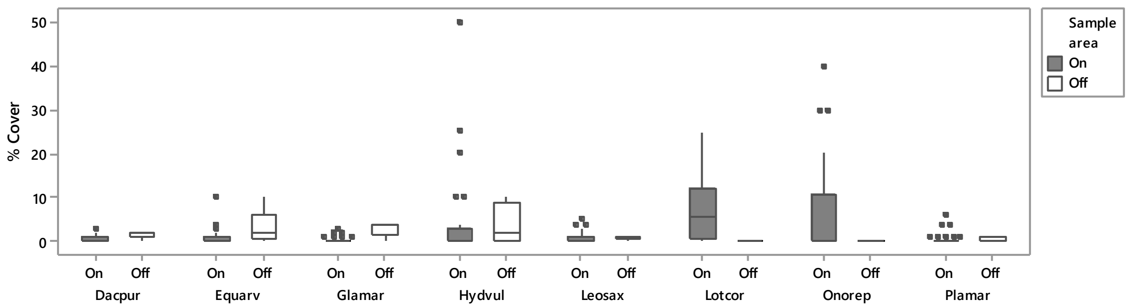


Species - Agrostis stolonifera (Agrsto); Bolboschoenus maritimus (Bolmar); Carex arenaria (Carare); Carex distans (Cardis); Carex flacca (Carfla), Eleocharis quinqueflora (Elequi)

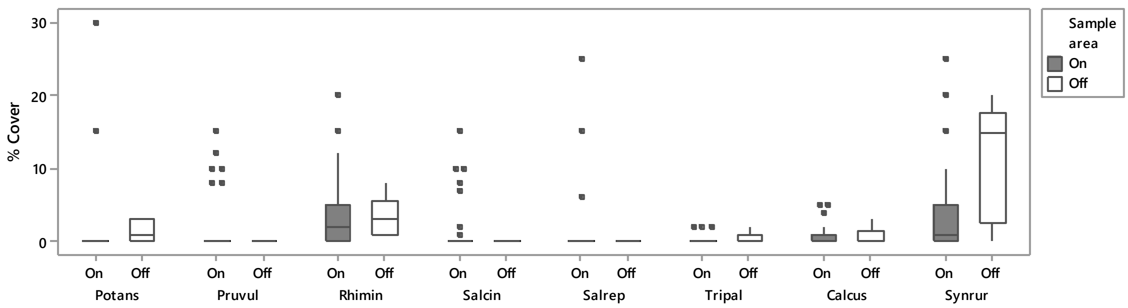


Eleocharis uniglumis (Eleuni); Festuca rubra (Fesrub); Holcus lanatus (Hollan); Juncus articulatus (Junart); Juncus gerardii (Junger); Poa humilis (Poahum)

Figure 87 - Boxplots showing the cover of key herbs/ bryophytes dune slack species with sample area (On and Off).



Species - Dactylorhiza purpurella (Dacpur); Equisetum arvense (Equarv); Glaux maritima (Glamar); Hydrocotyle vulgaris (Hydvul); Leontodon saxatilis (Leosax); Ononis repens (Onorep); Plantago maritima (Plamar)



Species - Potentilla anserina (Potans); Prunella vulgaris (Pruvul); Rhinanthus minor (Rhimin); Salix cinerea (Salcin); Salix repens (Salrep); Triglochin palustre (Tripal); Calliergon cuspidatum (Calcus); Syntrichia ruralis subsp. ruraliformis (Synrur)

Figure 88 - Boxplots showing the cover of key graminoids dune grassland species with time since impact (Short-term and Unaffected).

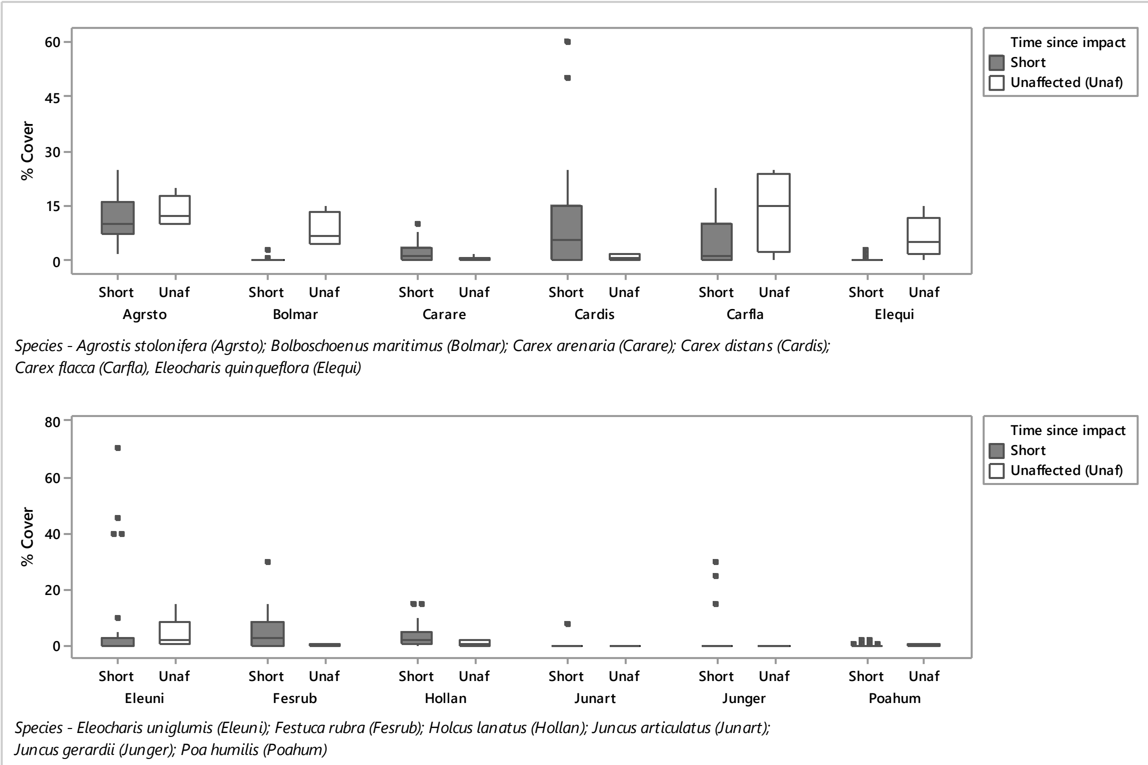
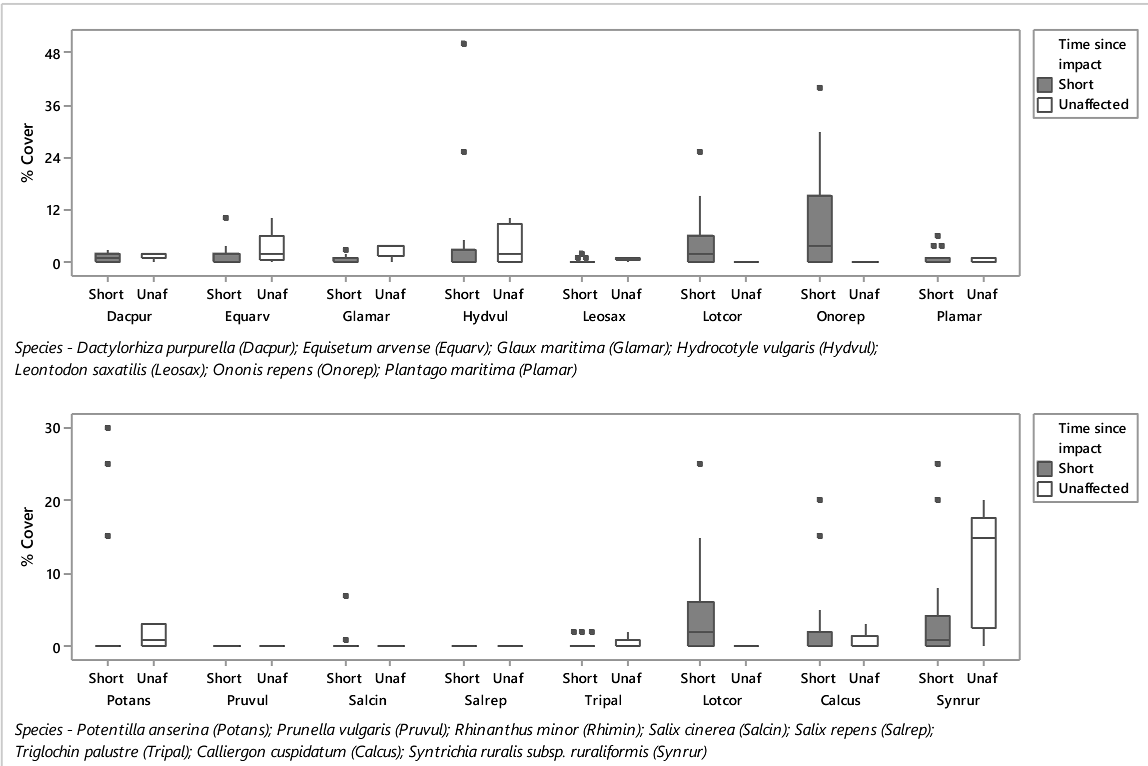


Figure 89 - Boxplots showing the cover of key herbs/ bryophytes dune slack species with time since impact (Short-term and Unaffected).



General Linear Model and Tukey Pairwise Comparison Test

Hypothesis 60– [If the water-table is lowered (and the dunes became drier) there is an expected loss or significant reduction in cover of typical wetland graminoids and herbs]. The wetland graminoids, herbs and mosses *Bolboschoenus maritimus*, *Carex nigra*, *Dactylorhiza purpurella*, *Eleocharis quinqueflora*, *Glaux maritima*, *Pulicaria dysenterica*, *Scorzoneroides autumnalis*, *Hypnum cupressiforme* and *Rhytidiadelphus squarrosus* all had a significantly reduced cover On the pipeline – supporting this hypothesis. When time since impact is considered five of these species had significantly higher cover in the Unaffected area compared to the pipeline during the Short and Medium-term (supporting the hypothesis), these were *Bolboschoenus maritimus*, *Eleocharis quinqueflora*, *Glaux maritima*, *Pulicaria dysenterica*, and *Hypnum cupressiforme*.

Hypothesis 61 – [Where the water-table is lowered (and the dunes become drier), cover of graminoids and herbs that are more tolerant to drier conditions will increase]. The grasses *Anthoxanthum odoratum*, *Holcus lanatus* and herbs *Centaurium erythraea*, *Euphrasia* agg., *Lotus corniculatus*, *Potentilla reptans*, *Prunella vulgaris* all had a significantly higher cover On the pipeline – supporting this hypothesis. There was also a significant increase in cover of *Rubus caesius, Salix cinerea* and *Salix repens* along the pipeline. However, the cover of the above species were not significantly different over time since impact (disproving this part of the hypothesis).

Hypothesis 62 - [Cover of bare ground will increase On the pipeline, at least in the Short-term]. The data disproves this hypothesis, with the cover of bare ground being significantly less On the pipe, and over time in the Short and Medium-term compared to the Unaffected vegetation. Total vegetation cover, graminoid and herb cover were not significant for sample area or time since impact. The total cover of moss species was significantly less On the pipe, and over time in the Short and Medium-term compared to the Unaffected vegetation.

A full summary of the results of the GLM and Tukey Pairwise Comparison for embryo/ mobile dune vegetation is given in Appendix 4 Tables 42-45.

Canonical Correspondence Analysis

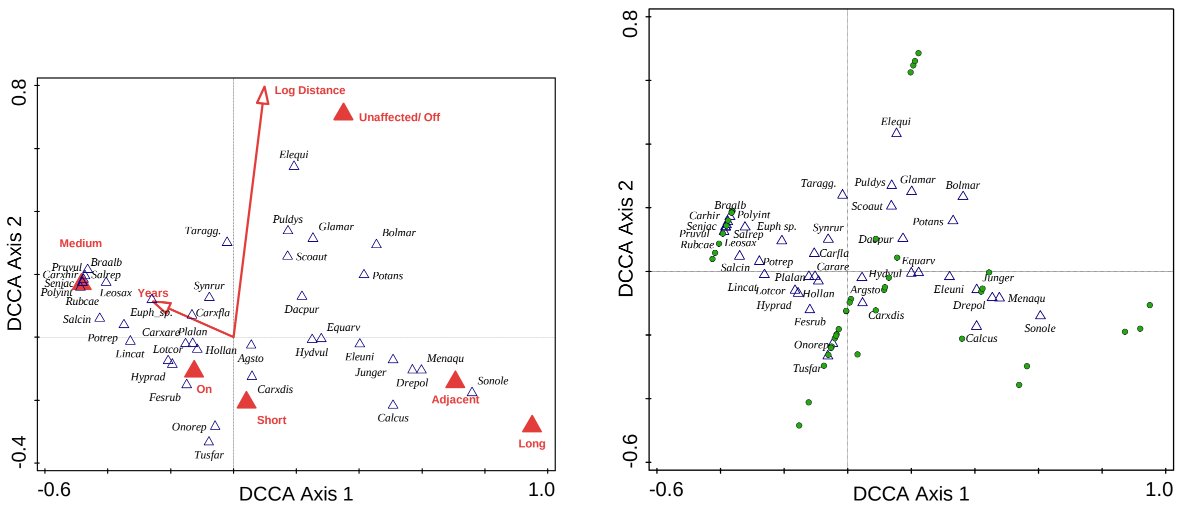
In CCA and forward selection of environmental variables with the dune slacks data the Medium-term factor explains the greatest amount of variation in the data. All of the time since impact factors, were significant, along with years and log distance. This is set out in Table 38.

Table 32 - Explanatory value of environmental variables considered in CCA analysis for fixed dunes. Significant effects are given in bold.

Environmental Variable	Explains %	Contribution %	Pseudo-F	P-value	P(adj)
Time since impact - Medium	**10.7**	**33.5**	**5.1**	**0.0002**	**0.0006**
Years	**9**	**28.4**	**4.7**	**0.0002**	**0.0006**
Log distance	**5.3**	**16.5**	**2.9**	**0.0002**	**0.00045**
Time since impact - Short	**3**	**9.4**	**1.7**	**0.0102**	**0.02295**
Sample area - Adjacent	2.5	7.7	1.4	0.0736	0.13248
Time since impact - Unaffected	1.4	4.4	0.8	0.746	0.746

The CCA plot (not shown) had a strong 'arch effect' (*Section 2.4.3*), therefore a DCCA[62] was completed and the resulting plot is shown in Figure 90. The biplot shows the explanatory variables for the On factor are associated with species more typical of the fixed dunes with *Carex arenaria, Festuca rubra*, *Holcus lanatus*, *Hypochaeris radicata*, *Lotus corniculatus* and *Plantago lanceolata*. With an increase in years there is an increase in species typical of more species-rich swards such as *Carex flacca*, *Euphrasia* agg., *Leontodon saxatilis* and *Linum catharticum.* The Medium-term factor appears to be associated with an increase in scrub species namely *Rubus caesius*, *Salix cinerea* and *Salix repens*, which corresponds to an increased maturity of dunes slacks, so too does the presence of *Polypodium interjectum*. The Unaffected/ Off, Adjacent and Long-term factors are associated with increased moisture. Interestingly, several of the species associated with Unaffected/ Off are salt-tolerant species (typical of brackish conditions) namely *Bolboschoenus maritimus*, *Eleocharis quinqueflora* and *Glaux maritima*. In contrast, species associated with the Adjacent and Long-term factors appear to be typical of fresh-water marshes *e.g. Calliergonella cuspidatum*, *Cardamine pratensis*, *Eleocharis uniglumis*, *Hydrocotyle vulgaris and Mentha aquatica*; although *Drepanocladus* cf. *polygamus* and *Juncus gerardii* were also recorded here and are salt-tolerant.

Figure 90 - Species-environmental variable biplot (a) and species-quadrats biplot (b) using DCCA (of the first two axes) with environmental variables selected by forward selection procedure. Total variation is 3.07, explanatory variables account for 31.9% (adjusted explained variation is 21.1%); 1st Axis pseudo- F=5.9, P=0.0002; All Axes pseudo- F=3.0, P=0.0002. The species (shown as blue triangles) are labelled by the first three letters of the generic name and the first three letters of the specific name. Quadrats are shown as green circles with the quadrat number.



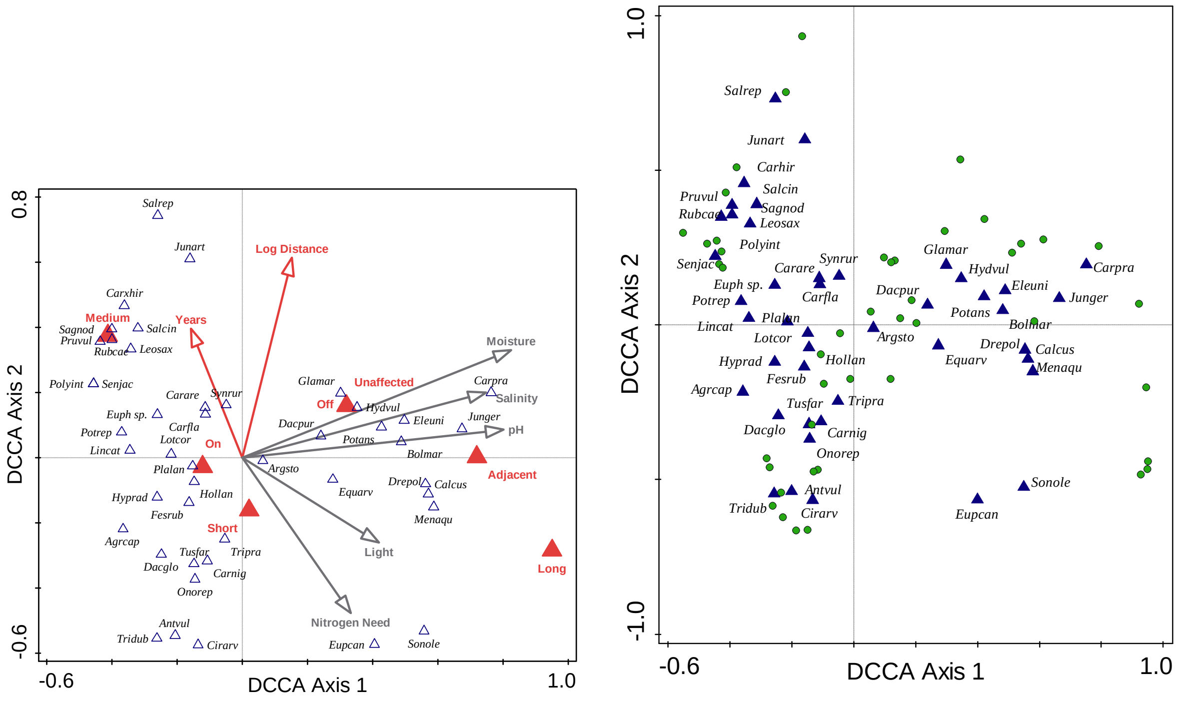
The inclusion of the Ellenberg values (Hill et al., 1999) as additional explanatory variables in the DCCA analysis (Figure 91) increased the percentage variation explained from 31.9% to 47.5%, and the forward selection process identified all five variables as being significant. Of these, moisture was the most significant explaining 11.9% of the variation. The plot shows that the

---

62 Detrending with 2nd order polynomial

explanatory variables of On, Short and Medium-term are situated towards the drier part of the moisture gradient. The Adjacent, Off, Long-term and Unaffected factors are found with the greatest moisture values, as well as increased salinity and pH.

Figure 91 - Species-environmental variable biplot (a) and species-quadrats biplot (b) using DCCA (of the first two axes) with environmental variables selected by forward selection procedure. The biplot includes Ellenberg values for moisture, pH, light, nitrogen requirement and salinity as additional explanatory variables. Total variation is 3.07, explanatory variables account for 47.5% (adjusted explained variation is 30.0%); 1st Axis pseudo- F=5.8, P=0.0002; All Axes pseudo- F=2.7, P=0.0002. The species (shown as blue triangles) are labelled by the first three letters of the generic name and the first three letters of the specific name. Quadrats are shown as green circles with the quadrat number.



Species Response Curves Distance and Time

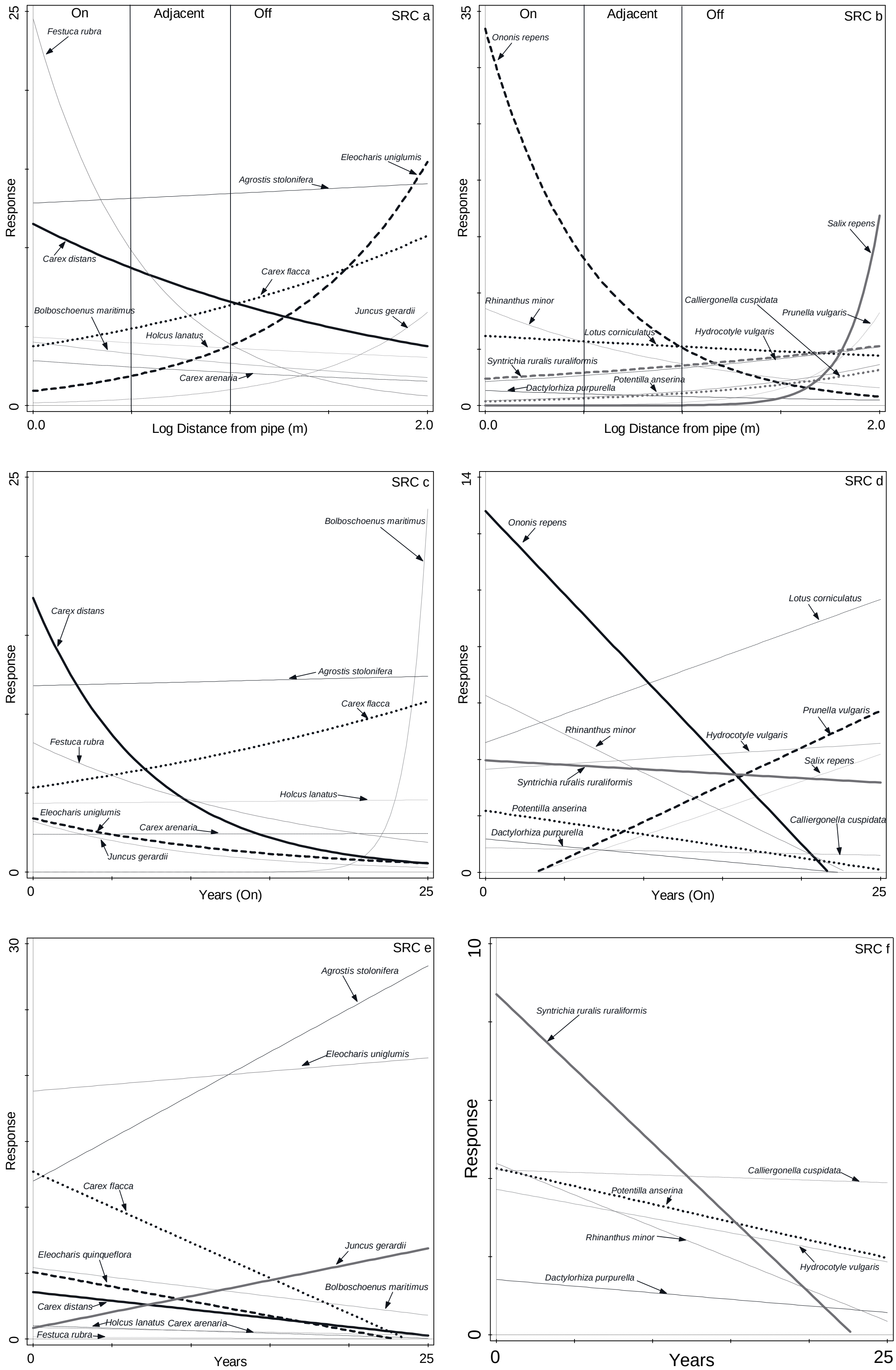
The Species Response Curves for the dune slacks uses a Generalised Linear Model (Figure 92). *Festuca rubra* shows a strong response in terms of cover decreasing with distance, from *c.* 25% On the pipe compared to 1-2% Off of it. *Carex distans* also showed a reduction in cover with increased distance from the pipe from 12% to 4%. The wet tolerant species such as *Carex flacca*, *Eleocharis uniglumis* and *Juncus gerardii* increased with distance *e.g.* *Eleocharis uniglumis* is found at *c.* 1-2% On the pipeline compared to *c.* 16% Off of it. *Ononis repens* showed a rapid decline with distance, with cove On the pipeline being *c.* 33% decreasing to 1-2% Off of it. There was also a reduction in cover of *Rhinanthus minor*. *Salix repens* showed a strong preference to the undisturbed Off sample area with it being absent On/Adjacent to the pipe. Other species such as *Calliergon cuspidatum*, *Hydrocotyle vulgaris*, *Potentilla anserina* and *Syntrichia ruralis* subsp. *ruraliformis* all increased in cover with distance but more gradually (Figure 92a&b).

When considering the change in cover over time data from the On sample area was compared to the Off sample area. For the graminoids *Carex distans* showed a strong response, with its cover decreasing sharply over the first 5 years (*c.* 17% to 7%) to being only found at a low-level of abundance by 15 years. In the undisturbed Off sample area *Carex distans* showed a more gradual decrease in cover from 4% to 0% over 25 years. In contrast, *Bolboschoenus maritimus* was absent from On the pipeline until 20 years when it increased sharply to *c.* 22%. In the Off sample area, it showed a gradual reduction in cover with time from 5% to 3%. *Festuca rubra* showed a reduction over time from 8% to 3% over 25 years, whereas in the Off sample area it is more or less absent. Similarly, *Carex arenaria* and *Holcus lanatus* have an elevated cover On the pipeline (3-4%) compared to Off of it (1%). On the pipeline *Juncus gerardii* decreased in cover over time but in the undisturbed Off section it increased. *Eleocharis quinqueflora* was not found On the pipeline in a sufficient amount to be plotted, indicating that this species preferred the undisturbed Off sample area (

Figure 92c&e).

Trends for the herbs/ mosses are more difficult to explain as several of the key species were absent from either On or Off the pipeline or were found in fewer quadrats so were not plotted. It may be that these species simply did prefer the disturbance caused by the pipeline installation as they are typically all more generalist dune species. *Ononis repens* showed a rapid decrease in cover over time from 13% after installation to being absent after 20 years (10% by 5 years, 6% by 10 years, 4% by 15 years). This species was not recorded in the Off sample area. Cover of *Rhinanthus minor* also decreased On the pipeline from 6% after installation to being absent after 20 years. This decrease was similar to that recorded in the Off sample area. There was an increases of both *Lotus corniculatus* and *Prunella vulgaris* over time On the pipeline, but again these species were not found in sufficient quantities Off the pipeline to be plotted. *Salix repens* was found On the pipeline but after an initial delay of *c.* 5 years, before it increased in cover.

Figure 92 - Species Response Curves (SRC) of log distance from the pipeline (a & b), years On the pipeline (b & d), years Off the pipeline (e & f) with typical dune slack species. The plot uses a poisson response distribution and a linear predictor. The response value indicates species abundance. For log distance an indication of the sample area (On, Adjacent and Off) has been given.

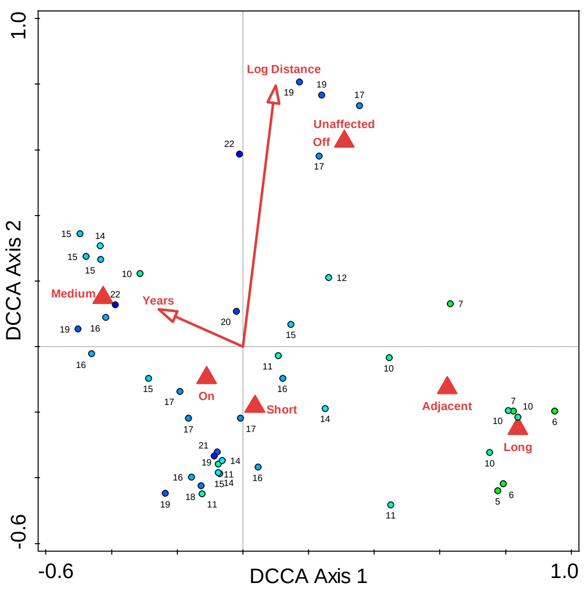


Species Diversity

Hypothesis 63 – [Species-richness will be highest in the Unaffected and Off areas, although there may be an increase in species-richness On the pipeline at least in the Short-term]. The species diversity diagram (Figure 93) shows a clear separation of the factors linked to the moisture, salinity and pH gradients (Figure 91). However, the species numbers associated with the On, Short and Medium-term factors (14-22) are similar to numbers recorded with the Unaffected/ Off factors – supporting the hypothesis. The Adjacent and Long-term factors are less species-rich with between 5 and 10 species.

No nationally rare species were recorded in the dune slacks. One nationally scarce species was recorded in this zone, *Centaurium littorale* which was recorded in a single quadrat on the pipeline at Talacre Warren in Wales. Three Near Threatened species were recorded; *Carlina vulgaris* (recorded in two quadrats On the pipeline); *Hydrocotyle vulgaris* (recorded in 18 quadrats, 13 of these found On the pipe[63]); and *Oenanthe lachenalii* (recorded in two quadrats, Adjacent and Off the pipeline). No plant species listed from Talacre Warren were listed on the Vascular Plant Red Data List for Wales (Dines, 2008). One quadrat in the dune slacks at Redcar contained *Hippophae rhamnoides*. This species is native in some coastal areas but is widely planted for stabilisation purposes. It is an invasive species and can pose a threat to dune vegetation.

Figure 93 - Species diversity diagram using species count showing species number in the dune slacks. Green circles indicate low species-richness, while blue indicate high-species richness within the zone; numbers are the actual number of species in the quadrat.



63 The other 3 records were recorded at Talacre Warren, Wales from on the pipeline.

4.7.2 Ecosystem Function

Areas of dune slack vegetation were restricted to Redcar and Talacre Warren. At Redcar, it is found in discrete patches along the pipelines and in the construction compound associated with the wind farm, with the largest continuous area recorded along and adjacent to the AMCO CATs pipeline. The dune slack communities at Redcar are complex and not readily defined to individual NVC types but show transitions from SD8a[64] to SD16d[65], SD14[66], and SD15[67]. There are also dune slacks which are more brackish and support saltmarsh communities referable to the NVC types SM15[68] and SM16f[69]. At Redcar, there are also considerable areas of swamp vegetation with S4a[70], S20[71], S21a[72] and S21c[73] represented.

At Talacre Warren, the dune slacks are restricted to a small area (0.16 ha) behind the dune ridges which were classified in the 1991 as a mosaic of dune grassland (SD9), mesotrophic grassland (MG1) and *Rubus fruticosus* agg. scrub. The dune slack vegetation at Talacre Warren is referable to the NVC types SD13b[74] and SD16b[75].

The extent of dune slacks (and swamp vegetation) at each of the study sites in 2015/2016 is given in Table 33. Due to differences in the size of the working width (*i.e.* the On sample area), the habitat areas (ha) are not directly comparable between sites, therefore the habitat resource is also provided as a percentage of the total site area.

Table 33 - Extent (ha and % of the total area) of dune slack (and swamp) habitat across study sites in 2015-16.

Site	Area (ha) in 2015-16	% of survey area
Redcar	1.5	12
Talacre Warren	0.2	4
Tetney Marshes	0.0	0
Total habitat area surveyed in 2015-16 (ha)		**1.7**
Proportion of total survey area (%)		**6.2**

Hypothesis 64 – [The extent (ha) of dune slacks is likely to decrease On and Adjacent to the pipeline following construction, unless specific post-construction restoration measures are used to create new areas of this sensitive habitat type].

64 SD8a *Festuca rubra-Galium verum* fixed dune grassland, typical sub-community
65 SD16d *Salix repens-Holcus lanatus* dune-slack community, *Agrostis stolonifera* sub-community
66 SD14 *Salix repens-Campylium stellatum* dune-slack community
67 SD15 *Salix repens-Calliergon cuspidatum* dune-slack community
68 SM15 *Juncus maritimus-Triglochin maritimum* salt-marsh community
69 SM16f *Festuca rubra* salt-marsh community, *Carex flacca* sub-community
70 S4a *Phragmites australis* swamp and reed-beds, *Phragmites australis* sub-community
71 S20 *Scirpus lacustris* ssp. *tabernaemontani* swamp
72 S21a *Scirpus maritimus* swamp, sub-community dominated by *Scirpus maritimus*
73 S21b *Scirpus maritimus* swamp, *Atriplex prostrata* sub-community
74 SD13b *Sagina nodosa-Bryum pseudotriquetrum* dune-slack community, *Holcus lanatus-Festuca rubra* sub-community
75 SD16b *Salix repens-Holcus lanatus* dune-slack community, *Rubus caesius* sub-community

Talacre Warren

As noted above, the dune slacks at Talacre Warren are restricted to an area behind the dune ridges which were formerly dune grassland/ mesotrophic grassland. The area was subject to sand storage during construction and has since been actively managed to create low-lying ponds and scrapes, with annual grass cutting to prevent the re-establishment of mesotrophic grassland. The quadrat data suggests this area is a mosaic of early successional dune slacks SD13b *Sagina nodosa-Bryum pseudotriquetrum* dune-slack community, *Holcus lanatus-Festuca rubra* sub-community a rare UK NVC type; and SD16b *Salix repens-Holcus lanatus* dune-slack community, *Rubus caesius* sub-community (a community of mature dune slacks). Table 34 shows the extent (ha) of dune vegetation at Talacre Warren and as a percentage of the total for each sample area *i.e.* On, Adjacent and Off the pipeline.

Table 34 - The extent (ha and % of total habitat resource) of dune slacks at Talacre Warren over 25 years following the installation of a pipeline, as recorded in 1991 (Ashall et al.), in 2000 (Carter Ecological Limited) and as part of this study in 2015-16.

	1991			2000			2015-16		
Habitat extent (ha)	**On**	**Adj**	**Off**	**On**	**Adj**	**Off**	**On**	**Adj**	**Off**
Dune slacks	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1
Habitat extent (%)	**On**	**Adj**	**Off**	**On**	**Adj**	**Off**	**On**	**Adj**	**Off**
Dune slacks	0	0	0	0	0	0	0	6	4

Redcar

At Redcar, there has been a loss of dune slack vegetation within the working width, with a 12% reduction in vegetation type (Table 35) – supporting the hypothesis. Much of this loss is from the construction compound associated with the wind farm, where the ground has become disturbed and hard-core laid. This has changed the water-table and substrate and has led to the establishment of ruderals. These areas are unlikely to recover to dune vegetation even in the Long-term. Loss of dune slacks was also recorded along the Project Breagh pipeline, which crossed through approximately 100m of dune slacks. Care was taken to minimise the impact on this sensitive habitat and the working width was reduced to approximately 6.5m (compared to 30m used elsewhere). While there has been a change in vegetation type from a brackish dune slack (SM15/ SM20) to fixed dune/ dune grassland community (SD9a/ SD8a), this area supports a number of the local rarities namely *Astragalus danicus*, *Thalictrum minus* and *Silene gallica*. In the Adjacent sample area, much of the dune slack vegetation was retained, although there appears to be a shift in vegetation type from SM15/ SM20 to MG1a-SD9 in the area immediately adjacent to the pipe along the fenceline. This has probably been caused by members of the public using the dune slacks (rather than fenced pathway) to cut through the dunes to reach the beach. Swamp habitat in the survey area between 2009 and 2016 appears little changed.

Table 35 - The extent (ha and % of total habitat resource) of dune slacks and swamp at Redcar since 2009 following the installation of the Project Breagh pipeline and construction compound for the Teesside OWF.

	2009			2016		
Habitat extent (ha)	**On**	**Adj**	**Off**	**On**	**Adj**	**Off**
Dune slacks	1.6	1.2	0.5	0.7	0.9	0.7
Swamp	0.4	0.4	0.8	0.4	0.4	0.6
Habitat extent (%)	**On**	**Adj**	**Off**	**On**	**Adj**	**Off**
Dune slacks	24	20	8	11	15	11
Swamp	6	6	13	6	7	10

4.7.3 Outcomes of Recovery

Hypothesis 65 – [Where the pipeline influences the water-table making it locally wetter, there will be an increase in dune slack communities; but where it becomes drier, dune grassland or fixed dunes may develop]. The recovery outcome of 91 quadrats classified as dune slacks prior to construction is shown in Figure 78. In the Short-term, after construction 72% of the quadrats were classified as dune grassland (Unacceptable Net Loss) which indicates that the water-table had been negatively influenced by construction causing the drying out of the dunes – supporting the hypothesis. There was also the complete loss of dune slack vegetation (Unacceptable Net Loss) in five quadrats in this zone where hard-core was laid to create a construction compound. However, dune slack vegetation was retained in 20% of the quadrats (No Net Loss). In the Long-term, dune slack vegetation and dune grassland was equally likely. All the dune slack quadrats in the Adjacent and Unaffected sample areas were retained, indicating that construction impacts beyond the working width were minimal.

Figure 94 - Likely vegetation outcomes of dune slack vegetation following construction, based on a comparison of pre-construction vegetation types with current vegetation condition. Percentage values given represent the proportion of quadrats within each sample area and time since impact that result in each given post-construction vegetation type. The biodiversity outcome is based on those outlined in Theme 3 *Section 1.7.3*.

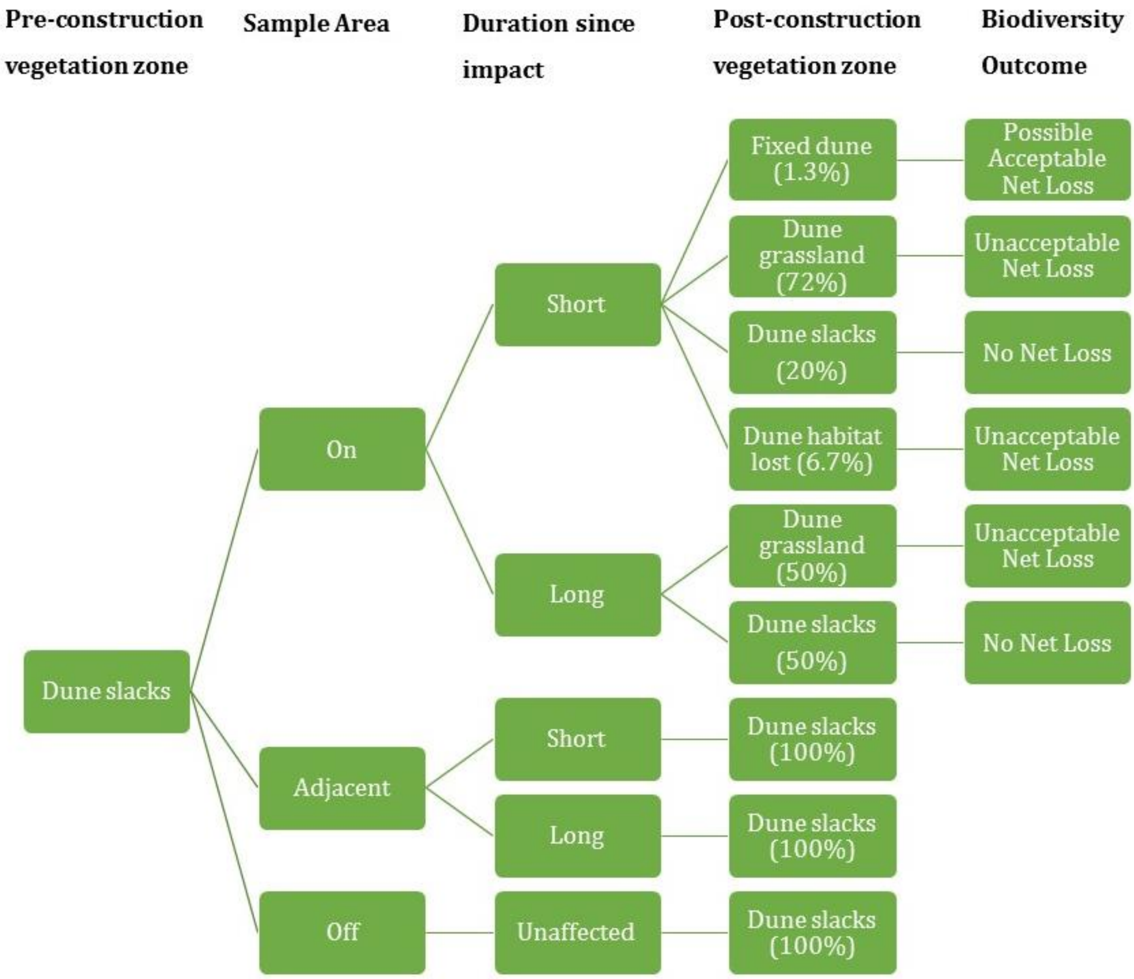


Photo Plate 4 - Sand dune species recorded at case study sites.

Centaurium littorale

Syntrichia ruralis subsp. *ruraliformis*

Astragalus danicus

Eryngium maritimum

Rhinanthus minor

Reseda lutea

Dactylorhiza purpurella

Ophrys apifera

Ammophila arenaria

Silene gallica

Ononis repens

Phleum arenarium

Viola tricolor

Atriplex patula

Euphrasia sp. and *Lotus corniculatus*

4.8 Discussion

4.8.1 Embryo/ Mobile Dunes

Sample Size

Species in the embryo/ mobile dunes were generally poor at producing significant results to support the hypothesis set out in *Section 4.2.3*. Although this may be in part due to the ecology of the zone, it is suspected that the sample size (29 quadrats) was insufficient to pick up any species or vegetation changes. The limited sample size in this zone is due to three main factors:

1) The embryo/ mobile dunes form a narrow band (only a few meters wide) at the top of the beach, meaning it is difficult to physically fit many quadrats in the sample area.

2) The embryo/ mobile dunes are subject to natural disturbance episodes *i.e.* storm events and high-tides. For example, at Talacre Warren, much of the front section of dunes was lost during the winter of 2013.

3) During construction, impacts to the front section of the dunes are often avoided so not to create a breach where tidal ingress could flood inland. At Redcar, Horizontal Directional Drilling (HDD) methods were used to allow trenchless pipeline installation in this zone so avoiding the embryo/ mobile dunes.

One of the key issues with the small sample size was the lack of quadrats from the Short-term, and so changes in the first 10 years following construction could not be assessed. As this zone is subject to frequent natural disturbance episodes it is likely the species respond quickly to the creation of bare ground with the main dominant grasses stimulated by sand burial and the establishment of annuals. Therefore, in the embryo/ mobile dunes the first few years after impact are likely to be the critical recovery window; and in actual fact the 10-year period (used to define the Short-term) would probably not be at a sufficiently fine-scale to detect change.

While a larger dataset may not have produced different outcomes when testing my hypothesis, it would have helped determined whether the results were a true reflection of vegetation change, rather than an artefact of sample size.

Graminoids

Elytrigia juncea and Leymus arenarius

The cover of both *Elytrigia juncea* and *Leymus arenarius* was not significantly different (with sample area or over time since impact) when considered using the GLM. When simply comparing species frequency as presence, from quadrats On or Off the pipeline, *Elytrigia juncea* was present in 40% of the On quadrats, compared to 13% of the Off quadrats; while *Leymus arenarius* was found in 20% of the On quadrats and 17% of the Off quadrats. This suggests that pipeline installation does stimulate *Elytrigia juncea* growth, but that it has little effect on *Leymus arenarius*. This is supported by the SRC (Figure 61), which shows that the cover of *Elytrigia juncea* decreases as you move away from the pipeline. *Leymus arenarius* also showed a weak decrease in cover. Both species develop as part of the initial development of dunes, in areas of unstable sands, where bare ground predominates.

Elytrigia juncea is an embryonic dune species that is capable of growing at the front of the dune system taking advantage of accumulations of sand and organic matter (Rodwell, 2000). It is capable of occasional immersion by the sea and is salt-tolerant to *c.* 6% Benecke (1930 cited in Bond (1952)). Therefore it is often the first of the dune-building species to establish, forming a species-poor vegetation community (SD4). Ranwell (1972) notes that *Elytrigia juncea* propagates readily by seed, with the emerging seedling root rapidly elongating downward to find moist sands. It then sends out horizontal roots close to the sand surface from which tillers are established. Further studies by Harris and Davy (1986) showed that following disturbance multi-node fragments of *Elytrigia juncea* have an advantage over seeds (and single-node fragments) in their ability to produce viable shoots following burial. These multi-node fragments are capable of imposing dormancy of subordinate buds, making more resources available to the dominant shoots, increasing the chance of successful emergence through sand.

Rodwell (2000) notes that this community "*may persist widely as a pioneer vegetation that is continually set back by more disturbance periods of wind and wave erosion*". Therefore, disentangling the effects of the pipeline installation from natural disturbance in areas where *Elytrigia juncea* dominates may not be possible.

Leymus arenarius dominated vegetation (SD5) develops in the zone between the *Elytrigia juncea* and *Ammophila arenaria* communities. It is more salt tolerant than *Elytrigia juncea*, and is capable of surviving in locations with up to 12% salinity, including salt-spray Benecke (1930 cited in Bond (1952)); however, it is susceptible to wind exposure which restricts its growth in the youngest most exposed dunes and is thought to require higher levels of organic matter Géhu and Géhu (1969 cited in Rodwell (2000)). Bond (1952) notes that its growth is through lateral spread, by vegetative extension of runners or the detachment of rhizome fragments. It is most vigorous in loose sand, producing flowers on single large tussocks, where few other species are present. Its growth is adversely affected by competition in particular from *Ammophila arenaria* restricting its extension across the semi-fixed dunes.

The CCA analysis (Figure 59) showed that both *Elytrigia juncea* and *Leymus arenarius* were associated with the Long-term and increased years, which was unexpected. This trend was also noted with the scatterplots for both On and Off the pipeline (Figure 55). Both species, were typically found as small discrete areas, with the most extensive area recorded at Tetney Marshes where pipeline installation occurred in 1970 *i.e.* in the Long-term. Therefore, it is expected that the association of *Elytrigia juncea* and *Leymus arenarius* with increased time in the CCA analysis reflects a site effect that is exaggerated with the small sample size.

Studies in France (Forey et al., 2008) demonstrated that disturbance by sand burial, drives increased species-richness of sand dune communities at a local scale. It showed that sand burial favoured those species that could produce roots and rhizomes in the deposited material.

Ammophila arenaria

Ammophila arenaria is one of three main grasses growing in the embryo and mobile dunes. It was suspected that cover of this species would be higher On the pipeline, as sand disturbance would stimulate growth, however, this hypothesis was disproven with my dataset. Comparing species frequency and presence in quadrats On and Off the pipeline, it was shown that it was recorded in fewer quadrats in the On sample area (60%), compared to the Off (88%), which also disproves the hypothesis. The increase in its cover with distance was also recorded in the SRC (Figure 61).

Ammophila arenaria grows most vigorously in open, mobile and semi-fixed dunes. It is a competitive stress-tolerator (Grime, 2001); growing where there is free-drainage, low nutrients, low organic matter and an absence of a differentiated soil profile (Huiskes, 1979). It is able to survive (and thrives) in mobile sands, and is able to tolerate burial of up to 1m per year, by the rapid production of elongated stem-internodes (Willis et al., 1959). *Ammophila arenaria* is a key species in dune-building, as its tillers enhance sand deposition, and roots and rhizomes stabilise mobile sand.

In the embryo dunes, it is only present as scattered plants, with its seaward expansion limited by its intolerance to immersion by sea water (Proctor, 2013). Studies have shown that it can only grow in substrates with <1% sea salt, while concentrations greater than 1.5% are lethal Benecke (1930 cited in Huiskes (1979)). Further inland, in the mobile and semi-fixed dunes *Ammophila arenaria* becomes the dominant species. Willis et al. (1959), notes that *Ammophila arenaria* forms almost pure stands in heavily accreting areas (referable to the NVC type SD6d), while less mobile areas are more species-rich.

The CCA plot with the Ellenberg values (Figure 60) shows that *Ammophila arenaria* is in close proximity to the Medium-term and Adjacent factors, suggesting it takes some time to return to the sward after pipeline installation. As with the other species the lack of data from the Short-term makes determining the recovery time frames of *Ammophila arenaria* in the embryo/ mobile dunes difficult to interpret. The general trend noted in the scatterplots for *Ammophila arenaria* (Figure

55) shows an increased cover over time On the pipeline (although this includes data from across the vegetation zones).

Carex arenaria

Carex arenaria is typical of areas subject to secondary erosion such as blow-outs (Rodwell, 2000), growing at the base of mobile and yellow dunes and in the transition zone between dune slacks (Noble, 1982). It was expected that its cover would increase following pipeline installation establishing itself in areas of created bare ground. The scatterplots (Figure 55) show a general trend for this species as increasing in cover over time On the pipeline, while in unaffected areas (Off) its cover showed a decrease. The SRC with distance also showed that *Carex arenaria* decreased with distance from the pipeline (Figure 61). However, the GLM for this species did not support the hypothesis. It is suspected that the absence of data from the Short-term strongly influenced this result.

Noble (1982) notes that *Carex arenaria* is a far creeping rhizomatous perennial, with a similar growth form to *Ammophila arenaria.* Both species have a hemicryptophyte and geophyte life-form; since the buds are not only located close to the surface but can remain viable at depths in excess of 100cm. It is suggested that individual severed rhizome fragments may remain alive and viable for more than 10 years even though its shoots and fine roots will have died. This survival ability and its life-form strategy may aid recovery following pipeline installation, with severed rhizome fragments re-growing from stored topsoil and subsoil, even where restoration is not completed immediately after construction.

Herbs

The GLM analysis showed no significant effects in terms of cover for any of the main herb species recorded in the mobile dunes.

Honckenya peploides is a stress-tolerant perennial species, forming low clumps of succulent, creeping shoots (Rodwell, 2000). It is a key species in the initial stabilisation of the dunes. Seer (2015) undertook a study to assess the effects of low-intensity stress caused by human trampling on beach populations of three strandline species (*Atriplex prostrata*, *Crambe maritima* and *Honckenya peploides*). It showed that low-intensity trampling did not influence the survival of *Honckenya peploides.* However, several other studies suggest that trampling activity by beach visitors was more harmful for plant development than natural stress (Santoro et al., 2012), decreased species-diversity and reduced initial dune development (Hesp et al., 2010). Whilst the impacts of pipeline installation in the working width is obviously more severe than trampling, it is interesting to note that the CCA analysis (Figure 61) showed that *Honckenya peploides* was positioned with increased years and increased log distance from the pipeline, away from the On, Adjacent or Medium-term factors indicating that it did not quickly return to the strandline/ mobile dune zone after construction.

Eryngium maritimum is a long-live perennial, Isermann and Rooney (2014) notes that various studies have shown plants live for an average of 10-15 years (with some individuals up to 30 years old). Flowering and fruiting often do not start until a plant is 4-6 years in age. At its northern limits of its distribution Stasiak (1986 cited in Isermann and Rooney (2014)) showed that seed production was reduced; and populations were maintained by vegetative reproduction through offshoots from rhizomes or root fragments. It therefore could be hypothesised that where it is lost from an area of dunes as a result of pipeline installation it would be slow to recover. This is supported by the CCA analysis which showed it was associated with the Medium-term. Isermann and Rooney (2014) also notes that *Eryngium maritimum* is vulnerable to direct damage from trampling both by humans and by larger grazing animals because its stems and roots are brittle; indicating that it would not tolerate impacts associated with pipeline installation.

Mosses

Low numbers of six moss species were identified in the embryo/ mobile dunes, with records typically recorded from areas where *Ammophila arenaria* was more frequent. Two of these species *Brachythecium albicans* and *Syntrichia ruralis* subsp. *ruraliformis* are noted as present at low abundances in SD5 and SD6 *Ammophila arenaria* mobile dune community (Rodwell 2000). Birse et al. (1957) notes that only a few species are capable of colonising and stabilising early mobile dunes, specifically mentioning *Brachythecium albicans* and *Syntrichia ruralis* subsp. *ruraliformis*. *Syntrichia ruralis* is an acrocarpous mosses that is capable of regular annual growth increments and forms discrete cushions. Both *Syntrichia ruralis* subsp. *ruraliformis* and *Brachythecium albicans* have similar Ellenberg values (Hill et al., 2004), requiring high light levels (8), dry sites (3), a basic substrate (6-7), and moderately infertile (3), while *Syntrichia ruralis* subsp. *ruraliformis* is slightly more salt tolerant. The CCA analysis (Figure 60) shows mosses such as *Syntrichia ruralis* subsp. *ruraliformis* being positioned in areas of the plot with increased distance from the pipeline and nearest to the Off/Unaffected sample factors. The scatterplots for *Syntrichia ruralis* subsp. *ruraliformis* (taken from the entire dataset) shows that as a general trend its cover decreases over time Off the pipeline, while On the pipeline it shows little change and remains at a low-level of abundance over time (Figure 55).

Recovery of Embryo/ Mobile Dune Communities

Interpretation of the likely recovery time frames of embryo and mobile dune communities using my datasets is particularly difficult due to the lack of data from the Short-term.

Three main communities were represented at the study sites SD4 *Elymus farctus* ssp. *boreali-atlanticus* foredune community, SD5 *Leymus arenarius* mobile dune community and SD6 *Ammophila arenaria* mobile dune community. Using the results of the GLM analysis, cover of the four main graminoids (associated with these NVC types), *Ammophila arenaria*, *Carex arenaria, Elytrigia juncea* and *Leymus arenarius* were not significantly different between the Medium-term and Unaffected vegetation. This suggests that these species had recovered to pre-construction levels of abundance by between 10 and 25 years (Medium-term). Similarly, none of the other key species showed any significant difference between the Medium-term and Unaffected vegetation. The likely time frame for recovery is also supported by the NVC survey maps. The 2000 survey map from Talacre Warren (Figure) shows vegetation recognisable as the SD6 mobile dune community developed from bare sand within 5 years following construction along the pipeline, although it may have had a more variable species composition and structure compared to Unaffected examples of the community. Similarly, at Coatham Common (Figure 68) SD6 established itself along the construction corridor within 5 years. The speed of vegetation establishment in this zone will depend on sand stability, nutrient availability and proximity of Unaffected vegetation (*i.e.* allowing rhizomatous growth).

The CCA plots suggest that the vegetation On and Adjacent to the pipeline is similar to the Unaffected/ Off vegetation and that its recovery is converging towards a common trajectory.

It can therefore be concluded that recovery of embryo/ mobile dunes is likely to be at some point before 25 years, and probably in the Short-term to Medium-term *i.e.* 10-25 years.

4.8.2 Fixed Dunes

In contrast to the sparsity of the data in the embryo and mobile dunes, the fixed dunes dataset used 771 quadrats and consequently a large number of the species were significant when tested using GLM with sample area and time since impact.

Graminoids

The key graminoids *Ammophila arenaria*, *Arrhenatherum elatius*, *Carex arenaria*, *Festuca arenaria*, *Festuca rubra*, *Holcus lanatus* and *Leymus arenarius* all showed significant differences in cover using GLM with sample area. The only species of note in this zone which were not significant in terms of cover were *Elytrigia juncea*, *Phleum arenarium* and *Poa humilis*.

Ammophila arenaria

Ammophila arenaria in the fixed dunes is the dominant species, and along with *Festuca rubra* defines the dune community SD7. The GLM analysis proved the hypothesis that cover of *Ammophila arenaria* is lower On the pipeline, at least in the Short-term, having returned to non-significant levels by the Medium-term. This was supported by the SRC with distance which showed a strong increase in this species with distance and over time (Figure 75a). Considering recovery over time, after construction, *Ammophila arenaria* achieved 12% cover in the first 10 years (equivalent to the interquartile range (Q1) in the Unaffected vegetation). Cover increased to 30% by 30 years (equivalent to the mean cover in the Unaffected vegetation). Considering its recovery over time, natural recovery of *Ammophila arenaria* in this zone (so that it achieved a similar vegetation cover to the mean value for the Unaffected area of *c.* 30%) would take around 30 years (Figure 75 c &d). The CCA plot shows *Ammophila arenaria* present along the years gradient near to the Short-term and On sample areas. While the scatterplots (which include data from across the vegetation zones) shows a trend for *Ammophila arenaria* increasing On the pipeline over time but at a lower level of abundance than the Off trend line which remains fairly constant over time Figure 55).

As in the mobile dunes *Ammophila arenaria* grows vigorously where the sand is less stable, but where the sand stabilises it loses its dominance allowing other species to become established; unless erosion re-establishes the succession (Ranwell, 1960a). In the fixed dunes, where *Ammophila arenaria* is actively growing it forms large discrete tussocks up to 100cm in height, with plants flowering regularly every year. However, as succession proceeds and sand stabilise, flowering becomes less frequent and plants become vegetative (Huiskes, 1979). This is known as the '*Ammophila* problem' whereby plants have a reduced height and density of foliage, with reduced tillers and seed yield (Greipsson, 2002) . It is suspected that the small vegetative tussocks are probably the remains of plants that became established when the dune was mobile, which indicates that an individual clone could be hundreds of years old (Huiskes, 1979). This lack of vigour in stable sands has particular relevance to post-construction pipeline restoration.

Following installation, often the primary aim of restoration in the fixed dunes and along the dune ridge, is to reinstate dune vegetation to the extent that windblown sand is controlled and naturally self-sustaining sandhills become established; with the secondary aim to reinstate something as close as possible to the natural vegetation (Environmental Resources Limited, 1990). Natural regeneration of *Ammophila arenaria,* sufficiently extensive and reliable to prevent sand erosion, is unlikely to occur further inland; therefore, planting of *Ammophila arenaria* is key in the initial stabilising sand. The failure of *Ammophila arenaria* to thrive is illustrated by Hewett (1970), who undertook studies looking at the colonisation of sand dunes following stabilisation with *Ammophila arenaria* at Braunton Burrows. The planting was completed in several phases between 1952 and 1961 across the site and included fore dunes and inland areas. The study showed that in those areas where *Ammophila arenaria* was planted within 100m of the shore it had a tussocky growth form; but where planted further inland (where there was a low supply of sand) the *Ammophila arenaria* plants were less vigorous. Quadrat sampling recording presence or absence of a species over time following planting, showed that the frequency of *Ammophila arenaria* had significantly declined across most planted areas and in the central area it died out completely. This resulted in considerable amounts of bare sand even though the *Ammophila arenaria* was planted at the same densities across the whole site. After 15 years, numerous dead and morbid *Ammophila arenaria* plants were recorded.

Festuca arenaria and Festuca rubra

Both *Festuca arenaria* and *Festuca rubra* showed significant responses (with the GLM analysis) with sample area and time since impact as was expected. The cover of *Festuca rubra* was shown to be lower On the pipeline in the Short-term, while *Festuca arenaria* which prefers more open conditions had a higher cover On the pipeline in the Short-term. However, when cover was considered with distance in the SRC (Figure 75a) the difference between the On and Off sample areas was limited and cover of both species was more-or-less constant. The SRC with years since construction however showed a stronger positive relationship for *Festuca rubra* with cover increasing with time both On and Off the pipeline (Figure 75). The mean value for *Festuca rubra* Off the pipeline (based on the boxplots Figure 71) was 13.5%, which was attained after construction by 10 years. In contrast the cover of *Festuca arenaria* remained constant at *c.* 8% On the pipeline, while it showed a strong decline over time Off the pipeline, becoming absent from the sward by 30 years. The CCA plot shows that *Festuca arenaria* is situated closer to the Short-term sample area, while *Festuca rubra* sits between the Short-term and Medium-term (Figure 74). Both species increase in cover over time (as shown in the scatterplots Figure 55) although *Festuca rubra* shows a stronger response.

Differences in the responses of the two species are perhaps due to their life-strategies with *Festuca arenaria* being a termed a competitive stress-tolerant species which colonises areas of bare sand. Whereas *Festuca rubra* is a competitive stress-tolerant ruderal species more typical of closed swards. The difference between the cover responses for the two species, while as hypothesised, is interesting considering, there has been much taxonomic reshuffling of the species. At various times *Festuca arenaria* has been a variant of *Festuca rubra*, with *Festuca arenaria* typical of the SD7 community (Rodwell, 2000). Hubbard (1954) describes *Festuca rubra* var. *arenaria* as "*frequent on coastal sand-dunes; it has extensively creeping rhizomes, scattered shoots, bluish-white leaves and usually densely hairy spikelets*"; while Stace (2010) recognises *Festuca rubra* and *Festuca arenaria* as distinct species. Hewett (1970) recorded *Festuca rubra* (probably *Festuca rubra* rather than *Festuca arenaria*) as having a significant increase in frequency over time (especially in the landward planted areas where it became the dominant species); noting that *Festuca rubra* is a species of stable conditions.

Other Graminoids

Carex arenaria showed a significant decrease in cover in the Short-term On the pipeline (with GLM), it is expected that this decline is due to its preference of growing in open dunes, and over time the colonisation by other species would have closed the sward, increasing competition. This is supported by the CCA analysis which showed *Carex arenaria* situated close to the Short-term sample area.

The cover of early successional grasses *Phleum arenarium* and *Poa humilis* was expected to decrease over time, but this was not significant when considered with the GLM. Hewett (1970) found that *Phleum arenarium* increased its frequency in the central areas of his study site, noting that it was expected to be excluded as closed communities developed (supporting my expectations). In the CCA plot it is showed closely associated with increased light (Figure 74) and closest to the Short-term. Hewett also noted that there was little change in the frequency of *Poa humilis* but suggested that it preferred more open habitats in mobile sand areas. This is supported by the CCA plot which shows *Poa humilis* associated with species of more open conditions such as *Anthyllis vulneraria*, *Festuca arenaria*, *Diplotaxis tenuifolia* and *Plantago coronopus*.

Herbs

Many of the herb species associated with open swards and areas of bare sand showed a significant increase in cover On the pipeline, and/or in the Short-term with GLM *e.g.* *Anthyllis vulneraria*, *Diplotaxis tenuifolia*, *Ononis repens*, *Plantago lanceolata*, *Potentilla reptans*, *Senecio jacobaea etc.* This follows the expected course of succession once *Ammophila arenaria* is established and surface stability obtained, other species are able to colonise between the tussocks.

The GLM data for *Ononis repens* shows a significantly reduced cover On the pipeline compared to Off. However, when considered in the SRC (Figure 75), it shows that the response was weak with cover decreasing by 1-2% with distance. In contrast, when the SRC was used to consider the change in cover over time On the pipeline, *Ononis repens* showed a strong increase over time. With its cover achieving a similar level of abundance to the unaffected vegetation (*c.* 7%[76]) by 12 years. In contrast Off the pipeline the species was shown to decrease in cover over time. The difference in response between distance and On/Off is perhaps due to the variability of dunes (both seaward and landward) included in the fixed dune vegetation type used for sampling. Hewett (1970) notes that at Braunton Burrows there was a significant increase in *Ononis repens* in the seaward plantation areas, but further inland there was little change in cover. Page et al. (1985) considered *Ononis repens* to be an opportunistic species rapidly exploiting sites which were temporarily

[76] based on the mean cover as shown in Figure 72

favourable. But noted that it was unable to compete from competition from other dicotyledons and from trampling.

Hewett (1970) also noted an overall increase in leguminous species over the study period (with the establishment of *Lotus corniculatus*, *Melilotus altissimus, Ononis repens*, and *Trifolium arvense*). When considering presence and absence of legumes in my three sample areas, the On sample area (across all vegetation zones) supported 17 species in contrast to 11 in both the Adjacent and Off sample areas. Many members of the plant family Fabaceae have nitrogen-fixing bacteria in root nodules and therefore have a competitive advantage over other species. Proctor (2013) notes that species such as *Lotus corniculatus*, *Ononis repens*, *Trifolium arvense* and *Trifolium repens* play an important role in the fixed dunes, increasing nitrogen in the soil. One of the most significant legume responses was with *Anthyllis vulneraria* which shows a rapid decline in cover over distance from the pipeline; and after construction On the pipeline (decreasing from *c.* 15% to becoming absent) by 22 years. In the Off sample area it was shown to gradually increase in cover over time (Figure 75). This was supported by the GLM analysis.

Mosses

Fifteen species were recorded in the fixed dunes of which the most frequent were *Brachythecium albicans* and *Syntrichia ruralis* subsp. *ruraliformis*. The total cover of mosses was not expected to change significantly On the pipeline and in the Short-term (due to a greater area of bare sand and less competition), but as noted (*page 176*) the total cover was significantly higher. This is probably due to the decreased competition from the taller species such as *Ammophila arenaria* which would typical shade the early pioneer mosses.

Neither *Brachythecium albicans* or *Syntrichia ruralis* subsp. *ruraliformis* (both pioneer species) showed a significant response to sample area or time since impact (with GLM). In a study by Birse et al. (1957) looking at the effects of burial by sand on dune mosses, they noted that both species are frequent in the fixed dunes, when *Ammophila arenaria* has established with other herbs. The study found that both *Brachythecium albicans* and *Syntrichia ruralis* subsp. *ruraliformis* were both capable of growing through up to 3cm of sand, which was a key survival strategy in shifting sands. In addition, their ability to produce rhizoids in accumulating sand and plasticity of growth form in emerging shoots was considered to be important factors.

However, two other species, *Ceratodon purpureus*, and *Oxyrrhynchium hians* had a significantly lower cover On the pipeline, and in the Short-term. *Ceratodon purpureus* is a species of well-drained substrates particularly sandy soils and Watson (1980) notes that it grows in dune-lands. Ellenberg values (Hill et al., 2007) for *Ceratodon purpureus* shows that it has a high light requirement (7), low moisture requirement (4), is tolerant of growing in slightly salty conditions (1), and prefers moderate infertile (3) and moderately acid soils (5). Birse (1957) showed that it is capable of growing in shifting sands; and produced long rhizoids (providing anchorage and water absorption) – indicating that it should behave similarly to the other pioneer species mentioned. In contrast, *Oxyrrhynchium hians* is a species typical of bare soils, growing in a wide range of habitats, although it may prefer wetter locations (Atherton et al., 2010). It is perhaps a more generalist species not capable of dealing with the extremes associated with the exposed sands.

In Hewett's study, he found that mosses were only recorded in the oldest areas of *Ammophila arenaria* planting where the vegetation was well established (Hewett, 1970).

Recent studies (Bu et al., 2015) to determine the factors that influence the development of dune-stabilising moss-dominated crusts showed that the frequency of watering and light levels had the greatest positive effect in the laboratory. The authors note that the quick establishment of moss-dominated crusts is important in the restoration of post-construction sites especially where there is a risk of erosion.

Bare Ground

The cover of bare ground was expected to be higher after pipeline installation, and this is supported by the GLM analysis which showed bare ground cover in the Short-term and On the pipeline was significantly higher than Unaffected/Off. By the Medium-term (10-25 years) cover of bare ground was not significantly different.

At both the Redcar sites and Talacre Warren, *Ammophila arenaria* planting was completed to reduce wind-blown sand and aid vegetation recovery. Kidson and Carr (1960 cited in Hewett (1970)) suggest that following planting of *Ammophila arenaria* a period of 2-3 years is required before surface stability is attained, and colonising species may not become established until this is ascertained. At Redcar, which has detailed quadrat data for the first three years after pipeline installation; bare ground in the fixed dunes decreased from 100% to *c.* 40% after the first year, and 16% after three years. This suggests a more rapid colonisation in the first year than Kidson and Carr noted, but from personal observations I would agree that once surface stability is attained, species-richness and abundance quickly increases. Kidson and Carr also noted that it took *c.* 10 years for planted areas to look natural *i.e.* losing the 'planted appearance'. At both Talacre Warren and at the older of the Redcar sites (restored 22-25 years ago) it is difficult to make out the pipeline route, and *Ammophila arenaria* has a natural appearance. In contrast at the youngest of the Redcar site (installed 6 years ago) the *Ammophila arenaria* setts can be clearly distinguished.

Jones et al. (2010b) also recorded vegetation change as a result of stabilisation using aerial photography. It showed that soils associated with the development of semi-fixed dune vegetation (referable to the NVC type SD7) took between 20-60 years, with typically 20-45% bare sand. My study showed vegetation recovery in the fixed dunes took between 10 and 25 years to develop vegetation consistent with the NVC type SD7. This would appear to be a much faster response than at Newborough Warren studied by Jones et al. (2010b). However, it should be noted that while pipeline installation completely removes the existing vegetation during construction; the topsoil (containing plant and root fragments as well as seed material), is stored separately and then returned to approximately the same position on the dunes as it was removed from. This means the soils are not developing from bare beach sand as was the case at Newborough Warren.

Recovery of Fixed Dune Communities

One main fixed dune community was represented at the study sites; SD7 *Ammophila arenaria* - *Festuca rubra* semi-fixed dune community. Considering the main graminoids of SD7 *i.e. Ammophila arenaria*, *Carex arenaria, Festuca rubra* all had a significantly lower cover On the pipeline in the Short-term, but by the Medium-term their cover was equivalent to the Unaffected vegetation (using GLM). Similar findings were noted for *Ononis repens* (which is characteristic of the main sub-community SD7c recorded at the study sites). The GLM analysis supports the evidence from the SRC plots which shows a similar recovery time frame of between 10-30 years for *Ammophila arenaria*, *Festuca rubra*, *Anthyllis vulneraria*, and *Ononis repens*. This is further supported by the habitat maps, which shows that at both Talacre Warren and Coatham Common, vegetation representing SD7 was recorded in the Short-term (within 5-10 years) along the pipeline routes. It should be noted that vegetation recovery was added through the planting of *Ammophila arenaria* at both sites, and therefore without this it may have taken longer to achieve equivalence to the Unaffected vegetation. As described, a natural composition and structure was attained after planting in the Medium-term. The CCA plot (Figure 74) showed that in the Long-term recovery was similar to the Off and Unaffected vegetation which is desirable, however it also showed that an alternative trajectory towards scrub in the Medium-term may also be possible. This scenario would be less desirable.

In conclusion, the fixed dunes are likely to recover in terms of species composition and structure within the Short to Medium-term. This follows the results looking at time frames and trajectories of vegetation communities at Newborough Warren that showed dry dune soils supporting SD7 established between 20-60 years (Jones et al., 2010b). However as noted in the CCA plot without management interventions succession to a more closed sward with tussock forming grasses or the development of scrub is likely in the Medium to Long-term. This is also supported by the study at Newborough Warren which showed succession of SD7 to rank taller grassland *i.e.* SD9 after around 40 years of soil development.

4.8.3 Dune Grassland

Graminoids

Ammophila arenaria

As discussed in the fixed dunes, the vigour of *Ammophila arenaria* decreases with distance from the shore in systems where there is a low sand supply. In the dune grassland, it was expected and proved (using the GLM) that *Ammophila arenaria* would not readily recover following installation and therefore the cover of *Ammophila arenaria* would be significantly lower On the pipeline. The decline of *Ammophila arenaria* in the dune grassland was also notable in its absence from the CCA plot (which only shows the top 40 weighted species). The SRC shows that with distance *Ammophila arenaria* is almost absent On the pipeline, while Off the pipeline cover reached up to 15%. When considering its recovery over time the SRC showed that On the pipeline there was a delay in establishment (of a couple of years) and that it only attained cover of 2-3% after 10 years (Figure 83). Similar findings were recorded by Ritchie and Gimingham (1989) who noted that there was little, if any reinvasion of *Ammophila arenaria* along the pipeline in Aberdeenshire. Where recorded in the current study at both Coatham Common and Talacre Warren, the plants were smaller with only a few leaves. Jansen (1951 cited in Huiskes (1979)) noted that in the dune grasslands, which are less favourable for *Ammophila arenaria*, you have an impoverished dune form, that is shorter, often with an absent inflorescence. Ranwell (1972) also noted that trampling can cause considerable damage to these impoverished dune forms of Marram.

Arrhenatherum elatius

One of the key distinguishing species between the NVC types SD7 (fixed dunes) and SD9 is the presence of *Arrhenatherum elatius* which is a frequent/co-dominant element of the sward Rodwell (2000). Other grasses such as *Dactylis glomerata*, *Poa pratensis* and *Holcus lanatus* are also common. This gives the dune grassland a tussocky structure, restricting the growth of hemicryptophytes and chamaephytes. There was no significant difference (using GLM) in the cover of these broad-leaved grasses between On and Off the pipeline indicating that the vegetation is able to quickly re-establish itself from plant fragments and seeds in the replaced topsoil. These tussock forming grasses are all clustered together on the CCA plot close to the On, Adjacent, Short- and Medium-term sample areas (which are poorly separated) - Figure 82. Similarly, the SRC shows no difference in cover of *Arrhenatherum elatius* with distance from the pipeline with its cover remaining *c*. 10% (Figure 83a). While the SRC showing cover of *Arrhenatherum elatius* On the pipeline with time shows only a small decrease from 12% to 9% over 25 years. Both *Holcus lanatus* and *Dactylis glomerata* did show a slightly stronger response with cover decreasing with distance from the pipeline and with time On the pipeline.

Fined Leaved Graminoids

Fine-leaved graminoids such as *Bromus hordeaceus* and *Luzula campestris* had a higher cover On the pipeline in the Short-term (using GLM). This is perhaps surprising when considering the development of the tussock forming sward discussed above. Similarly, in the SRC plots (Figure 83) *Festuca rubra* showed a strong increased in cover with distance, and On the pipeline over time (compared to similar strong decreased over time Off the pipeline). But at least in some local areas, once the surface stabilised, the sward developed a finer structure (often where there was localised rabbit grazing) where these grasses and other herbs tolerant of base-rich conditions developed. This vegetation is referable to the NVC type SD8. Plassmann et al. (2010) showed that following the re-establishment of grazing swards previously classified as SD9 could succeed to SD8. The CCA analysis shows that this vegetation type appears to develop in Medium-term On the pipeline (under suitable conditions), with the presence of *Galium verum*. This is also supported by the GLM, which shows significant differences between the Medium-term and the Unaffected for *Agrostis stolonifera*, *Festuca rubra*, *Poa humilis*.

Herbs

As with the typical grasses of SD9, the main herbs did not show a significant effect with sample area or time since impact (using GLM). The only exceptions were *Centaurea nigra* which had a higher cover On the pipeline, and *Equisetum arvense* which had a higher cover in the Short-term. The SRC with distance from pipe (Figure 83) showed that the legumes *Anthyllis vulneraria, Lotus corniculatus* and *Ononis repens* had higher cover On the pipeline decreasing with distance. This indicates that these species are able to exploit the bare ground along the pipeline, probably due to their ability to fix-nitrogen. One of the key species of SD8 namely *Galium verum* (a stress-tolerator) had a slow response following installation with recovery taking more than 25 years to reach its peak cover, this also corresponds with the CCA plot which is closely associated with the Medium-term. The recovery time frame for this species fits with the time frames of development for SD8 suggested by Jones et al. (2010b)). Page et al. (1985) also noted that species has a slow recovery time following disturbance.

The species diversity plot (Figure 84) showed that the most species-rich quadrats were found On the pipeline and in the Short-term, with a decrease in diversity in the Off/ Unaffected quadrats. Jones et al. (2010b) demonstrated that species-richness in dry dune systems showed a general increase with age in the semi-fixed dunes, but that species-richness reached a plateau, followed by a decline in the fixed dune grasslands.

In 2007, a topsoil inversion trial was initiated at Talacre Warren in the dune grasslands along the former pipeline working width (Jones et al., 2010a). The nutrient rich topsoil was buried (using a double-bladed plough) to a depth of 80cm, with the underlying mineral sand brought to the surface. The aim to was create conditions similar to mobile dunes. The first evidence of species colonisation was after 8 months. By 15 months[77], 16 species had become established, all of which were present prior to ploughing indicating they had grown from seeds, buried rhizomes or plant fragments. Fifteen months after ploughing there was a significant amount of bare sand (70-90%), but wind erosion had removed much of the mineral sand exposing the underlying organic layer, reversing the benefits of the topsoil inversion. As the trial area was On and Adjacent to the pipeline working width, I undertook quadrat sampling (5 quadrats) within the area in 2015-2016. The main change over the subsequent 8-year period was the loss of the bare sand, with vegetation cover between 98-100%, of this, herbs had a cover of between 73-84%. *Rubus caesius* was the most abundant species with cover between 50-72% (mean 61.4%) with frequent *Equisetum arvense* (up to 20% cover). Species numbers for the individual quadrats were between 10 and 15 species (mean 11.8) indicating there had been an overall loss in diversity since the 2008 survey. Across the five quadrats 23 species were recorded, of which 8 were graminoids, and 15 were herbs; there were no moss species. It appears that growth of *Rubus caesius* and *Equisetum arvense* (present in the wider survey area at a low level) was stimulated by the deep ploughing technique. Both species are perennials and rhizomatous and so are able to quickly regrow from root fragments. This is supported by comments by Rhind et al. (2013), who compared ploughing at Talacre Warren with findings from the Netherlands.

Scrub

At Coatham Common, there was concern that *Hippophae rhamnoides* which was already present in the dune grassland would further spread following pipeline construction through the mechanical break-up of root fragments (as noted with *Rubus caesius*). In the UK, *Hippophae rhamnoides* is only considered native along parts of the east coast between Sussex and Humberside (Pearson and Rogers, 1962) but has been widely planted to stabilise dunes outside this area. Along with producing copious amounts of berries which are readily consumed and dispersed by birds, it can spread vegetatively. Studies show it is able to fix nitrogen using root mycorrhizal fungi. Greipsson (2002) notes that it can add significant amounts of nitrogen to the system (17.9g N m^{-2} per year) which can in turn reduce the species diversity of dune systems. Its invasive nature, significantly reducing other plant species through shading and restricting other dune communities from developing (Richards and Burningham, 2011) means that its spread is generally controlled where sites are managed.

At Redcar, there is a large well-established patch of *Hippophae rhamnoides* growing in the working width area along the oldest of the pipelines at Redcar. This has become established in the last 25 years. The 2009 pre-construction report for the second pipeline (RSK, 2009) notes that a single

[77] September 2008

patch of *Hippophae rhamnoides* was recorded and that its spread could threaten the dunes at Coatham Sands. The size of the single patch in 2009 (measured using the GIS layers) was *c.* 10×5m. In 2016, the same patch had grown to *c.* 18×20m. In addition, during my survey, numerous *Hippophae rhamnoides* saplings were recorded[78] from the pipeline working width.

The data (GLM analysis) also showed a significant increase in *Clematis vitalba* On the pipeline compared to the Off sample area. On the ground it was notable that where it established it formed a dominant patch suffocating the underlying vegetation. At Talacre Warren management work is undertaken to restrict its spread.

The SRC plot (Figure 83) for *Rubus caesius* showed that there was a strong increase in its cover Off the pipeline reaching a maximum cover of 18%. On the pipeline cover of this species increased after construction although there was a delay before it re-established itself.

Mosses

Low numbers of 10 moss species were identified in the dune grasslands, although only six of these were recorded frequently. Three of these, were early successional species more typical of the mobile and fixed dunes, namely *Brachythecium albicans*, *Ceratodon purpureus* and *Syntrichia ruralis* subsp. *ruraliformis*. It is likely that the unidentified *Bryum* species are also pioneer species; although one sample was identified to *Bryum pseudotriquetrum,* a species more typical of dune slacks with a preference for high moisture levels (Atherton et al., 2010, Hill et al., 2004). The other species *Kindbergia praelonga* and *Oxyrrhynchium hians* are both common species capable of growing in a wide range of habitats (Atherton et al., 2010). Both species are capable of tolerating some shade (light = 5-6) and also prefer moderately fertile to eutrophic site (nitrogen = 5-6) (Hill et al., 2004). Rodwell (2000) notes that mosses can make up a prominent feature of the sward in SD8. The GLM analysis showed a significant difference in the total moss cover between the Medium-term and the Unaffected vegetation suggesting this was associated with the development of SD8 (predominately recorded at Coatham Common).

Recovery of Dune Grassland Communities

The separation of the construction factors (*i.e.* On, Adjacent, Short- and Medium-term with mesotrophic grassland) from the Unaffected vegetation (where scrub begins to establish) indicate that the successional trajectory following pipeline installation has a possible beneficial outcome. It appears that the direction and rate of succession is at least temporarily changed, and that it can provide opportunities to increase species-richness if the dominance of broad-leaved grasses can be restricted. This was noted at Talacre Warren where there has been an ongoing successional change from mobile dunes to semi-fixed dunes to dune grassland to mesotrophic grassland.

[78] And hand-pulled to help minimise further spread

However, it is clear that the pipeline installation in 2000 slowed the rate of succession. Prior to construction, MG1 accounted for *c.* 50% of the survey area, but five years after construction it was absent, increasing to just over 2% by 2016. Much of this change appears to be down to an increase of SD9 over the same period. At Talacre Warren part of the reason behind why the area was not recolonised by MG1 or dominated by scrub, is due to the annual cutting of the grassland in this area (Kim Norman personal comm). However, at Redcar which is not managed, across the three sites, there was a 31% decrease in cover of SD9 On the pipeline, replaced in part by a transitional sward (SD9-MG1) which has increased by 18% and an increase in willow and mixed scrub. This change in vegetation is mainly seen along the 1991 pipeline (installed 25 years ago).

The recovery time frame for dune grassland (referable to the NVC type SD9) is likely to be in the Short- to Medium-term, with key graminoid species such as *Arrhenatherum elatius*, *Holcus lanatus*, and *Dactylis glomerata* returning to the sward (at similar levels abundance to the Unaffected areas) within 10 years. The more species-rich examples including vegetation referable to the NVC type SD8 is dependent on ongoing management (*i.e.* grazing or cutting), where this occurs it may develop in the Medium to Long-term (15-35 years). This timescale fits with the development of SD8 along the 1991 Coatham Common pipeline; and with suggested time frames (of 40-60 years) for the development of soils supporting SD8 at Newborough Warren (Jones et al., 2010b). The reduced time for the recovery, after construction at the study sites, is probably due to the original dune soils and seed bank being returned to the locality where they were removed from as part of the restoration works.

The change in mobile dune systems to sites dominated by fixed-dunes with closed swards, and little bare ground has been recorded across the UK over the last 30-40 years (Jones et al., 2004). Many factors may contribute to this process including climate change, a lack of suitable management and deposition of atmospheric nitrogen.

4.8.4 Dune Slacks

Dune slacks are low lying areas that have a high water-table throughout the year, and are typically nutrient poor systems, that require low levels of nitrogen and phosphorous. They are sensitive to changes in ground water levels and its chemistry (Jones et al., 2006). The water-table tends to fluctuate through the year, between 40-60cm but over long periods it can fluctuate by over 1m (van der Hagen et al., 2008). Rhymes et al. (2014) showed that both wet and dry dune slacks show similar patterns in water fluctuations over the year, with a steady decrease in summer, followed by a rapid increase in early winter. The length and depth of winter flooding is critical in determining species composition (Grootjans et al., 2002). Local-scale variations in substrate, nutrient availability, during of flooding, water level and chemistry drive species diversity.

Several classifications systems of dune slacks have been developed depending on the successional development phase (Grootjans et al., 2002), water-table (Environment Agency, 2010, Ranwell, 1972) and vegetation types (Rodwell, 2000). The four stages of dune development suggested by Grootjans et al. (2002) are a useful tool in classifying dune slacks following pipeline restoration. These are outlined below:

1. small pioneer species establish on bare soil;
2. colonisation of phanerograms[79] adapted to low nutrient availability;
3. development of moss layer of pleurocarpic moss and typical dune slack species; and
4. rapid accumulation of soil organic matter leading to a decline in typical dune slack species (mature dune slacks).

Rohani et al. (2014) noted that soil organic matter is primarily controlled by above ground plant biomass; and that dunes dominated by low productive species have low accumulation rates allowing the pioneer stage to be maintained for longer periods. In contrast, those dune slacks with highly productive species accumulated soil organic matter ten times higher driving the rate of succession. This supports Grootjans et al. (2002) who states that a shift from pioneer to mature dune slacks can take 20-30 years, but the pioneer stage can be maintained for 30-60 years.

Considering all the environmental gradients that influence species composition in the dune slacks, determining species trends following pipeline installation, is more complicated than in the other vegetation zones; and is perhaps, more frequently driven by local site conditions. Therefore, much of the discussion set out below describes community changes rather than focusing on individual species, unless an individual species is characteristic in determining the change.

From the data, it appears that two main changes have occurred in the dune slacks following pipeline installation; the lowering of the water-table resulting in the reduction of typical wetland graminoids and herbs and the subsequent increase in species tolerant of drier conditions. However, these responses are also part of the natural process governing dune slack succession.

One study by Soulsby et al. (1997) focused on the post-construction recovery of the St. Fergus sand dunes crossed by pipelines between 1975 and 1984. Soulsby undertook a review of hydrological data collected between 1981 and 1993. One of the key considerations in the EIA was the need to maintain the sites hydrological processes. The site is particularly important for its dune slack known as Winter Loch which typically floods between October and May. Monthly monitoring of precipitation, temperature, and ground water was taken, and evaporation and soil moisture calculated. The data showed that over the 12-year period ground water levels were lower, but Soulsby concluded that this change was due to climatic factors and that there was little

[79] Raunkiaer's system of classifying growth forms – a phanerophyte is a plant with a growing point that survives adverse seasons as a resting bud well above the ground.

evidence to suggest the pipelines had a major influence on the hydrology of the dunes. Soulsby did note however that restoration of pipeline in some areas had resulted in slightly higher elevations than the original Winter Loch surface and these have resulted in drier conditions which were no longer subject to regular flooding.

Graminoids

Two graminoids (*Bolboschoenus maritimus* and *Eleocharis quinqueflora*) showed a significant reduction in cover On the pipeline and in the Short-term (with GLM *page 203*). This was also seen in the CCA plot and in the SRC plots.

As described in the saltmarsh (*Section 3.9.2*), *Bolboschoenus maritimus* is a tall, long-lived clonal species with shortly creeping rhizomes. It is a species of saline ground and shallow brackish water. In the sand dunes, it showed a similar response to pipeline installation as in the saltmarsh, with a significant reduction in cover On the pipeline and in the Short to Medium-term (as shown in the SRC and GLM analysis). In a germination study, Clevering (1995) showed that in general, vegetative propagation of *Bolboschoenus maritimus* was more effective than seed. This would indicate that where plants are lost from the pipeline corridor it is unlikely that they would recover from seeds in the seed bank.

Eleocharis quinqueflora is a small, shortly creeping rhizomatous perennial. Rodwell (2000) notes that it prefers base-rich habitats in sedge dominated communities of dune slacks. Following pipeline installation its cover and frequency was reduced probably due to habitat loss. Jermy et al. (2007) notes that the species "*is a plant of open vegetation and is helped out by grazing and minor disturbance"*, however, the level of disturbance from pipeline installation is more damaging than this. *Eleocharis quinqueflora* is shown in the CCA plot as strongly associated with the Unaffected vegetation. Similarly, *Eleocharis uniglumis* a species typical of depressions and pools on tidal flats was recorded in fewer quadrats after construction On the pipeline, and shows a clear preference in the SRC to being found more abundantly Off the pipe (Figure 83). At Redcar, an area of wet slacks was permanently lost after construction of a temporary work area used hardcore to raise the ground level. This area was not fully restored after work and resulted in a change in substrate and drainage.

There was also a reduction in the frequency of some of the common sedges that prefer wetter conditions *i.e. Carex nigra*, which may indicate a decrease after construction in moisture. At Braunton Burrows, Willis et al. (1959) notes that *Carex nigra* prefers sites with slightly longer periods of flooding (mean 5.3 months). While, *Carex flacca* (which has a wider moisture tolerance) showed an increase in cover with distance from the pipeline (as shown in the SRC plots (Figure 83a), although it also showed a gradual increase in cover over time On the pipeline (Figure 91c) compared to the Off sample area where it showed a decrease in cover.

Other graminoids species, indicative of more mesotrophic, drier conditions, showed a significant increase in cover *e.g.* *Anthoxanthum odoratum*, *Holcus lanatus* On the pipeline. *Arrhenatherum elatius*[80]and *Festuca rubra*[81] were recorded in proportionally more quadrats On the pipeline. *Festuca rubra* in particular showed a strong reduction cover with distance from the pipeline, and also showed a reduction in cover On the pipeline with time (Figure 92). The increase in the dominance of mesotrophic species is noted in Rodwell (2000) as characteristic of SD16, a mature dune slack community. The prevalence of mesotrophic species occurs when winter flooding becomes infrequent, resulting in less anoxic soil conditions.

One negative change noted at Redcar, in an area of dune slacks, (crossed by the pipeline) was that several plants of *Schedonorus arundinaceus* were recorded 5 years after construction (although not at significant levels). van der Hagen et al. (2008) noted that an increased presence of this species indicated wetter conditions but also was evidence of eutrophication. I believe the main reason for the presence of this species is probably due to members of the public using the dune slacks as an access point through to the beach, rather than using the narrow-fenced area provided for access along the pipeline. Prior to construction, the dune slack had been fenced off to prevent access and these fences remained in-situ after work; but during the 2016 survey it was noted that these fences had been cut. In addition, there was evidence of bringing horses through this area, and dog-walking which supports the theory of increased eutrophication.

Herbs

In the dune slacks, significant (using GLM) increases in cover On the pipeline were recorded with six species *e.g. Centaurium erythraea*, *Euphrasia* agg., *Lotus corniculatus*, *Potentilla reptans*, *Prunella vulgaris*, and *Sagina nodosa*. While four species showed a significant decrease *e.g. Dactylorhiza purpurella*, *Glaux maritima*, *Pulicaria dysenterica* and *Scorzoneroides autumnalis*. Those species that showed an increase in cover are typical of early successional slacks (SD13) with the exception of *Potentilla reptans* which is found in more mature dunes (SD15). Those species that showed a decrease in cover are typical of mature dune slacks that are wetter *i.e.* SD16 or SD17.

The SRC showed clear differences between the On and Off sample area with years (Figure 92) – as neither *Lotus corniculatus* or *Ononis repens* were present in a sufficient number of quadrats to be plotted in the Off sample area.

At Talacre Warren, the main area of dune slacks (situated in the former pipeline sand storage area which was dune grassland prior to construction) were created to support an introduced population of Natterjack Toads (*Bufo calamita*). These dune slacks have been excavated (scraped)

---

[80] *Arrhenatherum elatius* recorded in 12% of quadrats On, and 0% Off
[81] *Festuca rubra* recorded in 59% of quadrats On, and 20% Off

so to reach the water-table, and seasonal flood, holding water until the tadpoles have matured to the toadlet stage. The scrapes and pools are maintained by active management (removing vegetation and organic matter on a rotational basis) to reduce shading and infilling. The quadrat data suggests that the open scraped areas support the NVC type SD13b *Sagina nodosa-Bryum pseudotriquetrum* dune-slack community, *Holcus lanatus-Festuca rubra* sub-community (Rodwell, 2000). This is a rare community type in the UK with a local distribution, found at only a few sites. The Environment Agency (2010), estimated the UK extent as 26.5ha (Davy et al., 2006). Seventeen of the 29 species characteristic of SD13 were recorded in the Talacre Warren scrapes (Environment Agency, 2010). The national scarce plant *Centaurium littorale* was recorded here which corresponds to the European type *Centaurio-Saginetum* (Rodwell 2000). Surrounding the scrapes there is the mature dune slack vegetation community, probably SD16b *Salix repens-Holcus lanatus* dune-slack community, *Rubus caesius* sub-community or SD16d *Agrostis stolonifera* sub-community.

At Redcar, there was a greater range of dune slack communities that show transitions to swamp communities and relict saltmarsh. A detailed description of the NVC communities are set out in RSK Carter Ecological (2009) and are not repeated here, but some key observations are summarised.

One of the main areas of dune slacks in the central part of the site, was crossed by the pipeline. As the pipeline used open cut construction methods, the working width was reduced to an absolute minimum and access beyond the work area was strictly controlled by contractors. Impacts to the vegetation here included direct habitat loss, with a change from a mosaic of relict saltmarsh communities described as SM15c and SM20 (RSK Carter Ecological, 2009) to SD8a to SD9a, as well as strip of vegetation referable to the NVC type MG1a-SD9a along what became a footpath.

To the north of the dunes, along a disturbed vehicle track, several quadrats with a distinctly brackish species composition were recorded. These quadrats included species such as *Agrostis stolonifera*, *Dactylorhiza purpurella*, *Eleocharis quinqueflora*, *Eleocharis uniglumis*, *Glaux maritima*, *Hydrocotyle vulgaris*, *Leontodon saxatilis*, *Plantago maritima*, *Potentilla anserina*, *Rhinanthus minor*, and *Scorzoneroides autumnalis.* Several of these species are tolerant of increased salinity. Ranwell (1972) notes that these saline conditions rather than being a saline influence of the water-table are the consequence of occasional tidal flooding. This vegetation is probably similar to that described by Willis at Braunton Burrows as the *Plantago coronopus-Leontodon leysseri*[82] community, which are described as being particularly conspicuous in low-lying sites with prolonged flooding (flooded for between 1-5 months of the year) (Willis et al., 1959). Rohani et al. (2014) showed that longer inundation periods increased the number of small pioneer species.

[82] Now *Leontodon saxatilis*

In terms of NVC, this area is difficult to define but shows transitions between SD16d *Salix repens-Holcus lanatus* dune-slack community, *Agrostis stolonifera* sub-community and SM20 *Eleocharis uniglumis* salt-marsh community.

Scrub

The three main scrub species of the dune slacks *Rubus caesius, Salix cinerea* and *Salix repens* showed a significant increase On the pipeline when considered with GLM. van der Hagen et al. (2008) notes that scrub (especially *Salix repens*) often increases at sites with altered hydrological conditions where there is no active management; which leads to a reduction in species-richness, as a result of the accumulation of organic matter. At Talacre Warren the slacks support low growing patches of *Salix repens* (*c.* 10-15cm tall), but also small *Salix caprea* (up to 75cm) and *Rubus caesius* (*c*. 20-30cm). The dominance of the scrub at Talacre Warren is minimised by annual cutting and the creation of new scrapes. In contrast, at Redcar, which is unmanaged there are occasional large *Salix caprea*. In the 2009 pre-construction botanical survey (RSK Carter Ecological, 2009), it is interesting to note that there was very little scrub in the survey area. The SRC shows a clear increase in *Salix repens* with distance from the pipeline with the furthest areas supporting *c.* 15% cover. There was also an increase in cover with time On the pipeline, although it showed a delay in colonisation of *c*. 5 years before it reach cover at *c.* 9% by 25 years (Figure 92).

Mosses

Eleven mosses and one liverwort were recorded in the dune slacks. The most frequent of these were *Bryum pseudotriquetrum, Calliergonella cuspidata* and *Drepanocladus polygamus*. The total cover of mosses was significantly lower On the pipeline, and in the Short and Medium-term. Rhind (1999) notes that most of the rare bryophytes in Wales are confined to the dune slacks and many of these have a requirement for the early successional stage. *Bryum pseudotriquetrum* was only recorded in quadrats On the pipeline in the Short-term, and is typical of early successional communities giving its name to the NVC type SD13. It requires open sites, with high light levels. *Calliergonella cuspidata and Drepanocladus polygamus* were found in both Short- and Long-term quadrats. *Calliergonella cuspidata* is characteristic of SD15 where it often forms a thick carpet. It requires open sites, with high moisture levels. *Drepanocladus polygamus* is a coastal species requiring open sites that are more-less water logged. The SRC plot (Figure 92) shows that *Syntrichia ruralis* subsp. *ruraliformis* decreased in cover Off the pipeline over 25 years, however On the pipeline it remained more-or-less constant.

Recovery of Dune Slacks

The DCCA plot for the dune slacks shows that the trajectory of vegetation recovery in the Short and Medium-term does not appear to be heading in the same direction as the Unaffected/ Off vegetation which is positioned along the moisture environmental gradient (Figure 91). As noted (*page 204*) the On factor is associated with species more typical of the fixed dunes (SD7). The Medium-term factor although showing an increased species-richness (including some characteristic species of SD8), also shows an increase in scrub which may indicate a change site hydrology. This drying of the dune slacks after construction is undesirable and requires further investigation. Rodwell (2000) notes when describing zonations and successions of SD7, that dune grassland communities can be interrupted by the occurrence of slacks vegetation where the ground water table is sufficiently close to the surface to keep the sand permanently moist or at least seasonally flooded. The reverse could therefore be expected to be true, *i.e.* where there are hydrological changes to the ground water table after construction, dune slacks communities could shift to grassland. In such circumstances true recovery will not be achieved.

Recovery times for the dune slacks is very much dependent on where along the successional trajectory the required vegetation lies. Lammerts et al. (1999) documented the change in species composition and number over 80 years in a series of dune slacks, noting that within 2 years vegetation cover was *c.* 25% with 14 species. By 6 years vegetation cover had increased to 60-70% with 34 species and moss cover was *c.* 15%. By 37 years, dwarf-shrubs were dominant, vegetation cover was *c.* 95% made up of 14 species and pioneer species had been lost. By 80 years there had been a further loss of species. van der Hagen et al. (2008) also showed that pioneer species associated with early successional slacks developed quickly following restoration (within 4-7 years). Both of these studies show that under favourable conditions there can be a rapid establishment of pioneer species developing early successional slacks within the Short- to Medium-term. For example, establishment of SD13b *Sagina nodosa*-*Bryum pseudotriquetrum* dune-slack community, *Holcus lanatus*-*Festuca rubra* sub-community at Talacre Warren which has developed in the artificially created and maintained dune scrapes. Rodwell (2000) notes that SD13b is characteristic "of drier situations but in slacks that have been stabilised for just a short-time – perhaps only 20 years or so". This fits with the time frames recorded at Talacre Warren which was installed in 1994. Similarly, the development of SD16 (recorded frequently along the Redcar pipes) is also a dune slack community that develops where regular inundation stops, and the surface dries. Considering all of the dune slack quadrats my data showed that the outcome of recovery after pipeline installation in the Long-term (over >25 years) was equally likely to result in dune slack vegetation or dune grassland. However, it is probably more difficult to give a definitive recovery timescale for this vegetation zone.

CONSTRUCTION & RESTORATION

Chapter 5 Construction and Restoration

5.1 Introduction

The main focus of *Chapter 5* is to consider construction methods regularly used in the installation of pipelines and cables with reference to their potential effects on saltmarsh and sand dune vegetation (Theme 4). These are based on a review of EIAs, personal observations during Ecological Clerk of Works (ECoW), discussions with statutory ecologists and documented case studies.

In addition, the chapter pulls together information on potential methods for post-construction restoration, highlighting when restoration should be taken rather than leaving it to natural regeneration. Some of these methods have been widely used in the context of restoring disturbed saltmarshes and sand dunes after construction; but most have been developed to restore or retain favourable conservation status of designated sites as part of ongoing conservation work. This therefore, draws together published literature on the successes and potential issues that may result when considering restoration work.

The overall aim is to provide some guidance for decision-makers (developers, consultants and statutory bodies) as to what is achievable after pipeline or cable installation. However, it should be noted that each site will require tailor-made solutions for both construction and reinstatement. The goal is that a suitable mitigation strategy can be developed so that it not only returns the vegetation to its original condition but could also include habitat enhancements to benefit the wider ecosystem.

5.2 Construction Techniques

5.2.1 Open-cut Trenching

Open-cut trenching methods were used for the majority of my case study sites, including the Walney Island pipelines (South Morecambe, North Morecambe and Rivers Fields), the Coatham Common pipelines (AMCO CATS and Project Breagh), the Wytch Farm pipelines (Cleavel Point, Shotover Moor, Wytch Moor), and Point of Ayr, Talacre Warren. Open-cut trenching was also used for the Corrib Pipeline in Ireland, as well as the Cruden Bay and St. Fergus pipelines in Aberdeen. Two of these projects are described in more detail; the South Morecambe pipe that crosses saltmarsh, and the Point of Ayr pipeline which crosses sand dunes.

Methods

Open-cut trenching methods involve digging the trench using excavators. Pipelines due to their physical size, typically use the 'bottom pull' technique where the pipeline is pulled onshore from a laydown barge along rollers. The laydown barge welds sections of the pipeline together from its offshore location, before the pipeline is pulled onshore using a winch. This means the pipeline is restricted to being laid in a straight line and is unable to avoid local features. For cable-lay, the cable is typically laid out along the trench and then lowered into the trench using excavators. As with pipelines, cables are restricted in terms of the amount of bend they are capable of, so not to damage its internal structure, therefore they also typically require a straight alignment.

In sand dunes the working width is likely to be stripped of its existing vegetation and the top 10-15cm of sand stored separately from the underlying sub-sand. Individual turves or clumps of material for reinstatement will also be lifted and stored in a designated storage area (*e.g.* at Point of Ayr) or within a nursery area (*i.e.* Project Breagh). Sands from the different areas *i.e.* fore dunes, dune ridges and dune grasslands are stored separately to facilitate restoration. The sand is typically allowed to naturally dry out and is covered to protect it from the wind and extreme temperatures, as well as preventing premature seed germination.

In saltmarsh, open-cut methods often require the removal of species-rich turves from the mid-upper marsh (as completed at the Corrib and South Morecambe pipelines), so that they can be reinstated following installation. However, in many cases the lower marsh zones are left with vegetation intact so that it aids sediment stabilisation during construction.

It is typical that a temporary trackway is built running parallel to the trench allowing vehicle movements and access along the work corridor. Historically, the trackway was constructed by laying down a geotextile membrane and then covering this with a limestone hard-core. The trackway was edged to minimise the spread of hard-core into adjacent unaffected vegetation. Rae (1984c) notes that at South Morecambe the geotextile membrane was not strong enough for the task and it tore badly while the hard-core was removed, this resulted in stone being distributed over the saltmarsh surface. These stones then had to be hand-picked and removed as part of the reinstatement. In most cases the trackway is removed following construction, although at Inner Trial Bank and Tetney Marshes the track is still evident.

More recently, projects have used a temporary trackway such as wooden bog boards (Project Breagh pipeline) or aluminium panels (Race Bank OWF). The boards or panels are laid in a continuous strip, over a geotextile membrane, and are attached together and pegged down to minimise movement especially during high tides. The use of these trackways has the benefit that they are quicker to lay and recover; distribute construction traffic weight more evenly over the sediment surface; and restrict construction traffic so that it remains in the defined work area.

The entire area constitutes the working width and is generally between 15m and 30m wide, so that it can contain the access track, soil storage areas and trench. Although for Project Breagh the working width was minimised to *c.* 5m where it crossed through an area of dune slacks. It is often appropriate for the working width to be fenced to prevent construction traffic accessing the wider landscape. However, the process of fencing installation needs to be considered as it may cause additional impacts (that outweigh the benefits) particularly in saltmarsh.

Photos showing the various stages of the open-cut construction method for the North Morecambe and Project Breagh pipelines are given in Photo Plate 5. Figure 95 provides an indicative illustration of the key construction phases using open-cut trenching methods through sand dunes.

Examples

South Morecambe

Detailed information on the construction and reinstatement measures for South Morecambe have been obtained from summary notes by Rae, (1983, 1984b, 1984c, 1984a) held by Natural England. The pipeline was laid between May and November of 1982. A working width of 25m on either side of the centre of the pipeline route was marked out with chestnut fencing. Within the 50m working width, a 4m wide causeway was constructed to allow land-based excavators to dig the pipeline trench during low tide. The causeway was constructed by covering the vegetated marsh with geotextile sheeting over which a layer of limestone hard-core was laid. Turves from along the trench in the upper marsh were lifted and stored during construction. The 2-3m deep trench was dug using an excavator with a long arm reach. To prevent slumping the trench was dug overly wide and deep. Once the pipe was laid and the sediment replaced, the upper marsh turves were returned to their original position. The causeway material was removed, although a permanent stone retaining barrier was constructed around the edge of the upper marsh to prevent sediment erosion.

Point of Ayr, Talacre Warren

At Point of Ayr, the pipeline installation across the sand dunes took place between mid-March and the end of July 1994. In most locations, a 30m wide working width was used (allowing for machinery access as well as the trench), this area was extended to around 60m where sand storage was required (*i.e.* in the dune/ mesotrophic grassland). To minimise the width of the breach the sides of the pipeline trench was sheet piled to retain the sand and prevent collapse. Throughout the process, areas of bare sand along the working width were protected to prevent sand loss and deposition, across more sensitive habitats using a water-based bitumen emulsion, which was spread over the sand surface (Environmental Resources Limited, 1993).

Photo Plate 5 - Open-cut construction methods at North Morecambe and Project Breagh.

Open-cut trenching method, showing long-reach excavators digging trench from trackway. Photos taken by J Swan in 1993 during the construction of the North Morecambe pipeline.

North Morecambe, pipeline laid out along working width (crossing saltmarsh and mudflats), using bottom-pull technique.

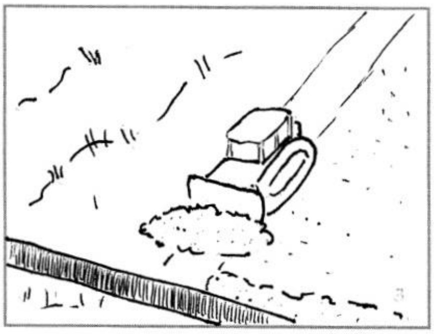
North Morecambe, showing limestone hard-core used for the access trackway .

Open-cut trenching at Project Breagh in 2011. Showing excavation of trench through sand dunes.

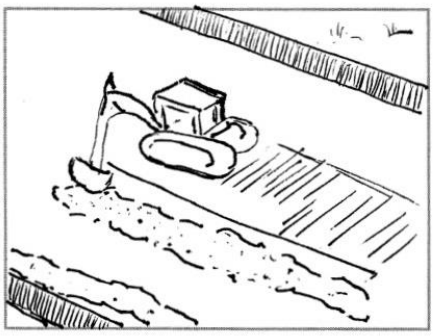
The Project Breagh pipeline laid out along the alignment prior to welding of the sections. Wooden boards used as trackway to provide vehicle access.

Dune slacks at Project Breagh fenced off to prevent access by construction traffic. The working width here was reduced to minimise impacts.

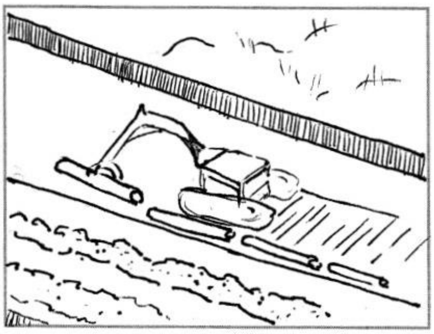
Figure 95 - Open-cut construction methods through sand dunes.



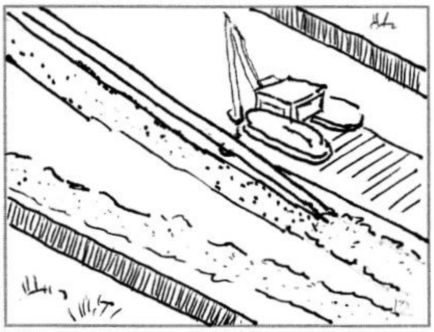
Installation of fencing to segregate working width. Harvesting of Marram and seed-material for restoration. Top-soil strip and storage along edge of construction area.



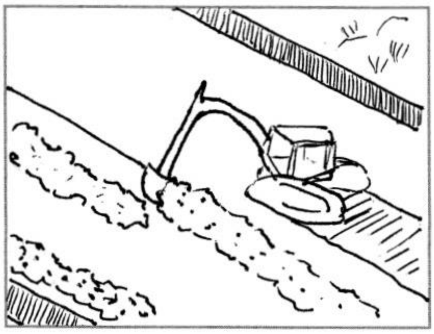
Low-pressure excavator and tracking allow access to dig trench. Sub-soil stored separately to top-soil.



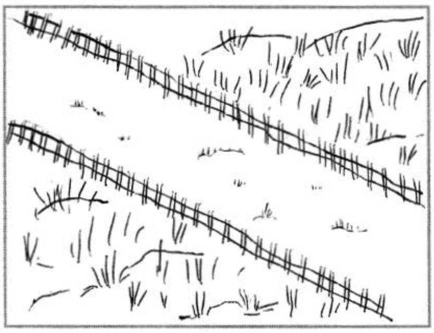
Pipeline laid out on along trench, and welded together in-situ.



Pipeline lowered into trench.



Trench back-filled with subsoil and then top-soil. Access track removed.



Post-construction restoration included redefining dune contours, planting Marram in mobile/ fixed dunes. Seeding of dune grassland using harvested seeds.

5.2.2 Cable Chain-cutter, Cable-plough

Over the last decade a number of cable burial methods have been developed to reduce installation costs and to speed up the cable-lay process (compared to open-cut methods). One of the resulting outcomes of this has been the potential to minimise the impact on sensitive habitats. Currently, these alternative cable-lay methods have been used more frequently in saltmarshes. With careful design, bespoke equipment can minimise impacts on the level of disturbance to birds and marine mammals, can maximise working times to avoid periods of high tides, and can reduce impacts associated with sediment compaction and vegetation loss. Various designs have been developed including bespoke cable burial ploughs, tracked chain-cutting machines and burial sleds. However, one of the major issues when using a bespoke method is that there is often little evidence (in terms of other nearby sites using the same approach) to present to statutory bodies as part of the impact assessment. It is therefore also difficult to design upfront mitigation and reinstatement as often the impacts will not present themselves until after construction. In addition, their use is often highly dependent on the underlying geology, surface sediments, required burial depth and length of cable being installed. Further details on cable burial methods are set out in BERR (2008).

Three cable-lay methods crossing saltmarsh are given as examples. At Thanet OWF and Race Bank OWF, bespoke cable-ploughs were used, while for the Lincs OWF a bespoke cable chain-cutter was used. These methods are described below.

Methods

Thanet Offshore Windfarm

For the Thanet OWF cable (Pegwell Bay, Kent) installed in 2009, several options for the cable-lay process were assessed prior to the installation. These included directional drilling (the original preferred method), open-cut trenching with turves lifted and then replaced and the use of a cable plough (Royal Haskoning, 2005a, Royal Haskoning, 2005b).

The 'as-built' method, involved using a cable plough system (Spencer ECA, 2014). The cable was installed in a 2m deep trench, in February 2010 during a period of neap tides. It crossed approximately 185m of saltmarsh, within a 15m working width. The works took approximately 4 weeks, although the actual time on the saltmarsh was *c.* 10 days (TEP, 2013). A field trial six-months previous allowed the methods to be finalised and agreed with Natural England and the Marine Management Organisation. Once the installation began, the use of the cable plough enabled the cable to be successfully installed across the entire saltmarsh in just a few hours using a small team of operatives. The cable was fed from a barge anchored at approximately 1.1km from landfall. The cable was supported along its length (using rollers and three low-ground pressure excavators) as the cable plough was pulled along by its independent power winch. The cable was then guided through the blade of the plough and positioned at a specified depth in a consistently formed narrow aperture, which was subsequently closed as the cable plough moved forward. This method of operation using the cable plough, caused fewer disturbances to the vegetation surface and sediment, when compared to using a conventional open-trench style of cable laying. Further protection measures to minimise the damage to the vegetation were also used, including using wooden bogs boards to create access tracks to protect the surface from heavy vehicles. Figure 96 provides an indicative illustration of the key construction phases using chain-cutting trenching methods for saltmarsh.

Lincs Offshore Wind Farm

In 2010, construction began for the installation of two cables associated with the Lincs OWF situated in The Wash, Lincolnshire. Initially HDD methods were proposed and agreed (Centrica Energy, 2007). However, due to unconsolidated sediment layers, that resulted in the loss of two drill pieces, it was decided that HDD methods were not suitable. After much research and discussions with statutory authorities an approach using a bespoke tracked cable-lay (Nessie III) and chain-cutter (Nessie V) was agreed. The methods outlined below are based on my own observations during construction as part of the ECoW, from the Bridge Watch (2010-2016) webpage, and TEP (2013). Photos are shown in Photo Plate 6. For the first cable, installed between mid-July and early-September 2011, the main activities were as follows:

- the sea defence was breached allowing vehicle access;
- Nessie V crossed the saltmarsh to meet an offshore barge holding the cable, with the cable subsequently loaded onto Nessie V;
- a low-ground pressure excavator, lay wooden bog boards across the upper marsh from the sea defence, allowing access to the creeks;
- flume pipes were placed in the creek channels using a low-ground pressure excavator. The flume pipes were required to maintain creek structure (creek shape) and function (maintain water-flow). The largest creek crossed by the works (known at Big Tom) was situated at *c.* 640m from the shore;
- Nessie V returned to the sea defence carrying the cable which it laid on the saltmarsh surface;
- trenching of the cable was completed by Nessie III, assisted by Nessie V (when it became temporarily stuck); and
- remedial works included removing flume pipes, and wooden bog boards and redistributing disturbed mud along the pipeline berm in the mid-upper marsh.

The second cable was installed the following summer (2012), following further discussions and the submission of a modified method statement, based on lessons learnt. Although the approach was similar to that outlined above the following key changes were made to the installation method to help minimise the impact on the marsh.

- work on the saltmarsh was restricted to good weather conditions (sunny, dry and windy), around a period of low-tides;

- a geotextile membrane was laid underneath the wooden bog boards, which were also strung together to help minimise board movement (encountered during the installation of the first cable);
- the geotextile membrane was also used in the creeks to aid flume pipe retrieval and to help minimise damage to the creeks structure;
- vehicle movements on the marsh were minimised;
- a steel tension rope was attached to Nessie III and an offshore vessel to steady the trenching machine;
- detailed emergency contingency measures were developed *e.g.* what should be done if one of the machines became stuck;
- the wooden bog boards were removed immediately after trenching operations;
- hand-tools and personnel on foot were used to replace lifted vegetation, and to re-open collapsed creeks;
- a low-ground pressure excavator was used to redistribute sediment from the mounded mud along the length of the cable into the trackways, on both the 2011 and 2012 cable routes; and
- creek repairs to Big Tom, were completed from the offshore vessels.

Race Bank Offshore Wind Farm

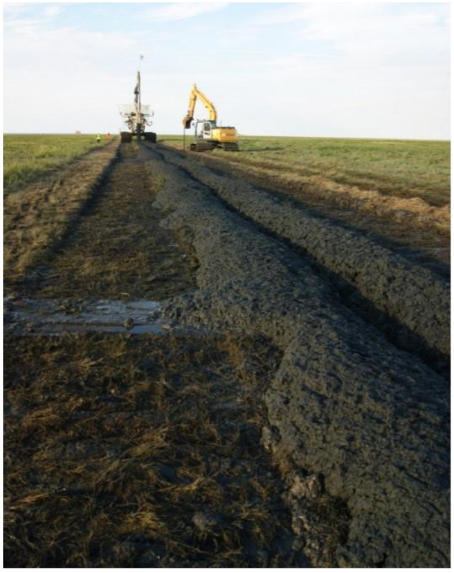
The Race Bank OWF required the installation of two cables crossing saltmarsh on The Wash, Norfolk (Bridge Watch, 2010-2016, Centrica Energy, 2009, DONG Energy, 2016). HDD methods were considered unsuitable following the completion of a geotechnical survey. An alternative approach was developed. This involved the design and build of a project specific cable plough, which was designed to be lightweight and exert low-ground pressures on the saltmarsh (with wide flat tracks). The cable plough was designed to cut a wedge in the sediment surface, drop the cable in as the soil was lifted, and then reclosed the sediment. The cable plough was assisted by a winch attached to an offshore vessel to help reduce the chance of it becoming stuck. An aluminium trackway was laid on the marsh surface to enable vehicle access. The project benefited from the lessons learned from the Lincs OWF although the increased use of the trackway by vehicles, resulted in compaction, and poor weather leading up to the installation, meant the saltmarsh surface was very soft, causing further damage. Both cables were installed in one year between May and September 2016.

Photo Plate 6 - Lincs OWF showing various stages of the chain-cutter trenching method.

Lincs Offshore Wind Farm. A creek on showing flume pipes designed to maintain creek structure and function during cable installation. The wooden bog boards provide vehicle access.

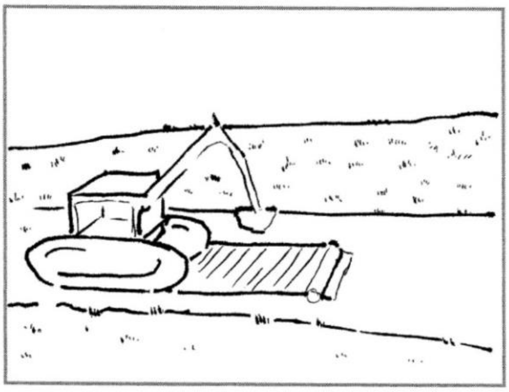
Lincs Offshore Wind Farm. The cable laid out on the saltmarsh surface prior to chain-cutting.

Lincs Offshore Wind Farm. Chain-cutter burying cable in saltmarsh. The photo shows the excess mud forming a berm along the route and creek flume pipes.

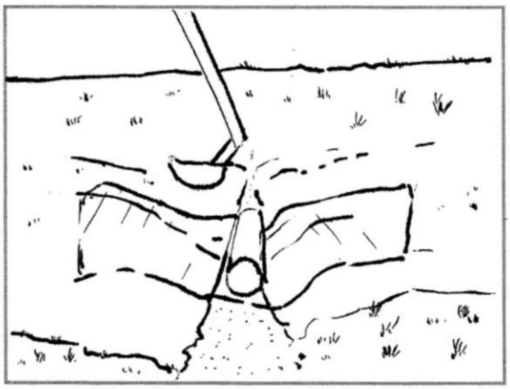


Lincs Offshore Wind Farm. Showing chain-cutter assisted by low-pressure excavator. The tracks of the vehicles show compaction along cable route.

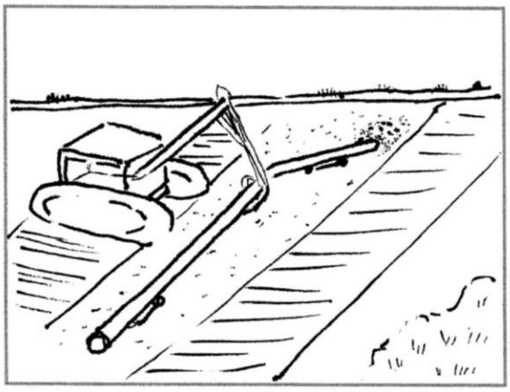
Figure 96 - Chain-cut construction methods through saltmarsh.



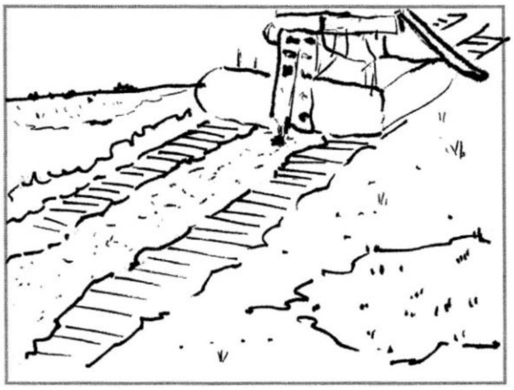
Low pressure excavators used to layout Terram and trackway to protect saltmarsh surface



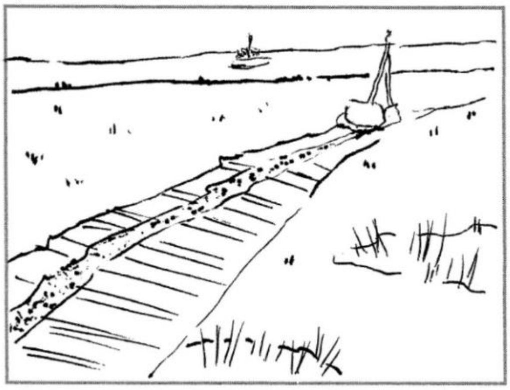
In creeks piping used with Terram to protect creeks, preventing collapse and maintaining tidal flow



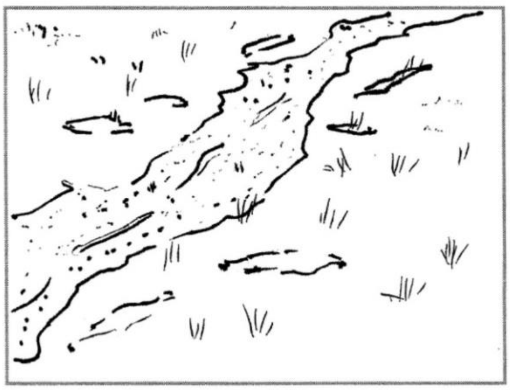
Cable laid out on rollers adjacent to trench line, or pulled along the rollers inland from offshore barge



Chain-cutter or plough lifts and buries cable in trench, which it digs and fills



Trackway and Terram lifted and returned to shore



Post-construction restoration may include re-contouring marsh to remove excessive mud from local areas and infill holes/ tracks. Creeks restored.

5.2.3 Horizontal Directional Drilling

One of the most preferable methods for pipeline and cable installation is to use directional drilling techniques (often termed Horizontal Directional Drilling HDD). This method is typically used at sensitive habitats, as it minimises disruption and damage to just a localised area at the drill site entrance and exit points. With careful planning entrance and exit points can be located in areas with low ecological value. These areas can then be reinstated at the end of the installation process when the directional drilling equipment leaves the site. The use of directional drilling is restricted to sites with solid rock or sedimentary material, as the drilling head can become damaged or lost in silt or soft mud (as Lincs OWF). In addition, the length of cable or pipeline that can be drilled in one section is also limited to *c.* 2km. Figure 97 shows the three main phases of directional drilling. HDD was used for the Teesside OWF, Walney Extension OWF, and is currently being used for the Nemo Link project. In addition, HDD methods were used to pass under the mobile and fore dunes at Project Breagh to minimise the risk of tidal ingress.

Teesside Offshore Wind Farm

The cable associated with Teesside OWF used directional drilling methods under the dunes at South Gare & Coatham Sands SSSI to avoiding damaging the dune vegetation (EDF Energy (Northern Offshore Wind) Ltd., 2004, Entec, 2008). However, a small area of dune slack vegetation appears to have been lost (during the construction of the temporary work compound), situated at the edge of the SSSI, adjacent to the industrial slag heaps.

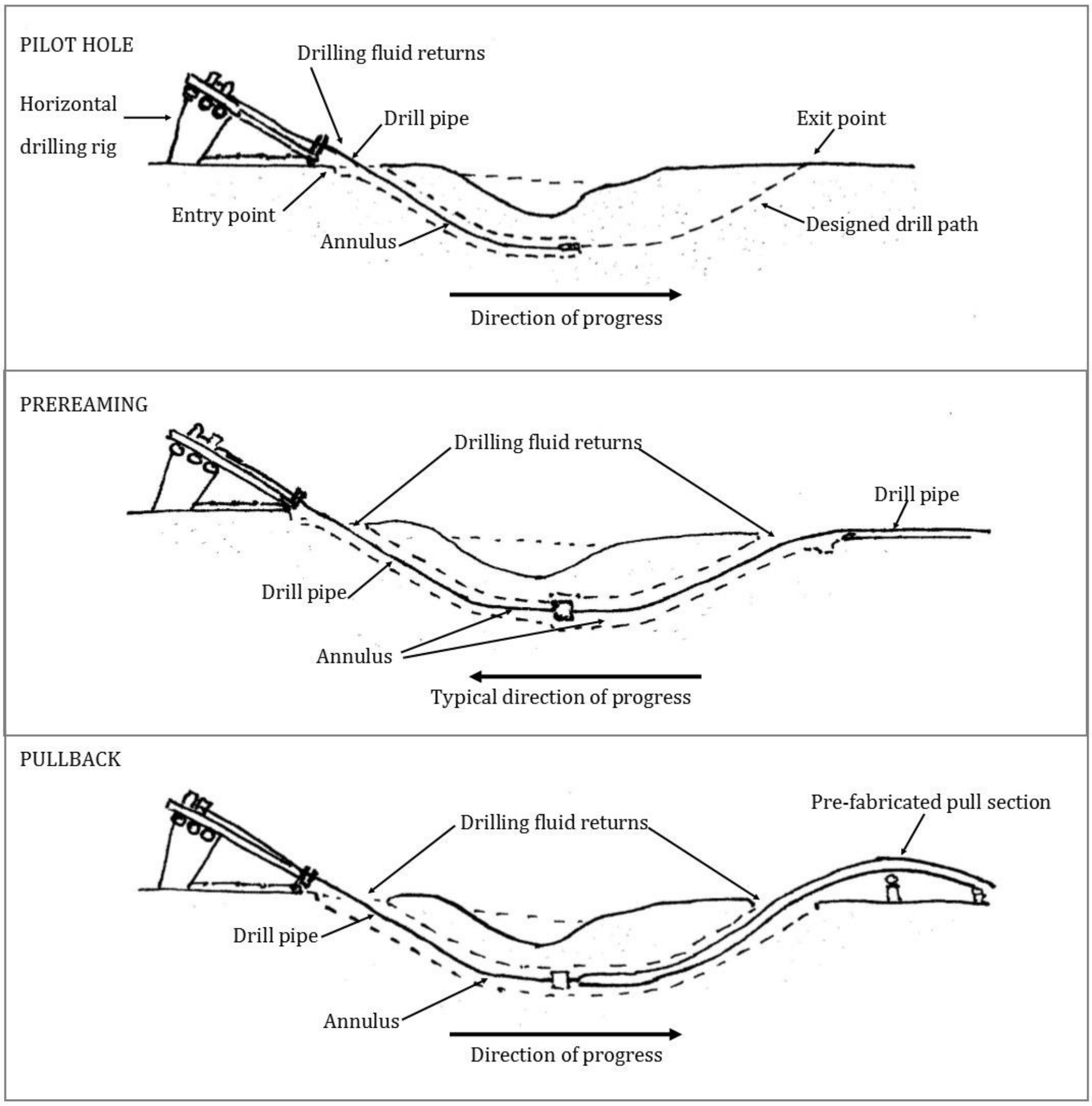
Walney Extension Offshore Wind Farm

Horizontal Direction Drilling was used for this project and as a result the saltmarsh habitat and small area of sand dune fore dunes at Middleton Marsh were avoided during construction (DONG Energy, 2013).

Nemo Link Interconnector

The Nemo Link project (currently being constructed in 2017) connects the UK and Belgium using subsea and underground cables which enables trading of surplus electricity between the UK and Europe. In the UK, the cable makes landfall at Thanet, Pegwell Bay, close to the Thanet OWF cable (Nemo Link, 2012, TEP, 2013). In Belgium, the cable makes landfall at Zeebrugge, where it crosses the beach and an area of dune vegetation known as De Fonteintjes. The use of Horizontal Direction Drilling methods at both landfalls means damage to saltmarsh vegetation in the UK and damage to the sand dunes is avoided.

Figure 97 - Horizontal Directional Drilling (HDD) method.



5.2.4 Summary of Construction and Reinstatement methods

Tables 36 and 37 provides a summary of the construction and reinstatement activities that were completed at each of the saltmarsh and sand dunes sites. In addition, I have included other projects that have been recently constructed, which show different working methods of interest to this thesis.

Table 36 - Saltmarsh site construction and reinstatement methods.

Case study	Years since installation	Construction method				Reinstatement method								ECoW used
		Open cut from temp trackway	Open cut from permanent causeway	Chain-cut, plough *etc.*	HDD	Natural regeneration	Seed harvesting	Plugs or pot grown plants	Turves (upper marsh)	Plant fragments (rhizomes, clumps)	*Spartina anglica* planting	Sediment capture	Creek reinstatement	
South Morecambe pipeline	1982	✓	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗	✓	✓
North Morecambe pipeline	1993	✓	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗	✗	?
Rivers Fields pipeline	2003	✓	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗	?
Cleavel Point pipeline	1986	✓	✗	✗	✗	✗	✗	✗	✗	✗	✓	✓	✗	✓
Shotover Moor pipeline	1986	✗	✓	✗	✗	✗	✗	✗	✓	✓	✗	✗	✗	✓
Wytch Moor pipeline	1986	✗	✓	✗	✗	✗	✗	✗	✓	✓	✗	✗	✗	✓
Thanet OWF	2010	✗	✗	✓	✗	✓	✗	✗	✗	✗	✗	✗	✗	✓
Inner Trail Bank	1972	✗	✓	✗	✗	✓	✗	✗	✗	✗	✗	✗	✗	?
Tetney Sealine Pipe	1969	✗	✓	✗	✗	No information								?
Morrich More pipeline	1990	✓	✗	✗	✗	✓	✗	✗	✗	✗	✗	✗	✓	?
Lincs OWF	2011-2012	✗	✗	✓	✗	✓	✗	✗	✗	✗	✗	✗	✓	✓
Race Bank OWF	2016	✗	✗	✓	✗	✓	✗	✗	✗	✗	✗	✗	✓	✓
NEMO Link	2017	✗	✗	✗	✓	No information, but as HDD methods used reinstatement was probably unnecessary								?
Walney Extension OWF	2013	✗	✗	✗	✓	No information, but as HDD methods used reinstatement was probably unnecessary								?
Corrib pipeline	2013	✓	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗	✗	✓

Table 37 – Sand dune site construction and reinstatement methods.

Case study	Years since installation	Construction method		Reinstatement method										ECoW used
		Open cut from temp trackway	HDD	Dune topography	Natural regeneration	*Ammophila arenaria etc.*, planting	Seed harvesting	Plugs or pot grown plants	Turves	Topsoil and nursery seed crop used for rapid revegetation	Creation of low-lying areas/ scrapes	Bitumen spray to stabilise sand	Sand capture *e.g.* chestnut palling or hessian	
AMCO CATS pipeline	1991	✓	✓	✓	✓	✓	✓	✓	✓	✗	✗	✗	✓	✓
Project Breagh pipeline	2011-2012	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓	✗	✓	✓
Teesside OWF	2013	✗[83]	✓	✗	✓	✗	✗	✗	✗	✗	✗	✗	✗	?
Point of Ayr pipeline	1994	✓		✓	✓	✓	✓	✗	✗	✗	✓	✗	✓	✓
Tetney Sealine Pipe	1969	✓[84]	✗	No information										?
Cruden Bay pipeline	1973	✓	✗	✓	✓	✓	✗	✗	✗	✓	✗	✓	✓	?
St. Fergus pipelines	1975-1976	✓	✗	✓	✓	✓	✗	✗	✗	✓	✗	✗	✓	?

[83] Construction compound built in dunes at Teesside OWF
[84] The Tetney Sealine Pipe was constructed from a permanent causeway.

Figure 98 - Potential short-term impacts of construction on saltmarsh.

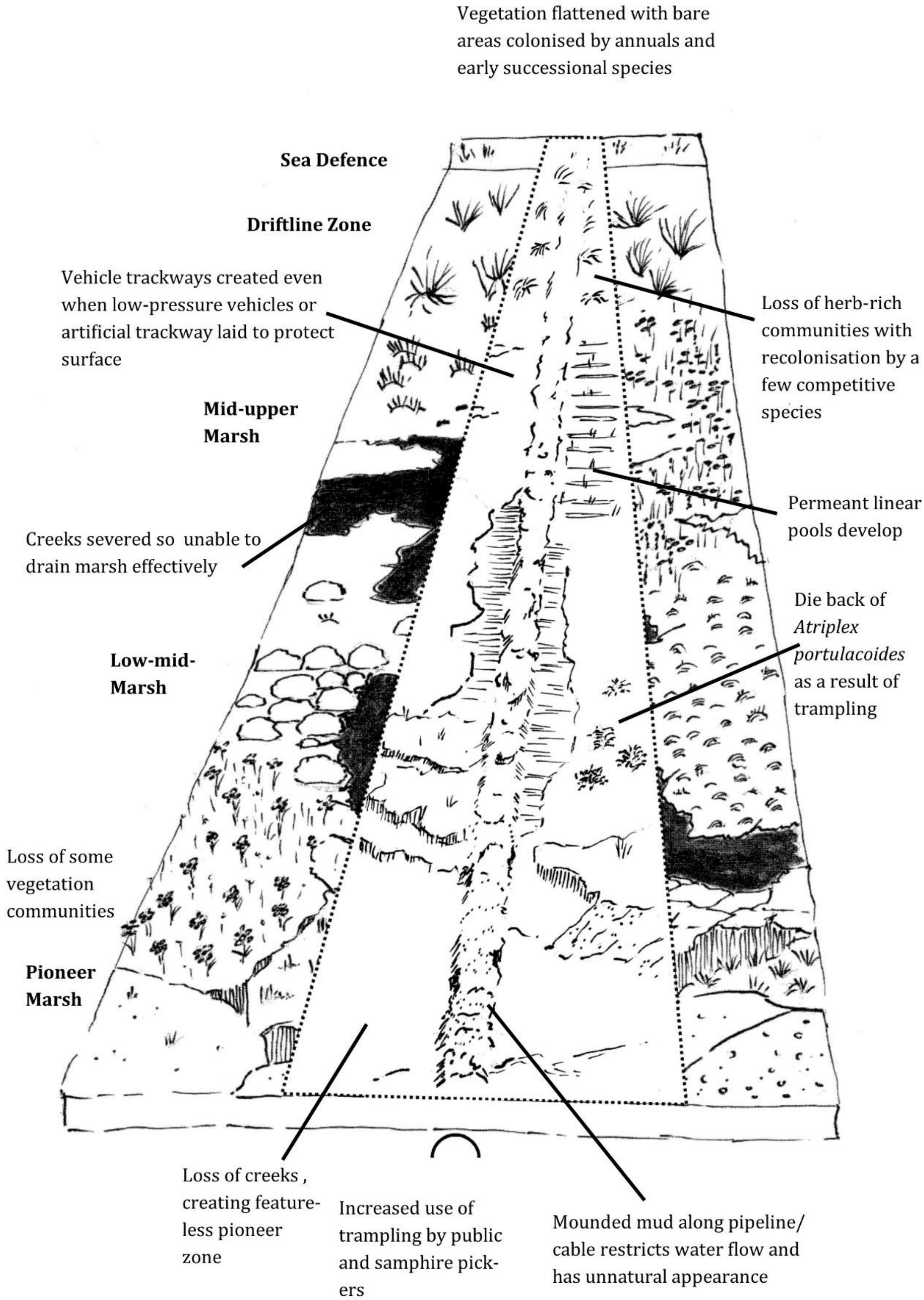
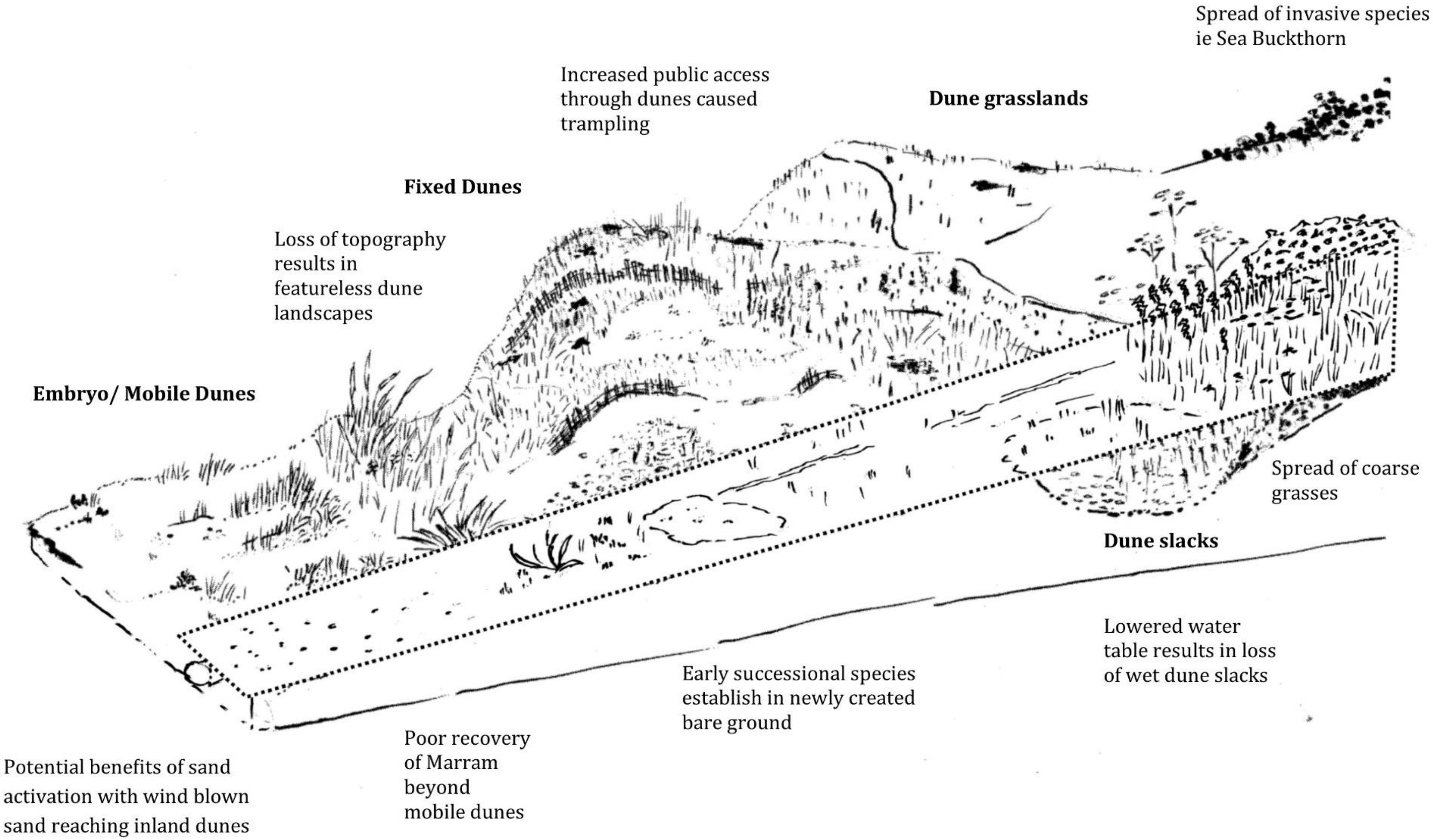


Figure 99 -Potential short-term impacts of construction on sand dunes.



5.3 Role of the Ecological Clerk of Works

The National Academies of Sciences (2017) notes that construction monitoring, during the project implementation stage, should be undertaken to ensure design specifications are met.

During construction, one of the most important team members is the Ecological Clerk of Works (ECoW), whose role is to oversee (and minimise) any construction actions that may result in an ecological (or environmental) impact. The ECoW main role is to ensure project compliance with planning consents, environmental permits, legislation, and protected species licences. With an over-arching goal to translate mitigation requirements into practical measures on the ground.

The ECoW should have sufficient experience in working with contractors, with knowledge of the project, construction processes and ecology of the site, to enable on the ground decision-making. Communication skills are vital when working closely with contractors so as to resolve potential technical difficulties as they arise. The ECoW needs to have confidence in handling difficult situations and be ready to stop works where necessary.

The ECoW is expected to raise environmental awareness to site staff through tool-box talks and site inductions, as well as to attend meetings with project managers to discuss any changes to the prescribed working methods. A key part of the role is to record those decisions so that the construction methods are documented, often through a daily diary. These ECoW records can be used as evidence to show that best-practice methods were used. The ECoW also plays an important role in liaising between contractors, project managers, stakeholders and local residents.

From reviewing the various EIAs for the projects included as my case studies, it appears that ECoW were used for the majority of the installation projects (as shown in Tables 43-44).

There is much information available on the role of an ECoW (Burns and Jackson-Matthews, 2016) and through the Institute of Environmental Management & Assessment (IEMA) and CIEEM.

5.4 Saltmarsh Restoration

5.4.1 General

The restoration (and creation) of saltmarshes has been widely documented, and case studies from across the UK (and elsewhere) have been identified in key literature reviews (Adnitt et al., 2007, Brooke et al., 1999, Zedler and Adam, 2002). The majority of the examples have come about as a result of managed realignment driven by flood coastal defence which has been completed in the

UK since the 1990s (Davy et al., 2011, French, 2006, Garbutt et al., 2006, Hughes et al., 2009, Mossman et al., 2012a, Reading et al., 2008).

Boorman (2003) identifies four main requirements that lead to saltmarsh development:

- a relatively flat stable area of sediment that is covered by the tide for a shorter amount of time than it is exposed;
- an adequate supply of suitable sediment available within the tidal window;
- sufficiently low water velocities to enable some sediment to settle out; and
- a source of plant material *i.e.* seeds or propagules to colonise the bare sediment.

For the restoration of existing saltmarsh habitats following the installation of pipelines/cables, these requirements need to be met, if restoration is to be a success; and although they are likely to have been in place prior to construction, they may have been modified by the works.

Davy (2002) notes that plant communities are dynamic, reflecting historical and current successional processes that involve interactions between species and between the vegetation and abiotic environment. Disturbance or damage to an ecosystem is likely to affect all aspects of its successional status meaning that the likelihood that it recovers to its original state is low without the restoration of the physical and edaphic environment.

The following section therefore focuses on the re-establishment of halophytic plant species following loss or damage (*i.e.* planting methods and species choice) and the need for site engineering to help vegetation recovery, for example, by reducing impacts from wave energy, aiding drainage and recreating original site topography. Post-construction management may also be required to control the use of vehicles and trampling by the public in restored areas, by using fencing and signage.

5.4.2 Species Selection

In most situations following construction, the objectives for vegetation re-establishment will be to recreate what was lost. Therefore, the selection of appropriate species will focus on the success of reinstating those species present prior to work. In previously degraded habitats where development occurs it may be appropriate to undertake enhancements to increase species diversity. Brooke et al. (1999) includes a review of the key British saltmarsh plant species providing details of their growth characteristics that can aid or hinder recovery and details the best propagation methods and recovery times (Appendix 5 Table 46). For each species, Brook undertook a screening exercise that focused on identifying species that:

- are sufficiently robust to withstand storm conditions, help prevent erosion of the seawall or cliff face, without encouraging macro/micro-level erosion in the saltmarsh;

- are able to help reduce wave energy and promote sediment accretion;
- are able to grow in each of the various tidal zones; and
- are able to recolonize naturally, both initially and within a 2-3-year period.

The screening exercise identified three groups of species:

1. species which appear to be potentially useful for seeding and/or planting to establish and maintain saltmarsh, or as pioneer planting to encourage natural regeneration *e.g. Puccinellia maritima*, *Salicornia* spp. and *Spartina anglica*;
2. species which could form part of a species mix from (1) in order to increase species diversity; or which may be suitable for introduction as the marsh matures following its initial establishment *e.g. Aster tripolium*, *Atriplex prostrata*, and *Atriplex portulacoides*; and
3. species which may require planting or seeding, if upper marsh vegetation is required or damaged *e.g. Festuca rubra*, *Limonium vulgare*, *Plantago maritima* and *Triglochin maritimum*.

Mossman et al. (2012b) looked at the differences in biological and environmental characteristics between managed realigned sites, accidentally realigned sites[85] and natural saltmarsh. The sites were of different ages ranging from 1 to 14 years old for managed realigned sites and 25-131 years for accidentally realigned sites. The study found a number of interesting findings which have implications for restoration of sites following pipeline/cable installation, these are summarised below:

- saltmarsh plant species rapidly colonised sites; but although species-richness of the whole site was similar to natural marshes within a year, plant communities in individual quadrats was not equivalent;
- mature realigned sites (*i.e.* after 50 years) were more similar to natural marshes, but some differences remained in terms of species diversity and abundance; and
- species such as *Atriplex portulacoides*, *Limonium vulgare*, and *Armeria maritima* were less frequently recorded at managed realignment sites.

5.4.3 Natural versus Assisted Regeneration

There are two main options for vegetation establishment; natural regeneration, and assisted regeneration (through planting or seeding), although often a combined approach is used. The use of natural versus assisted regeneration is largely determined by the existing environmental conditions, extent of damage and specific requirements set out by statutory bodies.

[85] Sites where for example sea wall had been breached and not subsequently repaired.

Natural Regeneration

In many instances, the preferred method for reinstatement is through natural regeneration allowing existing plant material *i.e.* seeds (from the seed bank), root fragments and rhizomes to become established. This has the benefit of material being local and typical of the site, with plants naturally finding their own niches. In addition, the cost of planting is avoided. The main disadvantage is that there will be a delay before vegetation establishes itself and this can lead to increased rates of erosion, scouring, collapse of creeks, and the creation of hypersaline pans. In addition, the species diversity and composition of these marshes may be altered in at least the short-term, as the availability of material from an individual species may be limited. One of the critical considerations for natural regeneration is soil handling techniques during construction, avoiding double handling and returning soil material back to its original profile. Vegetation recovery through natural regeneration was the approach used at two of the saltmarsh case study sites *i.e.* Thanet OWF and Inner Trial Bank. It is also likely that Tetney Sealine Pipeline was left to naturally revegetate. More recently both Lincs OWF and Race Bank OWF used this approach.

Mossman et al. (2012a) studied the success of species colonisation through natural regeneration at a managed realignment site in Brancaster in Norfolk. The study showed that initially the number of species increased yearly until it reached a maximum in year 4, when it approached species-richness values similar to local mature marsh. By year 5, 26 species had been recorded which represented 76% of the local species pool. The annuals *Salicornia europaea* and *Suaeda maritima* were the first species to become established, however surprisingly, eight perennial species including *Atriplex portulacoides* and *Puccinellia maritima* became established in the first year. Other species such as *Limonium vulgare* and *Spartina anglica* took longer arriving in year 2, whereas *Armeria maritima* and *Plantago maritima* did not appear until year 4. The study also found that the annuals *Salicornia europaea* and *Suaeda maritima* were found at higher levels of abundance than in the surrounding mature marsh, but that the perennial species were much less frequent.

Bossuyt et al. (2005) undertook studies into seed bank diversity and longevity in saltmarshes in Belgium. The study compared the similarity of the seed bank to existing vegetation. The vegetation of the study sites had 67, species, while the seed bank contained over 85 species, and a high seed density. Seed from the annuals *Chenopodium rubrum*, *Sagina maritima, Salicornia* sp., *Spergularia* spp. were the most abundant. These species tended to contribute to a large extent of the vegetation. However, there were also many seeds from nutrient-rich marshes and grasslands. Bossuyt found that the annual species had a persistent seed bank, but some target species (especially perennials) were missing *e.g. Puccinellia maritima*. With regards to pipeline/ cable installation, information on the seed bank is important in providing an understanding as what plant communities may develop. However, I have found that vegetative spread of rhizomatous/

stoloniferous species are often the most important means of vegetation recovery along the pipeline/ cable corridor, with lateral spread key to restoring plant communities similar to the surrounding vegetation. For example, at Lincs OWF, *Puccinellia maritima* had spread out from the retained plants by at least a metre, within a couple of growing seasons.

Assisted Regeneration

Alternatively, assisted regeneration can be used through planting and/or seeding. There are many examples where the results of assisted planting and seeding methods have been examined (Brooke et al., 1999, Handa and Jefferies, 2000, Sparks et al., 2013).

Seed Harvesting

Seeds can be obtained through harvesting areas of unaffected marsh (donor sites) adjacent to the site[86] or collection and storage of material from the site itself prior to work. Seed harvesting methods include vacuuming, using a brush-harvester, collection of strandline material, sweeping using a net, or hand collection of individual seed heads (depending on the species). One difficulty in collecting seed material can be the variation in the natural production of seeds making seed harvest unreliable, added to this are difficulties with poor weather conditions at the time of collection (Brooke et al., 1999). Therefore, the availability of seed material cannot be guaranteed.

In the UK, most species will flower over the summer and seed collection should be taken in late summer/ autumn when the seed is mature and dry before it is naturally shed. The optimal time for seeding is from mid-spring/ early summer (after any potential winter storms, but before dry hot summer conditions) around a series of low tides. Depending on the species collected, storage of seeds may require over wintering in cold refrigerated conditions to break dormancy and also may require scarification of the seed coat to aid germination, viability testing is advisable. Depending on the collection methods used, seed may also require sorting and cleaning of debris (Boorman, 2003).

None of the reviewed saltmarsh case studies recorded have used seed harvesting as a method, for reinstatement. Considering the issues associated with poor seed viability and germination (as discussed in *Section 3.9* and the results of seed sowing for reinstatement at Tollesbury managed realignment site), this makes sense. It is considered that reinstatement using seed harvesting should only be considered in areas of upper marsh where there is a sufficient time period between high tides. There may be a case for hand collection of specific species seed, such as *Limonium* spp. which could then be sown and grown-on as plugs for replanting at a later date, once established.

[86] with the landowner's consent, and approval from relevant statutory body

Commercial sources for seeds and plant material may also be sought, however the range of species is generally limited, and it is unlikely that the material will be of local (if even native) stock. Therefore, this approach is generally not recommended and is likely not to be agreed with the relevant statutory body. Alternatively, commercial seed suppliers could be asked to collect material from the site and grow this material on. This has the benefit that seeds are stored and processed correctly.

At Tollesbury, Essex, five techniques (Garbutt et al., 2006, Reading et al., 2008) were used to aid the process of re-vegetation these were; (1) saltmarsh seeds collected from adjacent marshes and sown at a low density ($500m^{-2}$); (2) saltmarsh seeds sown at a high density ($5000m^{-2}$); (3) saltmarsh plants were collected from the nearby marsh and propagated in greenhouses with plug plants planted in an random arrangement in a 2×2m grid; (4) turves of vegetation ($0.12m^2$ by 0.15m deep) were collected and planted in groups of four per one-metre square; and (5) untreated control *i.e.* left to naturally regenerate. The study showed that mortality rates for both the plugs and turf was extremely high (97%) and that there was no germination from the seeds sown treatment. *Aster tripolium* and *Puccinellia maritima* accounted for 95% of the surviving plant species. In 1996, a year after the study began, outside the treatment areas, *Salicornia europaea* was found at low densities of one plant per $10m^2$, this was followed by three species in 1997 (*Suaeda maritima*, *Sarcocornia perennis* and *Spartina anglica*). By 2001, 15 species had been recorded and in 2007 21 species. It was recommended that in low energy environments, located near natural marshes, a site should be left to regenerate naturally. The study found that there was rapid natural regeneration of pioneer and low marsh species, but high marsh species were under-represented. In addition, the dense cover of *Puccinellia maritima* restricted gaps within the vegetation into which other species could colonise.

Planting

Plants can be obtained through lifting individual rhizomatous plants and sub-dividing them, collecting rooted stoloniferous material or by lifting turves and vegetated plug. It may be appropriate to establish rooted plants in plant cells grown on at a 'nursery site' or plant immediately on site.

Where transplanting rooted plant material is an option, permission needs to be sought from the landowner. The collection of plant material from nearby donor sites may be difficult (as they are likely to be designated), and therefore discussions with the appropriate statutory body is important (Nottage and Robertson, 2005). In addition, consideration is required as to the species-composition of the donor site ensuring its species composition is similar and appropriate to the receptor site. Alternatively, lifting turves or plugs from the site itself, prior to construction, may be an option and this could provide a valuable source of material.

As part of the Corrib Gas Onshore Pipeline in Co Mayo, prior to construction saltmarsh, cobbles and the top benthic layer of intertidal sediments (*c.* 300mm in depth) were temporary translocated as turves to an adjacent site while the pipeline was laid, before being returned to their original position (Neff, 2014, O'Sullivan, 2010). The main challenges included the temporary storage of the turves at the correct height in the intertidal zone for as short a period as possible; and then reinstating those turves at the correct elevation to ensure the correct vegetation type was maintained. The GPS location of each of the 182 saltmarsh turves were recorded before being lifted, and their location in the temporary storage area mapped, so that each turf could be returned to its original location after pipeline installation. The turves were lifted and stored for 10 days during pipeline installation. The reinstatement was considered a success. In an article on the site by the Irish Times (Murtagh, 2015) it is noted that the Biodiversity Consultancy of Cambridge undertook an independent review of the project, and "*concluded that the project had been so carefully managed from an ecological point of view that by 2020, there will be no net loss of biodiversity – and possibly even a net gain*".

Saltmarsh turves were also used to restore the upper marsh at South Morecambe, which was a planning condition. The turves were obtained from a nearby site known as Silverdale Marsh. The 1984 survey reports (Rae, 1984a, 1984b, 1984c) notes that the marsh was re-turfed in June 1983 when tidal conditions were suitable. However, the reports also note that about a third of the reinstated turves died in the first year after an exceptionally dry summer. By the following spring, the turves were showing signs of recovery, but it was apparent that they needed a longer period to fully establish and knit together. In areas where the turves had completely died the root mat had helped stabilise the sediment and the bare ground was being recolonized by *Salicornia* spp. The report concluded that following a wet autumn in 1984 there was excellent vegetation recovery. For both North Morecambe and the Rivers Fields pipeline turves from the site were lifted prior to construction and were reinstated following installation.

The three sites at Wytch Farm, were also subject to reinstatement by planting. At Cleavel Point, *Spartina anglica* was planted (a common practice at the time to prevent sediment erosion) and wooden pilings and brushwood fencing were placed along the eroding edge to capture sediment. At Shotover Moor and Wytch Moor intact turves were lifted prior to construction and replaced following the installation of the pipeline. A minimum turf depth of 0.5m was recommended. In addition, it notes that patches of *Bolboschoenus maritimus* were returned to their original position (Adnitt et al., 2007, Brooke et al., 1999, Gray, 1986, 1985, Gray and Benham, 1986).

One further consideration is site access, which can cause difficulties in lifting larger turves as vehicles (even tracked ones) can cause significant sediment compaction and crushing of vegetation. Alternatively rather than lift entire turves, one option is to take cores 'plugs' of 80-150mm in diameter and to a depth of 150mm (using for example a bulb planter) (Brooke et al., 1999). Material can then be collected from a number of different locations limiting the damage even on a protected site. The other benefit of using plugs is that it includes native soil which has an the advantage of transferring seed and facilitating seedling emergence (Handa and Jefferies, 2000).

Sparks et al. (2013) undertook a study on plug planting densities. They used larger sods (25cm^3) so to encompass whole plants and aid sediment stability while being transported. They found that the half density plots (*i.e.* planted with 50% vegetation cover) had almost reached full vegetation cover after 2 years, and therefore planting at full density was generally unnecessary. The study also involved revisiting the donor site (1 year after harvest) and recording the condition of the marsh where sods had been removed. They found that the majority of sod holes had been refilled through natural sediment deposition and were beginning to revegetate.

Further difficulties arise with turf storage as the turves and plugs cannot be stacked and require regular watering and attention (as found at both Corrib Gas Onshore Pipeline and South Morecambe). As with seeding the optimal time for planting is from mid-spring/early summer. Hot weather should be avoided to avoid the shock of being transplanted. Spacing of plants depend on the required speed of the results and the aim of reinstatement. For example, if sediment stabilisation is the main aim then denser plantings will provide quicker vegetation recovery; but where the focus is on increasing species diversity or restoring vegetation communities then plantings may be further apart.

Assisted regeneration through sowing or planting (as part of mitigation) requires forethought as it may require 1-2 years lead in time for sufficient adequate stocks to be attained. In addition, there are significant costs associated with this method.

5.4.4 Engineering Options

Topography and Sediment Recharge

Lessons can be learned from the engineering techniques used for habitat creation and restoration projects, as well as previous pipeline and cable projects that aid understanding of restoring post-construction sites.

Saltmarsh soils are frequently waterlogged and anaerobic, and the relatively flat topography means tidal waters drain slowly. Young marshes at low levels of elevations are subject to rapid sedimentation as they are frequently flooded and submerged for longer periods. As a marsh matures and increases in elevation the rate of sedimentation declines rapidly (Hughes and Paramor, 2004, Pethick, 1981).

French (2006) noted that elevation is key to vegetation establishment; commenting that in the USA it is common to use dredged material to increase the surface elevation prior to planting or natural regeneration. French and Burningham (2009) showed that cohesive dredged sediments can be used to restore degraded mudflats and saltmarsh habitats in low wave energy sites. At North Shotley, Suffolk in the outer Orwell estuary, sediment recharge was completed in 1997, and was monitored for a 10-year period. During this period there was ongoing dewatering and compaction of the mud (with an increase in shear strength), and eventual colonisation of saltmarsh species. Apart from a few scattered *Spartina anglica*, no significant saltmarsh colonisation occurred until August 2000, when *Suaeda maritima* and *Salicornia europaea* were recorded forming a narrow *c*. 2.5m wide band; this increased so that by 2003 the band was between 20-30m wide. By 2008 a more-or-less continuous cover of halophytes were recorded over *c.* 80% of the area. This supported *Atriplex portulacoides*, *Aster tripolium*, *Limonium vulgare*, *Puccinellia maritima* and *Spergularia marina*.

In a recent review of managed realignment projects, Lawrence et al. (2018) concluded that for future managed realignment sites topographic features (such as small creeks and hillocks which increase drainage) should be created to create more naturally functioning marshes. This has relevance to the pipeline corridor which following installation often results in low-lying depressions that hold water, and have poor vegetation establishment.

ABPmer (2017) have undertaken a review of projects in the UK that have used fine dredge sediments to recharge inter-tidal areas. Typically, donor sites include navigation channels, ports, and marinas where sediment disposal is necessary to maintain their function, with most of the dredged material dumped at sea. There is a growing recognition that these dumped sediments could provide biodiversity gain through habitat creation (currently <1% of sediments are used in this way). The study considers projects and techniques as well the potential costs. The use of dredged sediments following pipeline/ cable installation to restore topography, and recharge lost sediments is yet to be attempted; however, in certain situations where a site shows slow natural sediment recharge and consequently poor vegetation recovery, this approach may be acceptable.

ABPmer highlights the main techniques for sediment extraction from the donor location and dispersal at the receptor site. These include using a barge-mounted excavator (where both the donor and receptor sites are accessible by water), or a pumped system (in less accessible locations) where sediment is collected and transported to a site by pipe. Alternatively, a combination of barge -mounted and pumped systems can be used.

In 2012 as part of Lymington Harbour's consent condition for the creation of a new breakwater, a saltmarsh habitat replenishment scheme was developed (Lowe, 2013, 2012). The scheme used dredged sediments from the adjacent harbour which was piped over the saltmarsh to a discharge pen situated along a main creek. Sediment retention structures were installed to promote pooling and sediment settlement. Sediment deposition levels were monitored during and after pumping work. The depth of sediment deposition was greatest along channels (estimated to be 0.5-0.7m in places), while further away deposition rates of between 0.09 and 0.22m were estimated. Photos from early 2013 shown in the summary report (Lowe, 2013) show plants (probably *Salicornia* spp.) growing in the centre of the discharge pen.

Pipeline and cable works can also result in raised areas of mud, along the pipeline/ cable length where sediments do not redistribute themselves back into the trench; or where vegetation and sediments are caught up in vehicle tracks. These raised areas form artificial berms or islands which disrupt water flow and can result in a change of vegetation both on the berm, but also around it. A berm of raised mud was created along the Lincs OWF cable and reinstatement works using a low-ground pressure excavator (and locally hand tools) was necessary to redistribute the sediment (Bridge Watch, 2010-2016). At Tetney Marshes a raised causeway was built parallel to the pipeline from which construction works were completed. Large sections (*c.* 775m) of this causeway remain in-situ, reaching 1-2m in height at several locations. The vegetation along the causeway is a mixture of *Elytrigia atherica* on the banks and mesotrophic grassland along the top.

Sediments and Drainage

It is known that poor drainage and consequently poor soil health on a saltmarsh is linked to poor vegetation establishment (Crooks et al., 2002, Davy et al., 2011, Mossman et al., 2012a). In such circumstances, it is probable that restricted local drainage is the cause of hypoxic sediments[87]. Compaction by earth-moving equipment (even those with low-ground pressure tracks) during construction and the subsequent restoration phases may affect local drainage (resulting in flooding) and cause low redox potentials. At South Morecambe (Rae 1984c), noted that surface water tended to lie on parts of the marsh along the causeway (presumably due to soil compaction), and these areas remained unvegetated. A similar issue was recorded at Lincs OWF.

Construction may also cause a more homogenous sediment surface with fewer creeks, which can result in slower drainage. Impeded drainage and bacterial decomposition of buried plant matter from the underlying soil surface can also cause anoxic conditions in low lying areas.

Mossman et al. (2012b) study took soil samples from the managed realignment sites and compared them against mature undisturbed marsh. Samples were taken at similar levels of elevation and the redox potentials recorded. In the mature marsh, redox potentials were high (average 117mV), compared to those at the managed realignment sites (average 34-99mV).

[87] oxygen concentration <63µM

Wider studies have also linked waterlogged soils with low redox potentials with poor vegetation establishment (Crooks et al., 2002, Davy et al., 2011).

Adnitt et al. (2007) notes that sediment grain size and depth and compaction all influence vegetation growth. Noting that plant establishment is likely to be more successful in well oxygenated sandy sediments with a firmer foundation (as sandy soils may require higher energy to erode). Adnitt also notes that compacted soil will inhibit root growth (so it is always recommended to use low-ground pressure equipment when undertaking restoration work).

The creation of artificial creeks or reinstatement of damaged creeks following pipeline/ cable installation may be necessary to aid drainage. Defra/ Environment Agency (2004) notes (with reference to managed realignment sites) that as natural development of a creek system is slow, and appears to only develop in newly accreted sediment (Reading et al., 2008), excavation of a drainage system should be considered, particularly for large sites.

At the WWT Steart Marshes managed realignment site in Somerset, a new creek system was dug across reclaimed farmland to the tidal breach (Photo Plate 7). The new creek was 2900m in length resulting in the excavation of 489442m^3 of sediment (McGrath and Jenkins, 2014). A creek system was also developed at the Freiston Shore managed realignment site in The Wash. Channels were initially cut into the agricultural soil based on the location of the original creek system, identified in aerial photography (Environment Agency, 2008). It is noted that the original 'starter' creek system has since widened and eroded to form a more complex system. However, parts of the site do not fully drain limiting vegetation recover and consequently sediment stability.

At South Morecambe, the main creek (Wylock Eea) was rerouted prior to the installation of the pipeline in order to enable trenching operations. Following installation it was decided to leave this in its new position, on the grounds that relocating it in recently backfilled soft sediments could cause scour to the pipe trench (Rae, 1983). Rae also notes that the meanders of two smaller tributary creeks were not re-created again because of potential scouring to the pipe. However, during the spring/ summer of 1984, additional reinstatement works to the creeks were undertaken, to make the channel more natural and to facilitate drainage after high tides (Rae 1984c). As part of this effort additional turves were laid along its edge to help restore the banks where there had been erosion.

At Lincs OWF, the pipeline crossed a large creek known as Big Tom, as well as three main tributaries. Big Tom was *c.* 6m wide at the crossing point, with the tributaries between 1-4m wide. Rather than reroute the creeks, protection measures were used. These included temporarily installing flume pipes in the channel to maintain water movement during tides, and to stabilise the banks to help minimise collapse. However, due to the size of the trenching vehicle some reinstatement works were necessary to repair the creek banks following the removal of the flumes.

Photo Plate 7 shows saltmarsh reinstatement works completed following cabling and as part of managed realignment. Examples include re-digging collapsed creeks using hand-tools and creating new short sections of creek to drain pools that have formed following sediment compaction.

Tides

Tides are central to the growth, development, and survival of saltmarsh, with incoming tides being critical in maintaining salinity, inputting mineral and organic nutrients as well as sediments into the system (Boorman, 2003). Each saltmarsh is subject to a unique set of tidal conditions that are dependent on the geography of the coastline. In the UK, saltmarshes around estuaries have a tidal range of around 4-5m, while in more open coastal areas the range is around 3m.

Saltmarsh vegetation usually occupies the shore between the mean high water of neap tides and the extreme high water of spring tides, roughly the top quarter of the tidal range. This means that for the majority of the time they are exposed to the air (Proctor, 2013). For example, unvegetated mud-flat is submerged twice every day; the pioneer zone is covered by the sea by all but the lowest of the neap tides and is submerged for around 40% of the time; and middle and upper saltmarsh growing around the mean high-water level will be submerged about 360 times a year, for an average of 1.2 hours a day; which equates to around 10% of the time.

One of the concerns of pipeline/ cable installation is that the working width is more frequently inundated by the tides due to sediment loss and compaction. An increase in frequency and length of tidal inundation will influence which species can recover depending on their submergence tolerance (Ranwell, 1972). In addition, permanent pools may develop which become hypersaline limiting vegetation growth (Beeftink, 1977). Linear pools (*c.* 130m in length) have developed at Inner Trial Bank along the edge of the former causeway (Photo Plate 8). Similar features have developed at Tetney Marshes, with aerial photos and the vegetation survey showing that a linear pool (*c.* 350m in length) has formed with scattered vegetation. At Lincs OWF linear pools were created along the working width by vehicle tracks (in particular in the mid-upper marsh). At Gibraltar Point on The Wash, Natural England report that military vehicle tracks are still visible after 25 years, as sufficient sediment does not settle into the track depressions to bring their surface levels back to that of the saltmarsh surrounding them (TEP, 2013).

Therefore, some measures may be necessary to reduce tidal inundation, and increase sediment capture, in particular, in areas of damage caused by trenching vehicle movements. As part of the sediment recharge at Lymington Harbour, sediments were discharged into a pen (created from willow and straw bales). The pen was designed to reduce the flow of sediment and water from the discharge point. In addition, semi-permanent sediment retention structures (using willow and straw bales) were installed in surrounding creeks; along with chevron shaped flow retarding features (Lowe, 2012).

At South Morecambe, a stone retaining barrier (using ragstone *c.* 40cm high) was constructed around the edge of the upper marsh in the vicinity of Wylock Eae. The ragstone wall was used to prevent sediments from being washed away, with the ragstones left in-situ after work (Rae, 1983). This is a prominent feature on the marsh today, and while it is not in keeping with the rest of the saltmarsh it has served its purpose. As a result, there is a clear difference between the vegetation growing in the upper marsh (which is dominated by SM16 *Festuca rubra* salt-marsh community) and that below the wall which is lower marsh dominated by SM14 *Halimione portulacoides* salt-marsh community.

At Cleavel Point, work to minimise sediment erosion included planting *Spartina anglica* and using wooden pilings or brushwood fencing along the eroding edge (Gray, 1986). The use of *Spartina anglica* to capture sediment is now not a favoured practice, partly because it is invasive and outcompetes with other saltmarsh species. But also, although it aids sediment deposition inland of plants, there is evidence that it can cause tidal scour in adjacent areas and around individual plants Bouma (2009 cited by Lush et al. (2016)).

Photo Plate 7 - Saltmarsh reinstatement methods on The Wash and at Steart Marshes.

Creek restoration, using hand-tools on saltmarsh after trenching.

Saltmarsh surface after trackway and geotextile membrane has been removed. Notice that the vegetation has become flattened, and subsequently died, but the root mat remains in tack. There is some yellowing of *Puccinellia maritima* and *Atriplex portulacoides* has been crushed and died.

Side creek dug using hand-tools to drain pooling water into nearby main creek.

Steart Marshes, Severn Estuary managed realignment. Former agricultural land have been converted to mudflats and saltmarsh through breaching the seawall. The artificial creek system can be seen in the center of the photo.

Photo Plate 8 - Long-term changes brought about after construction on saltmarsh.

Footpath and sediment compaction creating linear pools along former causeway at Inner Trial Bank.

Footpath through saltmarsh, showing that even minor levels of trampling/ compaction can cause significant impacts on vegetation growth.

Tidal pool that has developed in low-lying areas of the driftline vegetation, with much bare ground and annual species.

Raised causeway constructed to facilitate access at Tetney Marshes during the pipeline installation. The causeway supports mesotrophic grassland dominated by *Arrhenatherum elatius*. On both sides of the causeway there is now driftline vegetation, which was previously mid-upper marsh.

Re-routed alignment of Wylock Eae South Morecambe.

Stone retaining wall constructed at South Morecambe to prevent erosion to the mid-upper marsh.

5.4.5 Post-construction Management

Following pipeline/ cable installation at the majority of the case study sites, post-construction management has been minimal, allowing natural regeneration. Access restrictions to members of the public using fencing (usually along the landward edge) have been used at a few sites including Thanet OWF. While at South Morecambe the working width was temporarily fenced to restrict cattle grazing, allowing the vegetation to recover. There is evidence at Lincs OWF that the cable corridor is used by locals to reach Samphire (*Salicornia* spp.) beds, and at Inner Trial Bank the former causeway is regularly used by walkers to reach the offshore reservoir at low-tides. Information is perhaps key in gaining public buy-in to restoration efforts. Signage positioned at the landward edge adjacent to the working width providing information on the project and reinstatement goals may help discourage access.

Table 38 – Summary of potential impacts, possible re-instatement interventions and recovery outcomes in the driftline and mid-upper marsh.

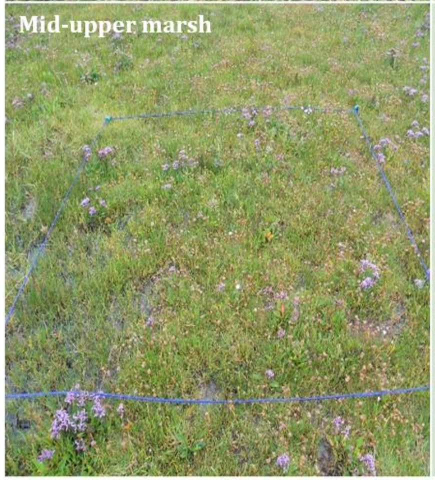
Vegetation Zone	Potential Impacts	Re-instatement	Recovery
Driftline 	▪ Impacts in the driftline centre around a change in topography and compaction, resulting a lowered redox potential. ▪ Where the topography/ redox potential is lowered, it is likely that there will be loss of *Elytrigia atherica.* ▪ Conversely, there will be an increase in ruderal or early successional species); ▪ Where the topography increases *i.e.* through a raised berm/ causeway, or displaced sediment *Elytrigia atherica* is likely to extend its dominance.	▪ *Elytrigia atherica* is a rhizomatous species and is cable of quickly recovering after flattening, crushing, and soil disturbance; unless the topography is lowered. ▪ It is likely that natural regeneration would be sufficient for recovery, although cultivation of material collected from site could also be considered.	▪ In the Short-term where impacts are minor, driftline vegetation recovers quickly. ▪ Severe disturbance results in the establishment of low-mid or pioneer marsh depending on the severity of impacts. ▪ In the Long-term driftline vegetation shows full recovery, although overall species-richness is less than Unaffected areas.
Mid-upper marsh 	▪ Impacts that create low-lying areas (through compaction or sediment loss) may either result in unvegetated pools or hypersaline pans, that become permeant landscape features; or these low-lying areas may be colonised by early successional communities *e.g. Salicornia* agg., reducing the overall species-richness of typical mid-marsh species, and the extent of mid-upper marsh zones. ▪ Species *i.e. Limonium vulgare* and *Atriplex portulacoides* are particularly sensitive to trampling and physical damage.	▪ Lifting and temporary storage of turves ahead of construction, with their replacement following installation is probably the best approach to maintaining species-richness and vegetation structure. ▪ Care should be taken to avoid leaving areas of bare ground as these are very slow to recover, due to low rates of sediment deposition. ▪ The use of dredge sediments could be used to infill low-lying areas. ▪ Planting of graminoids *e.g. Festuca rubra, Juncus gerardii* as plug plants (collected prior to construction and grown-on) could help re-colonise bare areas.	▪ Where turves are lifted and replaced the vegetation recovers within the Short-term. ▪ Were vegetation is lost and left to natural regeneration vegetation recovery will take until the Long-term, and may never achieve pre-construction vegetation composition and structure.

Table 39 – Summary of potential impacts, possible re-instatement interventions and recovery outcomes in the low-mid marsh and pioneer marsh.

Vegetation Zone	Potential Impacts	Re-instatement	Recovery
Low-mid marsh 	▪ Following construction, there is likely to be a significant increase in bare ground, with an initial loss in the extent of low-mid marsh. ▪ Where low-mid marsh is lost it will be replaced with early-successional communities *i.e.* pioneer marsh. ▪ But *Puccinellia maritima* is capable of growing in areas with reduced redox potentials so should recover quickly. ▪ *Aster tripolium* dominated swards *i.e.* SM12 are often found on areas of pioneer and lower marsh where the saltmarsh has been modified or recently disturbed (Haynes, 2016). ▪ *Atriplex portulacoides* is particularly sensitive to physical damage resulting in death of this dwarf shrub, and it is slow to regenerate. Where this species is present prior to construction it is likely to be a lost, potentially changing the community composition and structure.	▪ Natural regeneration of low-mid marsh species is relatively rapid (where the adjacent vegetation remains intact or the root-mat survives). ▪ If small areas of low-mid marsh are to be crossed then turves could be lifted (if dominated by *Puccinellia maritima*). ▪ Low-lying areas may benefit from the input of dredged sediments (or the use of biodegradable sediment traps). ▪ Permeant pooling of water should be avoided either by infilling with sediment, or by digging temporary creeks linking through to an existing creek enabling drainage.	▪ In the Short-term there will be a loss of low-mid marsh resulting in an increase in pioneer marsh. ▪ Species-richness of the low-mid marsh will decrease (with the loss of key species *i.e. Atriplex portulacoides* and increased dominance of *Puccinellia maritima).* ▪ By the Medium-term, low-mid marsh shows signs of recovery with the main species (with perhaps the exception of *Atriplex portulacoides*) returning to pre-construction levels. ▪ In the Long-term, low-mid marsh vegetation shows full recovery, although species-richness may be lower than Unaffected areas.
Pioneer marsh 	▪ Initially after construction all vegetation in this zone will be lost, with increased areas of bare ground and Algae spp. But there will be relatively quick recovery of key species *i.e. Salicornia* spp. in the lower sections and *Aster tripolium* and *Puccinellia maritima* towards the upper half of the zone. ▪ There may be a Short-term loss of *Spartina anglica* but by the Medium-term cover of this species will return to pre-construction levels. ▪ Creeks are typically frequent in this zone, and disruption to water movement through creek severance or redirection may influence drainage patterns across the marsh.	▪ Re-instatement in the pioneer marsh is likely to cause further vegetation damage or sediment compaction. ▪ Where there are specific issues with regards to raised topography *i.e.* mounded mud this should be dispersed; and low-lying areas could be infilled using sediment traps. Material may be brought in from offshore to minimise impacts on the other vegetation zones. ▪ *Aster tripolium, Salicornia* spp. and *Suaeda maritima* will re-establish from seed; while *Spartina anglica* and *Puccinellia maritima* by vegetative spread.	• Depending on the severity of the damage, pioneer species will re-establish themselves in the Short-term, although at a lower cover. The cover of bare ground will remain higher than Unaffected areas. • The extent of pioneer marsh is likely to increase overall, as it will develop in other zones where disturbance creates areas of bare ground. • In the Long-term, pioneer marsh will be retained at the outer reaches of the saltmarsh, but should be lost from inland sections.

5.5 Sand Dune Restoration

5.5.1 General

Sand dune restoration and management is well documented. One of the key reviews is set out by Greipsson (2002), which draws together a summary of the main issues and provides details on restoration techniques. Lithgow et al. (2013) identifies over 60 dune restoration projects, focusing on the type of dune habitat subject to restoration, the cause of disturbance and the main restoration techniques used. Much of the current focus of dune restoration is on reactivating over-stabilised dunes and creating bare sand with early pioneer vegetation communities through restoration of aeolian processes (Arens and Geelen, 2006, Pye et al., 2014, Pye and Blott, 2012, Lithgow et al., 2013). This is a shift in approach from standard practices taken in the UK (before the 1990s) when sand stabilisation and minimising sand movement was considered a priority (Rooney, 2010). At that time, many practical handbooks were available that focused on stabilising dunes and visitor management (Agate and Brooks, 2005, Doody, 2001, Houston, 1997, Ranwell and Boar, 1986, Defra/ Environment Agency, 2007).

The installation of pipelines/ cables through sand dunes provides an opportunity to create bare sand and pioneer habitats especially in over-mature stabilised vegetation. My review therefore draws on restoration examples which focus on artificial disturbance to create bare ground. However, due to the need to protect the pipeline/ cable from erosion, it is likely that vegetation planting will be also needed at least in vulnerable areas. Therefore, the section also considers vegetation re-establishment through the use of seeds and clonal offsets; as well as other engineering options where restoration gains could be included as part of the reinstatement process to help meet UK and local conservation targets.

5.5.2 Dune Rejuvenation

In the late 1980s there was a shift in the perceived value of windblown sand (Rooney, 2010). Much of the change in thinking was led by work completed in the Netherlands, when in 1987 the idea of dynamic dune management was presented and subsequently published (van der Meulen and van der Maarel, 1989). The idea gave particular emphasis to restoring aeolian processes to reactivate the dune system in a self-sustaining way. Dune stabilisation has occurred across much of northwest Europe over the last 60 to 100 years. This is of particular conservation concern due to the loss of early successional habitats and associated rare species, but also as without natural dune dynamics, systems are unable to recover from environmental change (Jones et al., 2010b). The reasons for dune stabilisation are widely recognised, Pye et al. (2014) summarises these as; less windy conditions (and fewer severe storms), higher temperatures and a longer growing season, increased atmospheric nitrogen deposition, reduced livestock grazing and grazing/

burrowing pressure by rabbits, over-protection of mobile sands through management *e.g.* by *Ammophila arenaria* planting, forestry, and using brushwood and sand fencing, and the identification of fixed, vegetated dunes as features of high conservation interest.

Dune rejuvenation has been the focus of much of the work completed in the Netherlands, which supports 10% of the EU coastal dune habitat. They have undertaken a range of actions including the removal of scrub and invasive non-native species, reintroduced grazing, restored wet dune slacks (through restoring hydrology, sod cutting and removal of vegetation), restored processes to reactivate windblown sand (through removal of built structures, and breaching the fore dunes by cutting large holes 100-150m wide (Photo Plate 9). The aim was to improve the quality of priority dune types namely, grey dunes, white dunes, humid dune slacks and dune forest which support a number of rare and threatened dune species (European Commission, 2017, Waternet et al., 2015).

Photo Plate 9 - Sand dune rejuvenation.

Dune rejuvenation in the Netherlands. Here the foredunes have been breached, so to increase wind blown sand reaching internal areas, and to create open dune habitat suitable for early successional species. There has also been scrub clearance.

Dune rejuvenation at Newborough Warren in North Wales. Here the foredunes have been breached and sand movement undertaken to lower the water table locally to create new dune slacks.

Arens and Geelen (2006) draws together findings of one of the early experimental dune rejuvenation schemes that involved vegetation stripping and dune re-profiling in the Netherlands. The aim of the project was to reverse vegetation succession and restore nutrient-poor ecosystems, without the need for continued human intervention. Restoration work followed the closure of a water extraction canal, infilled with the original sand, in an area of stabilised dunes. This created *c.*35ha of bare sand (*c.* 3km long and 100-300m wide), which was monitored between 1995 and 2003. The aim of the study was to determine whether the large-scale reactivation resulted in aeolian activity and structural rejuvenation of the landscape without ongoing management. Using aerial photographs, it was possible to map changes in sand burial and stabilisation over time through vegetation cover. The study found that aeolian process increased considerably in the first few years after destabilisation, but that over time stabilisation of the surface occurred through vegetation establishment. Pioneer vegetation and species were frequent (covering *c.* 5ha in

2003), there was also growth of new plants from old remnant roots. After 8 years, half the area was still bare, and the active area was still 2.5 times as large the stabilised area. But bare spots were scattered and had reduced in size (from *c.* 10ha in 1995 to <1ha in 2003). The authors concluded that the large-scale destabilisation had resulted in small-scale features; and that future management would be necessary to maintain the bare ground habitat.

In Wales, a large study into the requirements for dune rejuvenation by destabilisation was completed by Pye et al. (2014). The study highlighted the loss of rare species, most of which are associated with active aeolian process *i.e.* early successional vegetation. Using aerial photography at 12 key sites, the percentage of bare sand was shown to have decreased dramatically by an average 81% between 1940-50s and 2009. Seven of these sites had less than 5% bare sand. The study identified ten principal drivers of mobility/ stability in dunes; and a number of dune rejuvenation measures. These included measures to reduce vegetation density and height, increase sand supply and mobility, and increase local wind speeds and sand transport. The study suggested that appropriate targets for bare sand should be between 10-40% of a site, with a further 30-40% supporting pioneer, mobile dune and dune slack habitat.

There are opportunities when considering the installation of pipelines/ cables across sand dunes to increase bare sand and early successional habitats either along the working width or in adjacent areas. Early discussion between statutory bodies, engineers, contractors, and consultants could determine what is achievable and set restoration targets accordingly. During installation, contractors have access to machinery that could enable vegetation clearance, topsoil inversion, scrub removal, and recontouring of the dune topography to create localised blow outs, dune scrapes and slacks for example.

At Coatham Sands, the creation of bare sand and early successional vegetation along the Project Breagh pipeline was achieved through limited vegetation reinstatement (in terms of *Ammophila arenaria* replanting) in the fixed dunes allowing natural regeneration. The plugs of *Ammophila arenaria* tillers were planted at a density of *c*. 4 per metre squared. Compared to *c.* 10 per metre squared mentioned in some guidance documents, and 40 tillers per square metre used for the Point of Ayr pipeline, Talacre Warren. Although *c.* 10,000 plugs were used, this was about half the rate normally used. The other key difference between the Project Breagh reinstatement and the earlier projects, is that for both the AMCO CATS and Point of Ayr pipelines sand movement was controlled by using a water-based bitumen emulsion (sprayed over the sand surface) or hessian matting.

After 5 years at Talacre Warren the working width was classified as the vegetation types SD6 *Ammophila arenaria* mobile dune community/SD7 *Ammophila arenaria* - *Festuca rubra* semi-fixed dune community indicating at least some free sand. At present this process of temporarily halting/ reversing succession is an incidental outcome, however with a little thought it could provide benefits to the wider dune system.

At both Coatham Common sites, where the pipelines crossed areas of dune slack habitat, turves were temporarily lifted prior to construction and stored adjacent to the work (Photo Plate 10). Key to their survival was regular watering and retaining their existing topography. In addition, access by construction staff was restricted and all works in the area were overseen by an ECoW.

5.5.3 Vegetation Establishment

When considering vegetation establishment on sand dunes there are several key decisions that need to be made. These relate to the restoration outcomes and the required speed of vegetation establishment. In many scenarios, natural regeneration is considered the most appropriate restoration technique, especially on designated sites where the use of local plant material is preferable. This approach allows natural processes to occur which can lead to increased diversity both in terms of dune landform and species. However, following pipeline/ cable installation there is often a need to restore bare sand quickly to prevent loss of sand along the working width (potentially leading to an exposure of the pipeline/cable). As a result, planting is often adopted at least in vulnerable positions *i.e.* where wind/ tidal erosion is severe. Plantings may include seed, clonal offsets or plugs.

The origin of the material needs to be considered, ideally with vegetation collected from the site prior to construction. This can lead to storage and survival issues (whether on the site within the working width, or offsite in a nursery or store) as there may be several months between ground clearance works and reinstatement. Planting densities, the use of fertilisers or arbuscular mycorrhizal fungi, as well as materials to aid sand accumulation are also considered.

Natural Regeneration

There are many papers describing natural regeneration of disturbed areas following intentional disturbances in particular after sod-cutting, which help inform post-construction pipeline/ cable restoration choices.

Bekker (1999) undertook studies to determine seed dormancy and seed depth of plant species (in particular early successional species), following sod-cutting. It was found that seed dispersal between slacks was limited due to distance and due to the short period that each slack was suitable for species establishment. Local seeds in the seed bank, therefore, were likely to be of greater importance for re-establishment following sod-cutting and the removal of the organic top-layer. Bekker showed that most early successional species occurred in the seed bank in large numbers even over an extended period of time (39 and 80 years), with most seeds held in the top layers of soil between 0-10cm. The study showed that the composition of the seed bank (10-

15cm) from the oldest slacks (80 years) were still able to contribute to above ground species replacement after sod-cutting, even though early successional species were present at very low abundances in the established vegetation. Plassmann et al. (2009) undertook a similar study to compare the soil seed bank of dune slacks at two soil depths with the established vegetation and historical compositional data. The study showed that seed bank reflected earlier successional stages more closely than the current above ground vegetation.

One point to note, was that Bekker et al. (1999) found that some individual species *i.e. Centaurium littorale* were only found in the surface layer, and consequently this species could be lost after sod-cutting. *Centaurium littorale* was recorded in 29 quadrats, 5 years (*e.g.* 1999) after construction at Talacre Warren in the created dune scrapes (*Section 4.8.4*). However, in 2015-16 it was not recorded in my study quadrats (although a few individual plants were recorded in the wider slack area). It is considered that the regular removal of top soil and vegetation to maintain the open bare sand scrapes may have resulted in a reduced seed bank for this species.

The contribution of the seed bank in restoration management of wet dune slacks was also assessed by Bakker et al. (2005). The study undertook seedling germination tests using the top 10cm of soil from dune slacks. They anticipated that severe disturbance (caused by sod-cutting and mowing) would stimulate the growth of early successional species, therefore suggesting that the contribution of the seed bank could influence vegetation composition (as noted by Bekker et al. (1999)). However, the study found that the seed bank tended to reflect the former vegetation rather than altering the course of succession. They also found that seed rain from nearby sources was also important (with 76% of new species establishments not found in the seed bank), concluding that restoration work should be situated in a landscape where there are refuge populations. This supported work by Grootjans et al. (2002).

The distance of restoration areas from neighbouring slacks and compared species-richness and rarity over time was assessed by van der Hagen et al. (2008). It showed that the proximity of a seed source influences vegetation recovery especially in systems where dunes are not influenced by tidal input of seeds. Species numbers increased over time across the restored site, but diversity was highest in areas closest to the neighbouring slacks. This was particularly true of the Red list pioneer species.

With regard to pipeline/ cable installation, therefore to increase the likelihood of success of newly created wet slacks, they should be located near to existing seed source populations as there will be limited wet tolerant species present.

Assisted Regeneration

Dune restoration for many years focused on the stabilising of mobile dunes and fixed dunes, often through sowing or planting of sand binding grasses such as *Ammophila arenaria*, *Elytrigia juncea* or *Leymus arenarius*. Therefore, there is much documented evidence as to the outcomes of planting and seed germination (Greipsson and Davy, 1996, Harris and Davy, 1987, Hewett, 1970, Hobbs et al., 1983). Methods for seed harvesting, collection of material for clonal offsets and the establishment of nurseries with plug plants is given in Agate and Brooks (2005), Greipsson (2002).

Seeds and Clonal Offsets

As described in *page 221* Hewett (1970) documented dune stabilisation at Braunton Burrows using *Ammophila arenaria*. It was considered that due to the large extent of bare mobile sand natural regeneration of the site was unlikely. Monitoring surveys showed that over an 8-year period species numbers increased from 23 to 56 species, and bare sand rapidly decreased. Over time, *Ammophila arenaria* decreased in frequency replaced by *Festuca rubra* with the development of more stable dunes. Hewett suggested that most of the colonising species in planted areas had come from seed that had arrived after surface stability was attained; although it was noted that some of this seed may have been transported with the *Ammophila arenaria* transplants.

Hobbs et al. (1983) showed that growth of *Ammophila arenaria* offsets depended on the orientation of the planted rhizome. Horizontal rhizomes produced an increase in vegetation cover and rhizome development compared to rhizomes planted vertically. While vertically planted rhizomes gave rise to tussocky growth. The study also showed that rhizome lengths increased with depth of planting (up to 20cm). In contrast, *Leymus arenarius* exhibited no differences between rhizome orientation, but showed that shallow planting (under 10cm) improved rhizome and shoot growth. The study suggested that *Ammophila arenaria* should be planted horizontally when establishing it in bare areas (*i.e.* along the working width in mobile/ semi-fixed dunes) to minimise loss through wind erosion.

Studies in Iceland on harvested *Leymus arenarius* seed showed variations in seed-production and survival rates depended on the parent material (Greipsson and Davy, 1996). The study compared seed harvested from inland populations compared to coastal populations. Those plants growing in coastal locations were more vigorous and produced greater amounts of seed. The study also looked at seed burial and germination rates, finding that seed buried at a depth of 5cm resulted in 100% germination compared to deeper burial depths where germination rates declined. It is evident from this research that careful selection of parent material for seed collection is required, choosing those plants with vigorous growth; and when sowing (either by direct broad-cast over the dune surface, or sown in a nursery) consideration of seed burial depth is required.

Similar studies have been conducted with *Elytrigia juncea* looking at the survival of root fragments compared to seeds (Harris and Davy, 1986). The study showed that multi-node root fragments were more likely to produce viable shoots and were capable of surviving further disturbance episodes compared to seed germination.

Following the installation of the AMCO CATS pipeline, the sand was returned to its original location and the dunes were re-contoured to give a naturalistic topography. To prevent wind blow, chestnut palling was used to capture loose sand. Planting of *Ammophila arenaria*, *Elytrigia juncea* and *Leymus arenarius* tillers collected from the site prior to construction were used to bind sand in the fore- and yellow dunes. A similar approach was also used at Point of Ayr, Talacre Warren.

The Project Breagh pipeline benefited from reviewing the restoration successes of both the AMCO CATS and Point of Ayr pipelines. As an open-cut method was used the required time from vegetation clearance and reinstatement took over a year *i.e.* between March 2011 and January 2012. This meant the actively growing tussocks of *Ammophila arenaria*, (and *Elytrigia juncea* and *Leymus arenarius*) were collected and split into tillers with 6-8 shoots. These were planted into deep-rooted plug-trays using top-sand collected from the pipeline working width (Photo Plate 10). The *Ammophila arenaria* (and other grasses) were stored in a rabbit-proof fenced area near to the construction site, and were watered using an automatic watering system until they were replanted (Photo Plate 10). As the plugs used top-sand as a planting medium, additional native species germinated so that each plug contained a mixture of species. Those species recorded included *Carex arenaria*, *Festuca arenaria*, *Festuca rubra*, *Poa humilis*, *Phleum arenarium*, *Anthyllis vulneraria*, *Astragalus danicus*, *Erodium cicutarium*, *Hypochaeris radicata*, *Plantago coronopus* and various moss species. The plugs were re-planted in the fixed dunes along the pipeline and construction compound in winter 2012-13. In May 2013, some addition *Ammophila arenaria* planting was required where sand stabilisation had not occurred, but in general vegetation cover was considered appropriate, resulting in a mosaic of open sand, and early successional species.

Rare species

The reinstatement following pipeline/ cable installation of rare species or species with a limited distribution is likely to be an important restoration target. Hand collection of seed from these species is therefore likely to be important to boost the population and to aid dispersal across disturbed areas.

At Coatham Sands, for both the AMCO CATS pipeline and the Project Breagh pipelines, seed of target species (*Astragalus danicus* and *Thalictrum minus*) were collected by hand prior to vegetation stripping. Seed of other typical dune grassland species were also collected, dried, cleaned and stored in labelled paper bags until they were re-sown in the dune grassland and fixed dunes as appropriate. In addition, the pre-construction site was searched for plants of *Astragalus danicus*, *Dactylorhiza purpurella, Gymnadenia conopsea, Oenanthe lachenalii* and *Thalictrum minus*, which were lifted and grown in the nursery area during construction (Photo Plate 10). The plants were potted into 1 litre pots with as little disturbance to roots and surrounding sand and vegetation as possible. In May 2013, these were replanted into appropriate parts of the restored route across Coatham Sands – the orchids into damp low lying areas, and the other species into the crests of mounds as well as around the Beach Valve Station.

One of the critical groups, with widely perceived botanical value is members of the family Orchidacece. One of the critical requirements with orchids is the need to restore mycorrhizal fungi populations which are important for seed germination and seedling survival. De hert et al. (2013) looked at dispersal and recruitment limitation of three orchid species (*Dactylorhiza fuchsii*, *Dactylorhiza praetermissa* and *Herminium monorchis*) following scrub clearance in dune slacks. The study showed that all three species were capable of forming protocorms[88] in sites were the species had previously been absent, suggesting that dispersal limitation, plays a significant role in the inability of orchid species to colonize restored sites (supporting earlier research). In addition, it suggests that there is a relatively low specialisation of orchid species and mycorrhizal fungi. However, the authors note that germination was more frequently observed at sites where orchid plants were already present (which corresponded to other studies). With regards to post-construction restoration following pipeline/ cable installation, individual orchid plants can be lifted (*i.e.* Coatham Sands) but in addition reinstatement by seed should be considered even in disturbed and isolated locations.

Fertilisers and Growth hormones

In the past, the application of fertilisers to encourage vigorous growth of *Ammophila arenaria* and other sand binding grasses was routinely prescribed in dune management guidelines (Agate and Brooks, 2005, Greipsson, 2002, Scottish Natural Heritage, 2000). Studies by van der Putten (1990) focused on the difference in success of *Ammophila arenaria* establishment between using bundles of culms, disc-harrowed rhizomes and seeds; and also rates of fertiliser applications. The study found that an application rate of slow release NPK fertilizer (80-20-20 kg ha^{-1}) increased biomass significantly in particular with the rhizomes which produced more tillers and biomass. Where

[88] The ephemeral structure resulting from the germinated orchid seed and from which the first true shoots and root differentiate

fertilisers were not used the study showed that bundles of culms produced the highest biomass. Seedling growth with and without fertiliser was poor.

The use of fertilisers today, is not considered appropriate, particularly in designated sites, as it encourages increased biomass of grasses, increased dominance of ruderals and reduces overall species biodiversity. It was decided that for the Project Breagh pipeline no fertilisers would be used, and this encouraged a greater diversity of pioneer and early successional species as well as retaining areas of open bare sand.

The use of a growth hormone pre-treatment of *Ammophila arenaria* cuttings was investigated by Balestri et al. (2012). They showed that the application of the plant growth regulator alpha-naphtaleneacetic acid (NAA) increased root development. Whilst cytokinins, (6-furfurylaminopurine (Kinetin) and 6- benzylaminopurine (BAP) were more effective in promoting vegetative development in particular tiller production. The use of targeted growth hormone pre-treatment could be considered (over the use of fertilisers) where well-developed plants of *Ammophila arenaria* are required *i.e.* areas along the working width where erosion is likely to be severe.

Photo Plate 10 - Sand dune reinstatement methods undertaken at Coatham Common.

Planting Marram bundles into top-sand, for later reinstatement of dunes. The Marram was collected from site prior to construction.

Initial watering of Marram plant plugs, later an automatic sprinkler system was used to ensure all plants were frequently watered.

Temporary nursery area with rabbit-proof fencing.

Close up of plugs and pots showing other species that established.

Marram planting using material collected from site, grown in temporary nursery and then replanted as plug plants following pipeline installation.

Reinstated dune slack, turves after pipeline installation.

Reinstated dune slack, turves after pipeline installation. Plant labels used to record locations.

Soils

Typically, during construction, the topsoil and top layer of turf is first stripped to a depth of *c.* 20cm. This material is stored within the working width with the aim of retaining any plant material *i.e.* seeds and vegetative propagules such as rhizome fragments, for eventual top-dressing of replaced sand and soils during reinstatement. It is typical that material from each different vegetation compartment is stripped and stored separately *e.g.* from the mobile dunes, dune ridges, semi-fixed dunes and dune grassland. In addition, the subsoil from the trench is also stored separately. During restoration, the process typically follows in reverse with the subsoil laid down first and topped with the original topsoil stripped from each compartment.

However, depending on the aim of restoration there could be biodiversity benefits in either removing the topsoil and turf or by burying it under the subsoil (topsoil inversion). This is perhaps an option in landward dune grasslands, where for example species-poor, *Arrhenatherum elatius* dominated swards, tend to establish through ongoing nutrient-enrichment.

Topsoil inversion techniques (also known as deep ploughing) have been used in habitat creation and restoration schemes to help reduced nutrient-enrichment. Glen et al. (2017) reviewed the results of fifteen topsoil inversion sites; and showed that a reduction in fertility in agricultural soils was maintained over a minimum of 5 years. Specific dune examples include at Talacre Warren (Jones et al., 2010a) detailed on *page 229 .* Jones notes that topsoil inversion "*is potentially a useful technique in over-stabilised systems where natural burial by sand is unlikely to occur and is an alternative to large- scale destabilisation of natural dune features which may not be appropriate on small sites, or those close to built-up areas"*.

Olsson and Ödman (2014) undertook a study to compare the results of topsoil inversion and topsoil removal of xeric sand calcareous grasslands in Sweden[89]. This is a highly threatened grassland type which has been shown to depend on regular soil disturbance, low nutrient availability and high pH. The aim of restoration was to increase the amount of bare sand, and to encourage the colonisation of rare and specialised plant species. The key findings are that overall species-richness tended to decrease in response to topsoil removal, but not for topsoil inversion. But the proportion of specialist species (in particular annuals) increased in response to both topsoil removal and inversion. The study also showed that the reduction of nitrogen prevailed for 6 years after treatment.

Alternatively, in dune grasslands where there is a dominance of mesotrophic grasses, sod cutting as described previously, may be used to increase diversity and vegetation structure. Shallow sod cutting has also been used to restore species-rich grey dunes (van Til and Kooijman, 2007) in

[89] Natura 2000 code 6120

small-scale restoration projects. Following the establishment of the coarse grass *Calamagrostis epigejos,* shallow sod cutting (5cm deep) was completed in an attempt to recover Taraxaco-Galietum veri and Phleo-Tortuletum ruraliformis grassland. The study showed that within four years following treatment, characteristic plant species *i.e. Erodium cicutarium*, *Lotus corniculatus*, *Phleum arenarium*, *Saxifraga tridactylites* and *Viola curtisii* became established. There was also a significant decrease in cover of *Calamagrostis epigejos*. In addition, the vegetation structure became more diverse with areas of bare sand, moss patches, short grasses and herbs as well as dwarf heath.

Sand Stabilisation

Although the current direction of sand dune restoration is moving away from the stabilisation of dune sands; along the working width, some measures may be necessary to prevent erosion along the pipeline/ cable. In the past, various measures have been used, including sowing a nursery crop (*i.e.* as used in Cruden Bay), the use of a bitumen spray, hessian matting, geotextile membranes, and brushwood/ chestnut fencing.

At the Cruden Bay and St. Fergus pipelines in Aberdeen, the reinstatement involved using an imported topsoil and a nursery seed crop to stabilise the sand surface. At Cruden Bay, the landward slopes and flat dune grasslands were surfaced with a 2:1 mixture of imported topsoil and sown with a commercial grass seed-mix. The seed mixture comprised 5 parts *Lolium perenne*, 2 parts *Poa pratensis*, 4 parts *Festuca rubra* and 2 parts *Agrostis capillaris*. Nitrogen fertiliser was applied at the time of sowing and the area coated with bitumen (to stabilise the surface). Unsurprisingly, Ritchie and Gimingham (1989) note that the result was "*a bright green streak across the dunes*", with an established stand achieved within a year. In addition, a large number of weed species were introduced with the topsoil. After 3 years the sown grasses had decreased in frequency and cover, progressively replaced by *Elytrigia repens*, *Dactylis glomerata* and *Holcus lanatus*. Other species present included *Prunella vulgaris*, *Rumex acetosella*, *Ranunculus acris*, and *Senecio jacobaea* which were thought to have come from the surrounding vegetation. It was noted that natural regeneration of other native dune species was slow, and *Ammophila arenaria* was notable in its absence.

A similar approach was used for the two pipelines at St. Fergus, although a better-quality topsoil was used, and the use of bitumen spray was abandoned. The main difference between the Cruden Bay and St. Fergus sites was that the pipelines crossed a large area of dune slacks, which was also surfaced with topsoil and sown. Ritchie and Gimingham note that *"the community showed little resemblance to the surrounding slack vegetation, largely because the habitat was a good deal drier following disturbance and spreading of topsoil.*

The use of bitumen sprays as sand binders were used historically to bind the sand surface during initial vegetation establishment (as noted at Cruden Bay). It is clearly important that the chemicals used do not inhibit seed germination, seedling establishment or plant growth (Defra/ Environment Agency, 2007). The use of a bitumen spray and hessian matting was used at Talacre Warren on the steeper slopes of the dune ridges. In 1996 (two years after installation), the botanical monitoring report, notes that "*the hessian matting was intact, showing only slight signs of deterioration in a few places"*. The author concluded that "*it must have continued as a major influence on the development of vegetation"*. However, by 1999 the report notes that the hessian matting was barely in evidence and that it had no influence over the vegetation. With regards to the bitumen spray the author noted that in 1996 "*there was little sign of remaining 'Crelawn' and this had probably ceased to affect the vegetation"* (Carter Ecological Limited, 2000, Maldon Ecological Consultants, 1997) .

The use of brushwood and chestnut fencing is frequently used along pipelines/ cables to both help capture sand and to reduce erosion. The materials used, the materials porosity and angle of placement to the dominant wind all influence the amount of sand capture (or scour), and the shape and steepness of the accumulated dune. Further details are given in (Defra/ Environment Agency, 2007).

5.5.4 Post-construction Management

The need for post-construction management is often not considered once the pipeline/cable has been installed. At Talacre Warren, however the ongoing management of the pipeline is overseen by eni Liverpool Bay Operating Company. Management activies include the removal of self-seeding *Acer pseudoplatanus* and dense patches of *Clematis vitalba*. The former sand storage area is also managed by creating scrapes (for the Natterjack Toad, but with wider botanical benefits) and the dune grassland behind the main ridges is mown on annual basis to restrict sward height and prevent encroachment of *Arrhenatherum elatius*. These activities have been key in maintaining the species diveristy.

In contrast, the pipeline corridors at Coatham Sands are unmanaged. During the surveys in 2016, a large number of *Hippophae rhamnoides* saplings had self-seeded in the dune grassland along the pipeline installed in 2012. There is also a large established patch (*c.* 18×20m) producing berries (thought to be the source of the self-seeded material) along the original 2009 pipeline (*page 230*). The removal of these is a priority to prevent further spread. The site would also benefit from removal of some of the fencing installed to restrict access along the pipeline while the vegetation initially established. The fences are now redudant and are actually, causing impacts by restricting access through an area of dune slacks. In 2016, (five years after pipeline installation), there was still a significant amount of bare sand supporting a mosaic of early successional species, short species-rich turf and denser patches of *Ammophila arenaria*. Ideally grazing or cutting to minimise nutient enrichment which leads to the spread of mesotrophic grasses would be established.

Removal of Invasive Species and Scrub

Control methods and vegetation recovery following removal of invasive scrub species such as *Hippophae rhamnoides*, *Prunus serotina* and *Rosa rugosa* has increasingly been the focus of research (Boardman and Smith, 2016, Isermann, 2008, Isermann et al., 2007, Richards and Burningham, 2011).

Richards and Burningham (2011) documents the vegetation change following clearance of *Hippophae rhamnoides* at Merthyr-Mawr Warren. The study found that *Hippophae rhamnoides* reduced species-richness within the dense thickets from on average 8 species to 4. Only those species tolerant of shade were able to persist *i.e. Senecio jacobaea* and *Urtica dioica*. Following scrub clearance, it was expected that species-richness would increase, and the normal course of dune succession followed. However, the resulting soil disturbance, with the accumulation of organic matter and nitrogen allowed the establishment of ruderal species *i.e. Chamerion angustifolium*, *Lamium album* and *Senecio jacobaea*. These species became dominant and persisted for more than 10 years after clearance. Over time, although there was a gradual increase in species-richness, new species were either ruderals or common generalists rather than characteristic dune species. The study concluded that prevention of spread of *Hippophae rhamnoides* is key. When considering scrub clearance, it is sensible to concentrate efforts on those areas which have only been colonised for a short amount of time, as these are likely to have a larger seed bank of target species and be subject to less soil modification. Where these patches are small there is also a greater chance of seed from adjacent sources repopulating the disturbed ground. At Coatham Sands for example work should initially target the saplings (which could currently be hand-pulled), but also the larger patch which has grown by *c.* 20% in seven years.

In the Netherlands, during the Dynamic Dune conference in 2015, I observed large areas of tree and scrub clearance (particularly *Prunus serotina*). The clearance works involved a combination of mowing, brush-cutting and tree felling with the resulting arisings, removed from site. In addition, the topsoil was excavated so that the humus layer (containing tree/scrub seeds as well as organic matter) was removed leaving mineral sand. This approach allowed the establishment of early successional dune species (rather than a dominance of ruderals).

Grazing and Mowing

With the continued threat of over-stabilisation and nutrient-enrichment, undertaking appropriate levels of grazing is considered important in achieving long-term benefits to dunes (Boorman, 2011, Hewett, 1985, Millett and Edmondson, 2013, Plassmann et al., 2010, Ranwell, 1972, van

Dijk, 1992). However, it is unlikely that grazing would be established as part of post-construction restoration and is therefore only briefly mentioned here. The use of livestock on many sites to achieve appropriate grazing levels is difficult. The pros and cons of grazing (and mowing) are set out in Crofts and Jeffersons (1999), which although is not specifically related to dunes, covers all aspects of the subject.

Boorman (2011) notes that different grazing requirements are required for the different dune types. Mobile dunes have little need for the control of plant growth due to shifting sands and low competition. In contrast dune grasslands need to be grazed to maintain plant species diversity, so to remove prolific plant growth and reduce nutrient-enrichment.

Plassmann et al. (2010) undertook a study looking at the long-term effects of livestock grazing at Newborough Warren. The site was subject to low-intensity grazing using a mixture of cattle, ponies and sheep over a 16-year period. The study found that there was a shift from a species-poor tall-grass dominated sward to a species-rich community, with some quadrats hanging from SD9 *Ammophila arenaria-Arrhenatherum elatius* dune grassland to SD8 *Festuca rubra* - *Galium verum* fixed dune grassland. The influence of grazing on both dry dunes and dune slacks in terms of average species numbers was positive (although more pronounced in the dry dunes).

Where grazing is not an option, annual mowing maybe suitable especially in flat areas of the dune grassland. Annual mowing at Talacre Warren has restricted the spread of *Arrhenatherum elatius*. This is similar to findings by Hewett (1985) who showed a significant decrease in the species after monthly mowing (between May and September). Hewett notes that both mowing, and grazing alter the composition of the sward and the abundance of those species, but they do not remove them completely.

Access Restrictions and Signage

Until vegetation is adequately established along the working width it may be advisable to restrict public access through sensitive areas (*e.g.* areas of dune slacks or where erosion may be severe) using fencing. There is much information on the types of fencing (with benefits and associated issues) provided in Defra/ Environment Agency (2007). Signage is also advisable to assist greatly in gaining public co-operation, and this should be both informative and instructional. At Coatham Sands a simple sign attached to the fencing highlighted its purpose. This was successful, however overtime these signs and fences need to be renewed or removed depending on the success of reinstatement.

Table 40 – Summary of potential impacts, possible re-instatement interventions and recovery outcomes in the embryo/ mobile dunes.

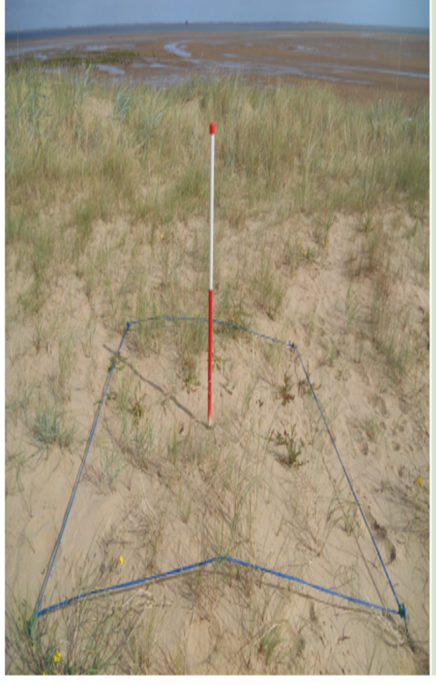
Vegetation Zone	Potential Impacts	Re-instatement	Recovery
Embryo/ Mobile Dunes 	▪ There is likely to be a loss in species-richness, species diversity was greatest in the Unaffected vegetation. ▪ There appears to be a loss of sand binding mosses, and some of the rarer species *i.e. Euphorbia* spp. and orchids post-construction On the pipeline. ▪ The mesotrophic grasses *Arrhenatherum elatius* and *Holcus lanatus* both showed an increase in cover (but not significantly so) following construction, possibly due to reduced competition from the main sand binding grasses and also releases of nutrients.	▪ Typically the embryo/ mobile dunes are avoided during construction (*e.g.* using HDD) so to protect the pipeline and inland sections from sand loss through wind blow. ▪ Where the embryo/ mobile dunes are cut through, they are typically reinstated to their original topography and *Ammophila arenaria, Elytrigia juncea* or *Leymus arenarius* planted to stabilise the sand. ▪ Potentially by excavating an open-cut section (perhaps not on the pipeline itself) dune dynamics could be restored allowing wind blown sand to move inland. This would create areas of bare sand suitable for the colonisation of early successional species. Which could have a Net Positive Impact on the dune system.	▪ The embryo/ mobile dunes are subject to natural disturbance by storm-events, which is probably mimicked by pipeline installation (*i.e.* creation of bare sand, vegetation loss). Typically, the species that grow in this zone are capable of quickly responding to disturbance (*i.e.* through germination or vegetative spread). As a result limited differences between On and Off the pipeline were recorded. ▪ A lack of data from the embryo/ mobile dunes, means an accurate assessment of the time for recovery is not possible. ▪ The four typical graminoids of this zone, *Ammophila arenaria*, *Carex arenaria, Elytrigia juncea* and *Leymus arenarius* were not significant between the Medium-term and Unaffected vegetation which suggests that they had recovered to the Unaffected levels of abundance by that time. Similarly, the other recorded species of this zone were all not significant over time.

Table 41 – Summary of potential impacts, possible re-instatement interventions and recovery outcomes in the fixed dunes and dune grassland.

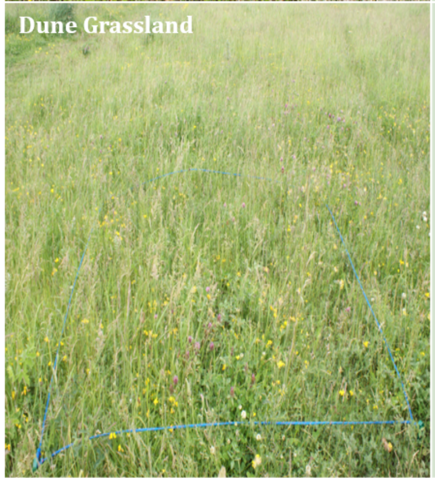
Vegetation Zone	Potential Impacts	Re-instatement	Recovery
Fixed Dunes 	▪ Pipeline construction results in the loss or reduction in cover, of the main grasses (*i.e. Ammophila arenaria, Elytrigia juncea* or *Leymus arenarius*) along the working width. ▪ There is an increase in bare ground and early successional species. There is also an increase in total moss cover. ▪ A large number of the species in this zone showed significant differences between sample area and over time, either increasing or decreasing following construction.	▪ The original topography of the dunes should be restored, unless the aim is to create a more varied ridgeline. ▪ Typically, the fixed dunes are replanted with dune stabilising grasses *i.e. Ammophila arenaria, Elytrigia juncea* or *Leymus arenarius.* ▪ Individual rare or scarce plants can be lifted and grown-on so that they can be replanted post-construction. ▪ Hand harvesting of seed may be possible to increase species-richness. ▪ There are opportunities to create areas of bare sand to allow the colonisation of early successional species.	▪ The fixed dunes showed the quickest recovery times with vegetation referable to the main NVC communities establishing within the Short-term. ▪ Where levels of impacts were higher, or there was a poor establishment of the planted grasses) there was a increased amount of bare ground, but consequently a higher number of early successional species including local rare and scarce plants. ▪ Succession to dune grassland was temporarily halted. ▪ Post-construction habitat management will increase the likelihood of a successful outcome.
Dune Grassland 	▪ The dune grassland supports a larger number of generalist species (compared to the other sand dune vegetation zones), in particular those that prefer mesotrophic conditions. Following pipeline construction, there was no significant differences in cover of the mesotrophic species *e.g. Arrhenatherum elatius, Dactylis glomerata*, *Holcus lanatus* and *Poa pratensis*, between the sample areas or over time. This indicates that these species quickly recover to pre-construction levels. ▪ In contrast, the working width had significantly lower cover of *Ammophila arenaria.* ▪ Fine-leaved grasses had a significantly higher cover On the pipeline.	▪ The dune grassland typically recovers well with little intervention. Brush-harvesting of seed collected from the site prior to construction can be reinstated. ▪ However, site diversity in terms of vegetation communities and species-richness can be increased by creating dune scrapes and dune slacks (by excavating down to the water-table). This encourages early successional species and wet-tolerant herbs.	▪ Recovery of dune grassland typically occurred in the Short-term. ▪ Succession to species-poor mesotrophic grassland was temporarily halted. ▪ Where interventions resulted in fixed dunes or dune slacks, these supported typical species within the Short-term. ▪ Post-construction habitat management will increase the likelihood of a successful outcome

Table 42 - Summary of potential impacts, possible re-instatement interventions and recovery outcomes in the dune slacks.

Vegetation Zone	Potential Impacts	Re-instatement (and mitigation)	Recovery
Dune Slacks 	▪ In the dune slacks there was a significant loss of wet-tolerant species *e.g. Bolboschoenus maritimus*, *Carex nigra*, *Eleocharis quinqueflora*, *Dactylorhiza purpurella*, *Glaux maritima*, *Hypnum cupressiforme*, *Rhytidiadelphus squarrosus* On the pipe following installation. ▪ However, these areas still typical retained a higher species-diversity than the other vegetation zones. Often supporting species-rich short-turf communities *i.e. Anthoxanthum odoratum*, *Centaurium erythraea*, *Euphrasia* spp., *Lotus corniculatus*, *Potentilla reptans*, *Prunella vulgaris.* ▪ Cover of scrub species was also significantly higher On the pipe.	▪ Areas of species-rich dune slacks should be avoided wherever possible as it is likely there will be a change in water-table that can significantly effect wet-tolerant herbs. ▪ Where avoidance of dune slacks is not possible then the working width should be minimised. All non-essential works should be located outside this area. ▪ In these locations, re-establishing the original topography is important. ▪ Dune slack turves should be lifted, and stored under suitable conditions, until following works when they can be replaced in their original locations. ▪ Seed-harvesting by hand of individual rare and scarce species should be undertaken. ▪ New areas of dune slacks (scrapes) could be considered as part of the mitigation process for example by locating these in dune grassland near to existing dune slacks.	• In the Short-term following construction there was a loss of typical wet-tolerant herbs, replaced by species associated with drier communities. • Determining recovery time frames for this vegetation zone is difficult as it depends on the required vegetation type ie early successional dunes slacks may develop in the Short-term, but more complex dune slack communities may take until the Medium- or Long-term. • Dune grassland developed in *c. 75%* of the quadrats which was an Unacceptable Net Loss. • Post-construction habitat management will increase the likelihood of a successful outcome.

5.6 Assessment of Effect and Mitigation Hierarchy

5.6.1 Significant Effects

As part of the Ecological Impact Assessment (EcIA) process, potential impacts need to be described[90] and assessed against likely effects on important ecological features. Where these effects are likely to support or undermine biodiversity conservation objectives[91], they are considered to have a significant effect (CIEEM, 2016a). CIEEM defines a significant effect as "*an effect that is sufficiently important to require assessment and reporting so that the decision maker is adequately informed of the environmental consequences of permitting a project*". Actions which result in a significant effect, do not necessarily mean that a project should be refused planning permission, but in such situations, the mitigation hierarchy should be applied effectively as part of the decision-making process.

5.6.2 Mitigation Hierarchy

The mitigation hierarchy is a sequential process adopted through current planning policy *i.e.* National Planning Policy Framework, to avoid, minimise, mitigate and compensate for ecological impacts, through the application of best-practice (Figure 100). Further guidance is provided by CIEEM (2016a).

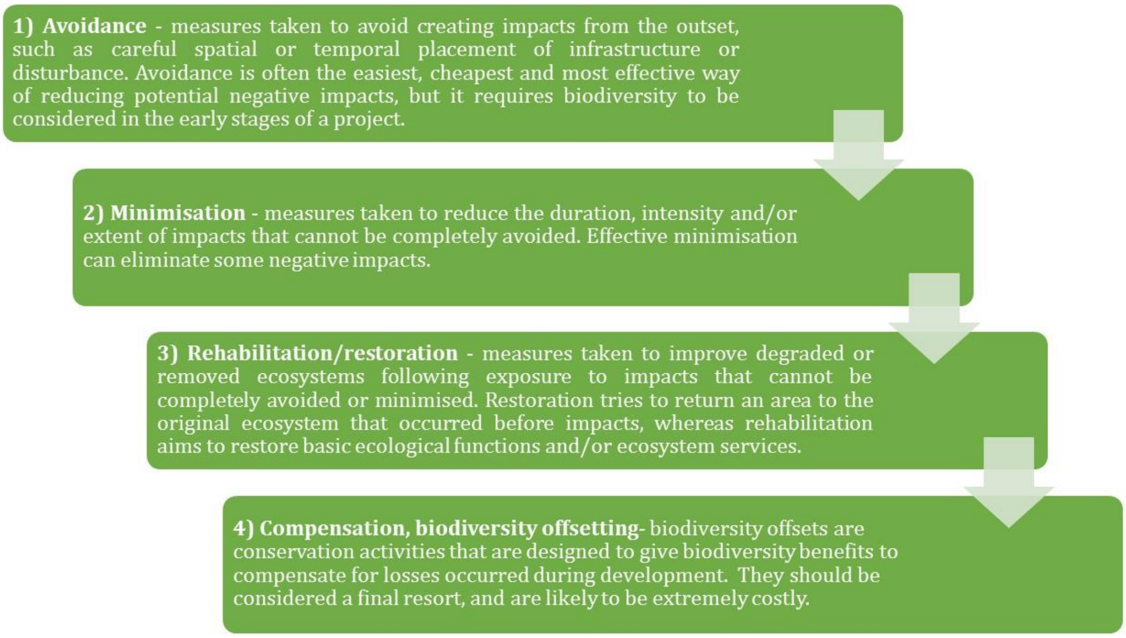
Collectively avoidance, minimisation and rehabilitation/restoration serve to reduce, as far as possible, residual impacts on biodiversity. Typically, however, even after their effective application, additional steps will be required to achieve no overall negative impact or a net gain for biodiversity. Biodiversity offsetting measures may therefore be necessary to compensate for any residual adverse impacts.

The mitigation hierarchy should be a key principle considered for all pipeline or cable installation projects, with the overall aim of achieving a 'No Net Loss' or a 'Net Positive Impact' scenario (as defined in *Sections 1.7.3* and *5.6.3*).

---

[90] CIEEM (2016a) suggest using characters such as positive or negative, extent, magnitude, duration, timing, frequency and reversibility should be used to describe ecological impacts.
[91] *E.g.* impacts on structure and function of defined sites, habitats or ecosystems and the conservation status of habitats and species (including extent, abundance and distribution)

Figure 100 - Mitigation hierarchy based on CIEEM (2016a).



Measures

Examples of avoidance and minimisation measures during planning and subsequent construction are set out below. Restoration measures have been outlined in *Sections 5.4* and *5.5* for saltmarsh and sand dunes respectively.

Avoidance measures

Avoidance measures can be divided into spatial, temporal and project design (BirdLife International et al., 2015).

Spatial avoidance:

- relocating the planned development activity so that it is re-sited to avoid impacts on key biodiversity features. For example, UK, European or International designated areas *e.g.* Sites of Special Scientific Interest, National Nature Reserves, Natura2000 areas (Special Areas of Conservation or Special Protection Areas), and Ramsar sites;
- avoidance of particularly sensitive vegetation types or where reinstatement is more difficult *e.g.* in sand dunes, this may include dune slacks that have a more complex hydrology and support rare plants or unusual plant communities. In saltmarshes, this may include species-rich examples of upper-marsh or vegetation communities with restricted distributions;
- avoidance of key functional features *e.g.* saltmarshes with large or frequent creeks, where changes in drainage patterns may cause vegetation loss, pooling of water or increased erosion;

- avoidance of sites with a particular geomorphology; for example, in saltmarshes it may be better to avoid sites with a silty substrate (*e.g.* as found on The Wash and at Walney Island) compared to more sandy substrates (as found at Pegwell Bay and Poole Harbour). As silty sites are more likely to suffer from problems of compaction and sediment loss than sandy sites which have freer drainage. The Corrib pipeline crossed saltmarsh that had developed over a peaty substrate which allowed intact turves to be lifted and subsequently replaced; and
- avoidance of known populations of rare or protected species *e.g.* Natterjack Toads within dune scrapes and temporary pools; or known locations of Seal haul-out areas, in particular when they have young.

Temporal avoidance:

- depending on the notification features on a site, avoiding key usage periods by protected species. For example, sites may be designated for their use by migratory and over-wintering birds so works may be restricted to the summer period; alternatively, if nesting birds are likely to be present avoiding the period between the 1st March until the 31st July would minimise disturbance;
- avoiding periods of high-tides in saltmarshes (or periods of wet weather), so that the marsh surface is as dry as possible while undertaking work;
- avoiding night-time working when species may be resting or roosting *e.g.* on the saltmarsh Marsh Harriers may roost in the upper-marsh; and
- habitats may be temporarily moved (*e.g.* through lifting turves, or removing individual plants) ahead of construction for later reinstatement.

Project design:

- use HDD construction measures (over open-cut methods) such as to limit on the surface impacts. Where HDD is not feasible due to underlying geology, consider alternative methods such as use of a cable plough, chain-cutter;
- locate work and storage compounds outside sensitive habitats;
- use low-ground pressure vehicles with caterpillar tracks to distribute vehicle weight more evenly;
- use trackways (*e.g.* aluminium panels in saltmarsh, and wooden boards in sand dunes) to distribute vehicle weight, rather than using a stone-hard core track. Underlay trackways with a suitable grade geotextile membrane. Do not leave the trackway in-situ;
- for construction equipment *e.g.* excavators use approved biofuels and avoid refilling when working in saltmarsh or sand dunes. Where refilling is necessary use drip-trays and pollution prevention measures; and

- An Environmental Management Plan should be developed and followed. This should include emergency contingency measures.

Minimisation

Examples of minimisation include:

- where areas of saltmarsh and sand dunes cannot be avoided the shortest possible crossing point, should be chosen. Similarly, the best route should be chosen to minimise crossing sensitive vegetation types;
- minimise the extent of the working width and any work compounds;
- ensure the work areas are clearly differentiated through fencing *etc.* so to minimise unauthorised access into the wider habitat;
- employ an independent ECoW to oversee works and provide site briefings to contractors. The presence of an ECoW can help minimise avoidable damage during certain operations, advise on any unexpected ecological issues and can ensure the satisfactory conduct of certain operations;
- ensure all contractors have received a toolbox talk on the site ecology, including information on why a site is important, and how they can help minimise impacts on the habitats and species present;
- in saltmarsh and areas of dune slacks restrict the number of vehicle movements, and limit the number of people accessing the site, even along trackways, to minimise sediment compaction and vegetation trampling;
- where trackways are laid over vegetation, minimise the number of days it is left in-situ so to prevent complete die-back of plants;
- minimise the spread of invasive non-native plant species (or other species) through appropriate vehicle inspections and cleaning;
- minimise dust generation (more applicable on sand dunes) during dry, hot weather by dampened trackways *etc.* periodically; and
- reduce noise by, for example turning off vehicle engines when stationary. This can minimise disturbance to birds *etc*. For example, on saltmarsh, waders may use the pioneer marsh at low-tide for feeding or resting, therefore excessive noise during this period can result in loss of condition.

5.6.3 No Net Loss

In 2011, the UK Government produced the Natural Environment White Paper (HM Government, 2011), which outlined the then Conservative and Liberal Democrat Coalition Government's vision for the future of landscapes and ecosystem services. In a Defra press release following the launch of the White Paper, Environment Secretary Caroline Spelman said, "*The true value of nature should be built in to the decisions we make – as individuals, organisations, businesses and governments – so that we become the first generation to leave the environment in a better condition than we found it*." The White Paper built on the recommendations in the Making Space for Nature report (Lawton, 2010), which included policy initiatives on biodiversity offsetting.

The EU has committed to halting the loss of biodiversity and the degradation of ecosystem services by 2020. The Biodiversity Strategy sets out 6 targets and 20 specific actions to achieve this objective. Action 7 is to ensure No Net Loss of biodiversity and ecosystem services. The EU Working Group (set up to review member states past experiences and collect views on how to implement with regards to existing policies and statutory instruments) notes that it is "*vital that any EU No Net Loss initiative anchors compensation/offsetting into a strict and systematic mitigation hierarchy*" (Working Group on No Net Loss of Ecosystems and their Services, 2013). This means that the first objective should be to try and avoid or prevent negative impacts. Where this is impossible, damage should be minimised, and restoration attempted. Compensation or offsetting should be a last resort.

In England, mandatory offsetting (through the European Habitats and Wild Birds Directives) is currently only required where a development with imperative reasons of overriding public interest (with no suitable alternatives) has significant impacts on the Natura 2000 network, or impacts sites occupied by European protected species. In such situations, the Directive requires that all necessary compensatory measures are taken to ensure the overall coherence of the network of European sites as a whole is protected. In addition, planning policy encourages, but does not absolutely require, local authorities to ensure compensation for development impacts on biodiversity (*e.g.* National Planning Policy Framework (NPPF) Paragraph 118, Section 40 of the Natural Environment and Rural Communities Act 2006, and Section 106 agreements). NPPF Paragraph 118 notes that "*where a development cannot satisfy the requirements of the 'mitigation hierarchy', planning permission should be refused*" (Ministry of Housing, 2012).

5.6.4 Biodiversity Offsetting

In 2012 Defra undertook a 2-year pilot Biodiversity Offsetting scheme covering six offsetting areas. Guidance was produced for developers, local authorities and providers, as well as providing technical information on how to calculate the offset units (Defra, 2012).

The guidance was designed to help practitioners calculate the level and likely success of any offsetting scheme using a standardised approach. The offset calculation is based on a matrix which considers; habitat type, habitat distinctiveness and condition, as well as the multipliers that consider the risk in creation/ restoration, location (in terms of offset strategy), and number of years to target condition. The guidance note also provides scores as for the technical difficulty of recreating and restoring the habitat, and an indication of the feasibility and time frames for restoration (Table 43). For habitats that are of high distinctiveness *i.e.* saltmarshes and sand dunes, it would generally be expected to be offset with "like for like" *i.e.* the compensation should involve the same habitat as was lost. For sand dunes, it should be accepted that it is nigh on impossible to recreate new habitat areas and that some habitats are irreplaceable.

Table 43 - Technical difficulties, feasibility and timescales for restoration of saltmarsh and sand dunes based on Defra (2012).

Habitat type	Technical difficulty of recreating	Technical difficulty of restoration	Time-scales for restoring	Feasibility of restoring
Saltmarsh	Medium	Medium	10-100 years	Dependent on the availability of propagules, position in tidal frame and sediment supply.
Sand dunes - yellow dunes	Very High / Impossible	Medium	50-100+ years	Dependent on sediment supply, and availability of propagules. More likely to be restored than recreated.
Sand dunes - grey dunes and dune slacks			100-500 years	Potentially restorable but in long time frames and depending on the intensity of disturbance.

Specifically, with regard to coastal habitats there are potential issues associated with the achievability of biodiversity offsetting. These include:

- restoring natural processes and functionality, in particular sediment inputs;
- guaranteeing 'in perpetuity' landownership;
- a significant proportion of suitable areas are already protected, therefore identifying suitable receptor sites is difficult;
- coastal areas are subject to more complex regulatory regimes with additional stakeholders;
- there are limited opportunities for large scale initiatives;
- habitat distinctiveness is typically high therefore there is a requirement for 'like -for -like' or 'like -for better'; and
- long time frames for achieving habitat functionality.

The Environment Bank (Unknown)estimated that the cost of offsetting coastal habitats (in terms of land purchase, and management agreements) as between £400-£470 million[92] – which would equate to between £40,000-£47,000/ha. ABPmer have completed a review of the implementation costs for completed UK managed realignment schemes. They showed there was a huge amount of variability in cost, depending on the location, engineering effort, and objective of a given scheme. An average cost of managed realignment schemes (over the past 25 years) is just over £35,000/ha, although when considering managed realignment sites since 1999 the average cost

92 assuming 10,000ha land needed for development, with a risk multiplier, assuming land developed is in moderate condition, assuming 50:50 brownfield: greenfield land development, *etc.*

increases to just over £40,000/ha. However, the study showed that compensatory schemes typically were more costly (than schemes implemented for other reasons), at just over £72,000/ha (ABPmer, 2015).

5.6.5 Biodiversity Net Gain

Biodiversity offsetting has not been widely taken up, in part due to concerns from environmental NGO's that the policy might create a 'licence to trash'. Currently, the concept of Biodiversity Net Gain is gaining momentum. The concept behind this approach is that developments leave biodiversity in a better state than before. It is an approach where developers work with local government, wildlife groups, land owners and other stakeholders in order to support their priorities for nature conservation. CIEEM has published ten draft principles for achieving Biodiversity Net Gain (Figure 101). These principles seek to promote a structured approach to delivering biodiversity gain which embeds the mitigation hierarchy (avoid-reduce-mitigate) thus minimising impacts on the natural environment (CIEEM, 2016b).

Figure 101 - Biodiversity Net Gain – adapted from CIEEM (2016b)

An element of caution is required, when considering the use of managed realignment schemes to compensate for developments, as Mossman et al. (2012b) concluded that saltmarshes created by managed realignment schemes do not provide habitat of a similar species or community diversity as natural marshes. The paper goes on to say that therefore managed realignment sites do not meet requirements set out under the EU Habitats Directive as an option for compensating habitat loss (through development or sea-level change).

MONITORING

Chapter 6 Monitoring

6.1 Introduction

The focus of *Chapter 6* is to review the most commonly used methods in determining the baseline vegetation condition and post-construction recovery of impacted sites (Theme 5). The purpose is not to provide specific methods for these widely used approaches, but to consider the pros and cons of each method with regards to saltmarsh and sand dunes assessment.

The chapter also summarises the original survey methods used for my case study sites, this illustrates some of the best examples, but also those where monitoring was, in my opinion, not sufficient to determine recovery.

Finally, the chapter provides what I consider is the best-approach, and provides some indication to the minimum requirement, in terms of survey time frames and survey extent.

6.2 Successful Monitoring

As discussed in *Section 1.6.2*, one of the main failures in the EIA process, is that there is a lack of requirement in determining success criteria at the project onset. Success criteria should use measurable attributes or targets against which the effects of post-construction recovery or restoration can be monitored. This is reinforced by Bellmer (2001) who notes "*before construction commences, it is necessary to establish how success will be defined. With these clear objectives, restoration progress can be readily gauged and corrected if the system is not on track*". Similarly, Holl and Cairns (2002) notes that a monitoring protocol with clearly defined goals needs to be established at the project planning phase, not after implementation. These goals need to be specific with measurable criteria of success. Without using such milestones or evaluation criteria, it is impossible to generate early warnings when the rate or direction of restoration is not followed. The use of standard methods and published protocols for a specific habitat type in a geographic region, gives added confidence when interpreting the results.

O'Reilly (2015) identifies 10 characteristics of successful vegetation monitoring schemes:

1. targets need to be specific, clear and measurable;
2. focus on a few targets (ideally just one or two);
3. consider how the data will be analysed before the field method is designed rather than after the survey;

4. ensure the survey method is repeatable: If two surveyors were to do the survey independently, they should get more or less the same results. If not, then the method is flawed and may lead to misleading conclusions;
5. data should be collected as measurements or counts and should avoid subjective estimates *i.e.* percentage-cover;
6. use a scientifically valid method that eliminates survey bias;
7. stratification of sites or habitats reduces variance between samples;
8. the sample size is big enough to give a reasonable level of statistical power;
9. the designed field method is easy to understand and apply; and
10. the field method is not too time-consuming.

When considering the monitoring methods used for saltmarsh and sand dune surveys there frequently appears to be a lack of consideration when designing the monitoring strategy, when related to the ten points highlighted by O'Reilly. In particular, monitoring, following construction, typically fails to define specific measurable targets, does not consider how the data will be analysed and often fails to consider survey bias and sample size. While the field method is mostly designed not to be too time-consuming, it can be over simplified and does not collect sufficient data to determine change. This is perhaps due to financial pressures by the client, especially as long-term monitoring is not always costed into a project at the planning stage and/or the site is owned/ managed by other developers once installed. It appears that frequently the survey strategy relies on a single surveyor or team to complete the entire monitoring, which when this may be over a 10-year period is probably unrealistic. Therefore, designing a suitable monitoring strategy should be an integral part of the planning process, with the ongoing monitoring requirement set out in the planning consent as a specific planning condition.

In addition, to the ten points set out by O'Reilly (2015), I would also add the following (based on my experiences):

- is the monitoring survey likely to cause additional damage to the site *e.g.* through the collection of samples or by trampling;
- surveys should be repeated at the same time of year throughout the monitoring period, as for both saltmarshes and sand dunes the species recorded (and its frequency/ abundance) will change over the seasons;
- plant species data should be recorded from across all plant groups *i.e.* both higher and lower plants, rather than just using indicator species, as this can limit the future use of the data;
- if using permanent quadrats or transects, consider how they will be accurately relocated during future surveys. This is especially important in featureless environments, such as saltmarsh;

- consider setting out in the monitoring strategy the level of botanical skill/ experience required to complete the survey work, so that if others undertake the work, it will be completed to the same standard; and
- consider whether monitoring requires additional specialists. Rather than just focusing on botany (or ecology), for example it may be necessary to consider hydrology or sedimentology.

6.3 Monitoring Considerations

6.3.1 Survey Extent

The baseline survey is likely to require a survey area of, as a minimum, several hundred metres in the vicinity of the proposed works; and may also need to consider multiple crossing locations. The baseline survey should help to inform route options, for example in saltmarsh areas, it may define a route which avoids large or numerous creeks; and in sand dunes may help avoid sensitive dune slacks.

The pre-construction survey extent may be smaller, but it needs to be of a sufficient area to encompass both impacted and unaffected areas. The survey width should extend beyond the proposed working width with an adequate buffer so that any modifications to the impacted area can still be assessed. It also needs to include a large enough unaffected area to act as a control. For example, a site with a 30m wide proposed working width should probably include an additional 10m wide buffer (to provide a contingency area for route alignment changes[93]) and should extend out beyond this by a further 50m either side of the pipe/ cable. This would result in a survey width of approximately 140m. The length of the survey extent would be determined by the distance of impacted habitats *i.e.* saltmarsh or sand dunes.

Samples should be distributed over the entire area for which inferences need to be made Fancy (2000 cited by Holl and Cairns (2002)). One of the proposed methods for monitoring (*Section 6.6.2*) uses a random stratified sampling approach, where a certain number of samples are randomly placed within each vegetation zone.

The post-construction survey extent should replicate the pre-construction survey.

6.3.2 Length and Frequency

Following restoration, most monitoring projects in the UK continue for around 5 years (although at some of the sites *e.g.* Thanet, monitoring was only undertaken for 1 or 2 years). The length of monitoring is typically designed to demonstrate compliance rather than being based on ecological

[93] *E.g.* unforeseen emergency access of construction vehicles

principles (Holl and Cairns, 2002). Many targets therefore have short-term goals which can inhibit long-term restoration (*e.g.* sowing quick growing grass species in dunes to stabilise the surface may inhibit true sand species as noted at Cruden Bay). In addition, short-term monitoring cannot determine whether a habitat is self-maintaining (persistent) and whether it is resilient to natural events *e.g.* storms. Holl and Cairns (2002) notes that monitoring should at least continue until the predetermined goals are achieved.

Lockwood and Pimm (1999) note that a restored community is considered persistent when the turnover in species composition falls to a level resembling the natural turnover rate. In addition, they note that it is easy to over-estimate when persistence is achieved. In a review of 87 projects, they found that 48% of restoration projects stopped monitoring before the goals were achieved, with the majority of these stopping despite none of the stated goals being met. While only 20% of the sites were successful in meeting the prescribed functional and structural goals. In addition, the study found that around 60% of the sites were partially successful. *E.g.* at Salmon River saltmarsh Lockwood and Pimm (1999), notes that the project restored a wide diversity of plants typical of saltmarshes and biomass production, however, the original species-richness of the site was not restored. They also note that out of the 87 projects sampled, only two sites restored the original species composition.

Based on my research, tentative recovery times in saltmarsh and sand dunes are set out in *Sections 3.9* and *4.8* and are summarised in *Section 7.3* and Tables 44-45. With the vegetation zones taking anything from 10 years to over 40 years to recover. However, there is a difference between monitoring to determine full recovery and showing that it is recovering. It is highly unlikely that a construction project will undertake monitoring over a 30-year period (as may be required to document the full recovery of mid-upper marsh) or even longer to document dune slack recovery. Therefore, the requirement for monitoring should aim to show that vegetation recovery is proceeding along the required trajectory. It is unlikely that each vegetation zone would be monitored for differing lengths of time, unless a specific zone was showing signs of not meeting recovery targets. Therefore, it is suggested that a minimum monitoring period of 10-15 years is used, but that it may need to continue beyond this.

Following restoration, monitoring to assess vegetation condition should be carried out frequently, so as to determine whether restoration efforts are proceeding along predicted trajectories. However, over time the frequency of monitoring can be reduced. For example, for the first year after construction, monthly condition checks of a sites condition may be necessary (these may focus on specific condition attributes *e.g.* creek severance or vegetation dieback). Then on an annual basis, starting in the year of construction (Year 0), vegetation sampling should be taken, with surveys repeated at the same time of year subsequently. For saltmarsh the recommended survey period is between May and September[94] and for sand dunes between May and August[95]. Once the vegetation appears to be recovering as required, the annual surveys may be reduced to once every 2 or 3 years.

6.3.3 Measures of Success, Indicators and Attributes

Criteria for assessing monitoring should validate or confirm transitional stages of recovery, providing an early warning where recovery is not proceeding as predicted (Holl and Cairns, 2002). The use of multiple criteria helps minimise the likelihood of false positives[96] or false negatives[97]. In most cases a combination of functional and structural criteria should be used. Although many projects just focus on recording structural attributes from a single group *i.e.* plants due to the relative ease of measurement.

Lockwood and Pimm (1999) notes that returning a site to its original structure will be harder to achieve than returning it to its original function, as structure has more ecological constraints. They note to restore function it may not be necessary to restore specific species, as ecosystem functions appear to develop consistently with a broad variety of species.

Bakker et al. (2000) undertook a review of defining attributes for ecological restoration. The review highlighted typical attributes focusing on vegetation monitoring:

- biodiversity (expressed as species-richness or abundance);
- presence of specific vegetation communities; and
- target species (*i.e.* Red-list species, umbrella species, political flagship species or indicator species that are characteristic of species plant communities or conditions).

Holl and Cairns (2002) highlights several problems associated with using species as indictors of environmental conditions *e.g.* although each species indicates something, no individual species can indicate everything; extrapolation from one species to another is often unreliable; and different indicators take different lengths of time to respond.

In practice a combination of attributes defining restoration should be used, as single measures can produce misleading results. *E.g.* considering species-richness, an eutrophic site may have a higher species-richness than a mesotrophic or oligotrophic site; but in restoration terms the oligotrophic site would be preferable. The use of rarities to define restoration success may be too

[94] An early survey *i.e.* May will pick up annuals *i.e. Cochlearia danica* while later surveys in August-September aid identification of *Atriplex* and *Salicornia* spp.
[95] Fixed dunes benefit from surveys in May-June so to record annuals, while for dune slacks surveys in July-August are recommended.
[96] A false positive is caused by setting low action thresholds, so that the data indicates that some undesirable effect has occurred when it has not.
[97] A false negative is caused by setting too high action thresholds, so the data implies that no deleterious effects have occurred when they have.

ambitious for most sites, only occurring if the species is present in the soil seedbank. Added to this, often the species are so endangered that their ecological requirements are not fully understood so the likelihood of restoration success based on their presence is low. The use of plant communities to define recovery can also provide misleading results, especially in dynamic or disturbance led systems such as sand dunes, where a decision is needed in determining which successional stage is considered to be the target community.

For example, in a study looking at restoration success following saltmarsh reclamation, species and community level targets were considered (Chang et al., 2016). The study found that 10 years after restoration, the permanent transect data showed that 78% to 96% of the target species were found at the restoration site. However, the vegetation mapping, showed that the diversity of the saltmarsh communities was low, with 50% of the site covered by a secondary pioneer marsh community. The authors concluded that if the study had just considered target species as criteria, restoration success could have been claimed after the 10 years; however, the diversity of communities in the saltmarsh was much lower than desired and therefore this target was not met.

Davy (2002) states that difficulties in the identification of appropriate restoration targets "*are often symptomatic of our generally very incomplete understanding of how plant communities are structured".*

When setting site goals/targets it is worth using SMART[98] objectives. In addition, how the target is phrased can make a difference as to the level of outcome and whether it will be achieved. *E.g.* three examples for a target relating to species composition are given below:

1. to establish sufficient plant diversity to provide wildlife habitat (this goal is not measurable and is open to interpretation); or
2. to return all species observed during the pre-construction survey to the site (this is probably an unrealistic goal as it is highly unlikely that all species will return, and therefore this target may never be achieved); or
3. to return all species (with cover over 5%) observed during the pre-construction survey (this is a measurable goal, and probably more realistic than target 2).

Reviewing the findings for the saltmarsh and sand dune sites analysed as part of this project it is clear that targets have to be site specific. The study showed that typical species of a vegetation zone were more likely to show statistically significant differences between the On and Off sample areas. In addition, cover of bare ground also showed significant differences between the On and Off sample areas for both saltmarsh and sand dune habitats.

[98] S - specific. M - measurable. A - agreed upon/ achievable. R – realistic. T – time-based.

6.4 Commonly Used Methods

Appendix 6 Table 47 highlights those methods typically used in environmental assessments to determine the site baseline prior to construction and following construction as part of monitoring. It is typical (and often appropriate) that a combination of methods are used. Ideally, the baseline survey would be comprehensive enough to be repeated after construction to help determine vegetation recovery. However, in practice the survey methods are often modified over the course of the project due to various constraints not foreseen at the start including:

- a reduced resource budget (*i.e.* time and finance) available for the post-construction monitoring compared to the pre-construction survey;
- a change in route alignment of the 'as-built' pipeline or additional impacts beyond the working width, that may result in the pre-construction survey area not being fully assessed;
- a change in construction method leading to an underestimation of the development impacts (*e.g.* assessed use of HDD which was not suitable due to the underlying geology);
- a lack of timely input regarding the survey strategy and construction methods, resulting in additional monitoring measures being required;
- a change in project ownership over the course of the post-construction monitoring[99];
- a change in surveyors over the project leading to differences in survey sampling;
- a poor record of survey methods (or difficulties in relocating samples) making it difficult to replicate the original survey, causing analysis problems between survey years;
- a change in the survey window between the pre- and post-construction sampling *i.e.* an early survey may miss late developing species and vis-versa;
- vegetation recovery not being as predicted (either in extent or over time) resulting in additional surveys necessary to monitor vegetation change; and
- an advancement of survey technologies resulting in new survey methods (or increased accuracies) over the course of monitoring. This is especially applicable where monitoring extends over a period of 10-years.

Therefore, some flexibility in the design of the baseline and subsequent surveys is likely to be necessary, perhaps ensuring the initial surveys cover a large enough extent and include additional quadrat samples that can be used if required.

[99] *E.g.* for offshore wind farms, completed projects are required by the energy regulator (Ofgem) to be sold through competitive tender to offshore transmission assets owners (OFTO's).

6.5 Case Study Survey Methods

A variety of survey methods have been deployed to assess the vegetation condition before and after construction across my study sites. The information summarised here has been sought from EIAs, specific botanical monitoring reports and notes provided by statutory bodies.

6.5.1 Saltmarsh

The most comprehensive of the surveys available for this study are associated with the three pipelines on Walney Island. The three sites (South Morecambe, North Morecambe and Rivers Fields) span a period of roughly 20 years with the oldest site being installed in 1982 and the youngest in 2002. At the oldest site (South Morecambe) the focus of the pre-construction survey was the mid-upper marsh. The planning condition required a preliminary ecological survey of Wylock Marsh to be carried out prior to work, and that the upper marsh should be returned, as far as possible to its condition prior to installation. There were no planning requirements to reinstate the lower marsh, as it was considered that *Spartina anglica* would eventually reinstate itself (Rae, 1983). The preliminary survey was completed in the autumn of 1981 (Rae, 1981). The upper marsh was surveyed using a sampling grid, with quadrats marked at 10m intervals along the pipeline route. Thirty-six grid squares were surveyed (either side of the pipe), with a further nine quadrats used as a control. Within each grid square, 25 small quadrats ($10cm^2$) were randomly taken, with the presence/ absence of species recorded. In the lower marsh (extending approximately 200-900m from the shore) field notes recording species composition were made. Following construction, four reports (Rae, 1983, Rae, 1984b, Rae, 1984a, Rae, 1984c) were produced after regular site visits to monitor vegetation condition. Post-construction monitoring appears to be a visual (qualitative) assessment rather than a repeat of the grid sampling survey.

The two more recent pipelines (North Morecambe and Rivers Fields) were both surveyed by the same team using botanists from the Natural History Museum, and used broadly the same survey approach. Transects were established running perpendicular to the pipeline during the pre-construction survey. The transects extended beyond the work area so that the affected areas could be compared to the unaffected areas. Along each transect, seven quadrats were positioned, one along the trench line, two 25m from this, two 75m further out and a further two control quadrats taken in unaffected vegetation. Post-construction monitoring was completed annually repeating the baseline surveys, although the location of some of the quadrats were moved slightly to realign themselves with the pipeline route.

In contrast, several of the other sites used as case studies for this project had very limited monitoring information available.

The oldest case study site (Tetney Sealine Pipeline) was installed in 1971, and it appears that this project was not subject to any baseline or post-construction monitoring[100]. This is not unexpected as much of the wildlife legislation did not come into effect until after this project had been completed. A survey of the wider saltmarsh area was completed in 1988 by the RSPB (Burgess, 1988) which gives an indication of the vegetation condition at that time *i.e.* 17 years following the pipeline installation.

For the Inner Trial Bank project on The Wash, a number of ecology studies were completed by the Institute of Terrestrial Ecology (ITE) between 1972 and 1975 to assess the implications of the scheme. The botanical studies included surveys of the *Zostera* spp. beds, and the plant communities of the saltmarshes and adjacent reclaimed farmland. It looked at the role of algae in mudflat stabilisation and the development of saltmarshes using modelling (Central Water Planning Unit, 1976). A vegetation map was produced by examining aerial photographs and included 12 line transects along which vegetation and sediment accretion data was taken (Randerson (1975) summarised in Hill 1985). Vegetation was recorded every 100m along the transect and with permanent 10m×10m quadrats. As the scheme was shelved, no specific post-construction surveys were undertaken. However, in 1985 the Nature Conservation Council commissioned a study to assess vegetation change across The Wash, and this survey repeated the original transects surveys (Hill, 1988). The study aimed to determine vegetation condition and rates of accretion. One of these transects, (Transect 4 known as Trial Bank) was recorded in close proximity to the causeway.

At Wytch Farm, Poole Harbour, the oil flowlines crossed several discrete areas of saltmarsh habitat. A study by the ITE (commissioned by BP) sought to determine the impacts of pipeline construction across the Poole Harbour saltmarshes (Gray, 1986, Gray and Benham, 1986). These studies set out the baseline conditions through a description of the vegetation communities present at three specific areas known as Cleavel Point, Shotover Moor and Wytch Moor. The report also contained a literature review of current best practice for saltmarsh restoration.

Interestingly, the most recent of the sites used in this study, had the least available data. The cable associated with Thanet OWF crosses saltmarsh at Pegwell Bay. Initially, in 2005, a Phase 1 Habitat survey was completed by Royal Haskoning of the onshore cable route (including the saltmarsh). At this time, the landfall was positioned further to the north (approximately 750m away). This original route alignment was granted consent in November 2005. However, in 2007, a new alignment was applied for and gained consent which included changing the landfall location. As a result, the route would come ashore across a wider more intact area of upper, middle and lower saltmarsh, however little baseline information is provided. Following installation of the cable in

[100] There is a possibility that surveys were taken but the reports have been lost in the intervening period

February 2010, monthly monitoring using species-listing and fixed-point photography was used for six months starting in March, however no quadrat data was collected (Royal Haskoning, 2010). In 2011, the monitoring divided the saltmarsh into four vegetation zones and included 16 $1m^2$ quadrats, four in each zone. In each zone, two quadrats were recorded in adjacent undisturbed saltmarsh and two quadrats along the affected cable corridor. The percentage cover of each plant species within the quadrat was estimated within a grid of 20cm squares. The locations of the quadrats were determined on site by visual assessment of the zonation of plants, and the locations were recorded using a hand-held GPS (Royal Haskoning, 2011). No further monitoring of this site was completed.

6.5.2 Sand Dunes

For the projects crossing sand dunes a far more detailed approach to the assessment process has been completed; and consequently, baseline and post-construction surveys are more robust. This may be due to the additional perceived biodiversity value attached to sand dune habitats in contrast to saltmarsh.

The dunes at South Gare & Coatham Sands SSSI have been subject to three main pipeline/ cable projects since 1990. For the oldest project (AMCO CATS pipeline) the ES included a detailed botanical survey by Dr R Carter (Environmental Resources Limited, 1990). This included a survey of the dune system to determine the range of habitats and plant species present in the wider area; and a more detailed survey focusing on vegetation lying within 50m of the proposed pipeline route. The detailed survey involved developing a grid system of rows and quadrats centred on the pipeline route, with species data collected with Domin values. Unfortunately, the post-construction monitoring reports for the AMCO CATS pipeline are missing. However, in 1993, the wider area was resurveyed as part of the proposed Britannia Pipeline which would also make landfall at Coatham Sands. This scheme was also subject to an EIA and detailed botanical surveys (by the same author); although the project was later shelved (Environmental Resources Management, 1994). The Environmental Statement refers to the mitigation and avoidance measures that were used for the AMCO CATS pipeline; however, it does not provide specific survey data or comment on vegetation condition of the reinstated AMCO CATS area.

In 2009, surveys were completed ahead of the construction of the Project Breagh pipeline. This included a detailed NVC survey and species-listing by Dr R Carter, of the pipeline and adjacent area to inform the EIA (RSK Carter Ecological, 2009). Following construction in 2010-2011, quadrat sampling along the pipeline was taken on a grid system with species data collected with Domin values. This survey was repeated annually between 2012 and 2015.

The final project affecting dune habitat within South Gare & Coatham Sands SSSI was a temporary construction compound built as part of the Teesside OWF. A baseline vegetation survey was completed in 2003 (Entec, 2008, 2004) as part of the EIA. The survey area encompassed a 500m wide corridor either side of the proposed cable route and incorporated sand dunes and grassland. Historical NVC surveys were sourced including the 1990 survey (Environmental Resources Limited, 1990) to provide a context to the survey. Quadrat data and botanical target-notes were taken to allow vegetation diagnosis to NVC level to be made. As HDD methods were used to avoid the majority of the dune habitat the impact of the scheme was reduced. However, the construction compound was built in an area of dune slacks and it appears that none of the baseline quadrats included this area. No post-construction monitoring was taken.

At Point of Ayr, Talacre Warren the vegetation has been well documented, and several botanical surveys have been completed across the dune system (including areas beyond the pipeline installation). Of the greatest relevance to this project is the detailed NVC report with accompanying maps and data (Ashall et al., 1991) produced as part of the wider Sand Dune Survey of Great Britain study (Dargie, 1995). Prior to the construction of the pipeline a pre-construction botany report was taken as part of the EIA (Environmental Resources Limited, 1993). This survey identified the vegetation along and adjacent to the pipeline corridor prior to construction and included species-lists recorded in vegetation habitat parcels. Following construction, annual botanical monitoring was taken along and adjacent to the pipeline between 1996 and 1999 (Carter Ecological Limited, 2000, 1999, Maldon Ecological Consultants, 1998, 1997). Three monitoring areas were developed covering the Seaward Dune Ridge, Landward Dune Ridge and Dune Grassland. These were divided into survey blocks, within which vegetation sampling was taken on a grid system, using a random number generator to locate quadrats on the x, y coordinates. A 2m×2m, sub-divided quadrat was used, with presence/absence data collected for each cell.

Photo Plate 11 – Pre- and post-construction survey methods on saltmarsh and sand dunes.

Dr Richard Carter during post-construction monitoring survey of sand dunes.

Dr Jonathan Mitchley during post-construction monitoring survey of saltmarsh.

Ground-truthing of saltmarsh vegetation after LiDAR digital image classification.

Magnetometer survey of saltmarsh prior to construction to identify Unexploded Ordnance ahead of trenching.

Seismic survey of saltmarsh to determine underlying geology.

GPS-guided UAV survey using a drone to record saltmarsh vegetation condition and cover.

6.6 Survey Recommendations for Future Projects

Based on my experiences in consultancy and research as part of my PhD, the following survey recommendations are given.

6.6.1 Approach

The baseline survey submitted for the planning process is likely to need updating with an extended scope prior to construction. This revised method will form the pre-construction survey. This will ensure the pre-construction survey is up-to-date (as often obtaining planning permission can take several years); and will enable changes in the route alignment[101], construction methods, survey windows, and opinions from statutory authorities to be incorporated into the monitoring protocol. Having reviewed survey methods used for the case studies, a change in the construction methods after the baseline assessment has been assessed, is one of the main reasons why monitoring schemes struggle to document vegetation change. At this stage, success criteria with appropriate milestones should be developed.

Following construction, the monitoring protocol should be reviewed, to ensure it is sufficiently detailed to assess the 'as-built' scheme. Only where there is a compelling reason should the methods be changed. In such a situation agreement should be made with the statutory bodies overseeing the project. Following each post-construction survey, the survey data should be evaluated against the success criteria to determine the direction and rate of recovery.

As part of the post-construction survey there needs to be an assessment of the physical impact to the site. It is suggested that a pre-determined site-specific scale is developed so that it can be used throughout the project to track recovery. For example, a matrix could be used as suggested in Figure 102 for saltmarsh recovery, where a score out of 25 can be assigned based on vegetation and surface sediment condition. Photo Plate 12 shows six example quadrats taken following cable installation on saltmarsh. Each quadrat has notes on the vegetation and sediment condition, with a score given based on the proposed condition matrix. Other indicators of early success could include the presence of seedling germination (recording the species); inward growth over disturbed area of surrounding vegetation *e.g.* *Puccinellia maritima* which produces lateral extensions which root at the nodes; and creek condition *i.e.* maintaining tidal flow preventing permanent pools.

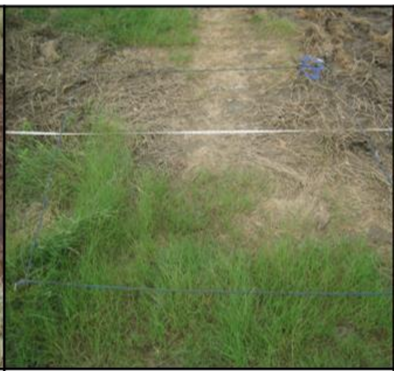
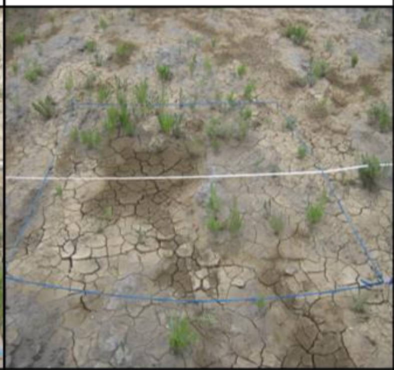
---

[101] perhaps due to discovered UXO (Unexploded ordnance) or results of geomorphological surveys

Figure 102 - Example condition matrix for assessing saltmarsh condition following construction based on sediment and vegetation condition. A low-score indicates minimal vegetation/sediment damage which would be expected to recover quickly, while a high-score indicates severe damage which may take a prolonged period to recover.

Condition assessment of saltmarsh vegetation and surface sediment post-construction			**Sediment Surface Condition**				
			1	**2**	**3**	**4**	**5**
			Normal/ unaffected sediment condition.	Sediment surface broken, with bare mud. Compaction slight 0-2cm deep.	Minor sediment compaction (2-5 cm deep) but not holding permanent water at low tide. Displaced vegetation or soil very minor.	Moderate sediment compaction (5-10cm deep), localised pools of water remain at low tides but typically free draining. Evidence of displacement of vegetation or mud as sods.	Severe sediment compaction >10cm deep, permanent standing water *i.e.* not retreating at low tide. Large sods of soil overturned/ displaced.
Vegetation Condition	**1**	Normal / unaffected vegetation condition.	1	2	3	4	5
	2	Evidence of vehicle tracking with crushing/ snapping and dieback of sensitive species *i.e. Atriplex portulacoides*.	2	4	6	8	10
	3	Vegetation dieback, but root mat intact and signs of regrowth typical of vegetation zone.	3	6	9	12	15
	4	Complete loss of vegetation, although signs of regrowth atypical of zone ie pioneer marsh (*e.g. Salicornia*) growing in low-mid marsh.	4	8	12	16	20
	5	Complete loss of vegetation and no signs of regrowth.	5	10	15	20	25

Photo Plate 12 - Six example quadrats showing vegetation and sediment condition on saltmarsh after construction.

		
Photo 1 shows an unaffected quadrat with *Atriplex portulacoides* growing normally. There is no sediment disturbance. This quadrat would score a 1 on the condition-scale.	Photo 2 shows a quadrat where sensitive species *e.g. Atriplex portulacoides* has been lost. The *Puccinellia maritima* generally remains intact. The sediment surface has been broken and there is evidence of bare mud. This quadrat would score a 4 on the condition-scale.	Photo 3 shows a quadrat where the *Puccinellia maritima* has started to dieback, but the root-mat remains intact. Water drains from the surface at low-tide. The sediment has been compacted by *c.* 4cm compared to surrounding unaffected vegetation. This quadrat would score a 9 on the condition-scale.
		
Photo 4 shows a quadrat with patchy *Puccinellia maritima* (typical of the zone). Much of the vegetation and root-mat was lost following construction. There has been moderate sediment compaction (*c.* 8cm deep) but water drains away at low-tide. This quadrat would score a 12 on the condition-scale.	Photo 5 a heavily disturbed quadrat with *Salicornia* agg. (atypical of the zone). Sediment with moderate compaction, but free-draining (other than in local pools). This quadrat would score a 16 on the condition-scale.	Photo 6 shows a quadrat with severe sediment compaction and complete vegetation loss. There is permanent water retention even at low-tide. This quadrat would score a 25 on the condition-scale.

Sufficient time and resources should be allocated to monitoring. The National Academies of Sciences (2017) notes that "*the cost of conducting a monitoring program can be substantial".* It goes on to say that one common issue of monitoring is selecting too many attributes that project budgets cannot sustain. Therefore, it is critical to monitor only what is necessary to answer the most critical management questions and knowledge uncertainties. An assessment of restoration projects conducted through the early 1990s showed that monitoring cost averaged 13% of the total project cost, but ranged from 3% to 67% Shreffler (1995 cited in National Academies of

Sciences (2017)). Fancy (2000 cited in Holl and Cairns (2002)) notes that 25-30% of a monitoring budget should be allocated to data management and reporting.

6.6.2 Proposed Methods

The methods set out in Appendix 6 Table 48 pull together the information provided earlier in the chapter. The survey period is divided into the baseline, pre-construction and post-construction surveys. Whilst each project needs to be considered on an individual site basis the following approach set outs broad methods that could be tailored to each site. An indicative survey schedule over a 15-year monitoring period is also provided Figure 103.

Figure 103 - Indicative survey schedule.

Task	Year(s)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Baseline survey						■	■	■	■				
Planning submission		■	■	■	■	■	■	■	■	■	■	■	■
Pre-construction UAV survey	Year -1						■	■					
Pre-construction survey	Year -1								■				
Construction (avoiding nesting bird season)	Year -1									■	■	■	■
Post-construction monthly checks	Year 0	■	■	■	■	■	■	■	■	■	■	■	■
Post-construction UAV survey	Years 0, 5, 10, 15						■	■					
Post-construction survey	Years 0-5, 7, 10, 13, 15								■				

Conclusions & Future Research

Chapter 7 Conclusions & Future Research

7.1 Introduction

In concluding this thesis, *Chapter 7* returns to the initial five research themes identified in *Section 1.7*. It aims to address the main questions posed, regarding the success of vegetation recovery in saltmarsh and sand dunes when affected by pipeline or cable construction. What has become evident through my study, is that while the original focus was on post-construction restoration, the results provide useful information on vegetation change, time frames for recovery and successional outcomes following disturbance (whether that disturbance was natural, part of habitat management or as a result of construction). Finally, the chapter also identifies potential areas of future research.

7.2 Theme 1 – Attributes of Vegetation Recovery

Theme 1 centred on defining attributes which best reflected vegetation recovery (in terms of vegetation structure and function) for both saltmarsh and sand dune habitats. Many studies have considered the concepts behind vegetation recovery, *i.e.* the direction of succession, factors influencing vegetation establishment and time frames for recovery as part of restoration projects, following disturbance or habitat creation (Bakker et al., 2002, Boorman, 2003, Brooks et al., 2015, Crooks et al., 2002, French, 2006, Garbutt and Wolters, 2008, Mossman et al., 2012b, Van Loon-Steensma et al., 2015). However, there are few examples directly applicable to pipeline or cable installation (Ritchie, 1980, Ritchie and Gimingham, 1989).

From my study, it is evident that there is not a simple answer when deciding which attributes determine recovery. My research has shown that the most appropriate attributes vary by habitat type, vegetation zone, vegetation community and site location. Therefore, site specific attributes will always need to be developed with consideration to site restoration objectives.

The following statements however, may provide further guidance.

- The cover of typical species associated with the zone (such as outlined in the Common Standards Monitoring (JNCC, 2004b, 2004a) or constant species defining vegetation communities (set out in Rodwell (2000)) were more likely to show significant results between the On and Off sample areas and over time. However, it is advisable that these species should not be the sole focus when considering appropriate attributes. As restricting sampling to just a few species may reduce the statistic power of analysis and reduce the chance of showing where vegetation change has occurred (O'Reilly, 2015);

- Cover of bare ground was a key attribute when considering significant differences between the On and Off sample areas (*e.g.* low-mid marsh, pioneer marsh, fixed dunes and dune slacks); and between the Short-term and Unaffected areas (*e.g.* mid-upper marsh, pioneer marsh, fixed dunes and dunes slacks);
- Cover of early successional species were typically higher On the pipeline. For example, in saltmarsh, *Puccinellia maritima* and *Salicornia* spp. were significantly higher (both species are capable of growing in locations with reduced redox potentials). In the sand dunes species such as *Festuca arenaria*, *Anthyllis vulneraria* and *Diplotaxis tenuifolia* all showed significant increases to the creation of bare ground along the pipeline;
- Vegetation zones subject to natural disturbance *i.e.* the embryo/ mobile dunes and driftline showed fewer significant differences between the On and Off sample areas or over time, reflecting their ability to recover quickly; and
- The use of species biodiversity measures[102] provided little additional information in answering the bigger recovery picture in all vegetation zones, with the exception of the pioneer marsh.

7.3 Theme 2 – Time Frames for Recovery

One of the key considerations of the severity of an impact is the likely time frame required for full recovery. Typically, Environmental Statements (ES) are often very vague about likely recovery time frames. Key to determining significant effects is having sufficient scientific evidence upon which to base the evaluation. The best examples were able to draw on the experiences of previous, nearby, similar projects.

For example, the Project Breagh ES (RWE Group, 2010) referred to the success of the sand dune recovery shown on the adjacent AMCO CATS pipeline. The ES noted that in the intervening 18 years, the vegetation in the working width (including dune slacks) was barely distinguishable from comparable vegetation outside the work area (supported by quadrat data). One observation made by the author, was that in the fixed dunes, which had been planted with *Ammophila arenaria*, the vegetation was typically denser than in the Unaffected areas. For the Project Breagh pipeline, this observation, led to the decision to plant the *Ammophila arenaria* at a lower density. The ES concluded that reinstatement of the SSSI to a favourable condition was an achievable objective.

Similarly, the North Morecambe pipeline was able to refer to the recovery of saltmarsh vegetation on the South Morecambe pipeline. George et al. (1992) noted that photographic evidence given by Rae (1983) showed noticeable recolonisation of *Spartina anglica* (low/ pioneer marsh) within

[102]Simpsons Diversity Index, Shannon Diversity Index, Shannon Evenness Index, Margalef Diversity Index, and Berger-Parker Dominance Index

2-years after the pipeline was laid. They also noted (from their own observations) that 10-years after reinstatement the working width was indistinguishable from the surrounding marsh.

However, the use of previous projects to inform impact assessments should be taken with caution. As each site will respond differently depending on the construction methods, construction period, the underlying sediments, hydrology, vegetation communities and species *etc*. Recovery time frames often reflect the severity of the impact, and how well the habitat was protected during construction. They can be significantly reduced by following best-practice working methods and undertaking suitable restoration.

For future impact assessments, these should follow the CIEEM (2016a) guidelines, whereby the potential residual impacts (including recovery times) should be clearly set out. This will enable the determining authority to make a judgement "*as to whether or not a project is authorised, and, if given, whether the effect is important enough to warrant conditions, restrictions or further requirements such as monitoring*".

Based on my research, tentative recovery times in saltmarsh (*Section 3.9*) and sand dunes (*Section 4.8*) are set out below and summarised in Table 44-45. These time frames are indicative, as the recovery times for each site and construction project will vary depending on the vegetation zones and community types present (and their extent) the dominance of key species, construction methods, severity of impact and restoration techniques used.

7.3.1 Saltmarsh

Saltmarsh:

- Driftline – where impacts are less severe recovery maybe within the Short-term (within 10 years), although where the vegetation is completely lost, and the topography is altered the re-establishment of *Elytrigia atherica* may take 20-25 years (Medium-term).
- Mid-upper marsh -is dependent on the dominant vegetation type. Where it is perhaps less species-rich then recovery may occur within the Medium-term (20-25 years), with an intermediate vegetation type *i.e.* SM13a developing in the Short-term (*c.* 10 years). But species-rich examples with slower growing perennial species *i.e.* SM13b-d, SM16, SM18 may take longer *i.e.* Medium-Long-term (25-35 years) or as with S21 it may not re-establish naturally without assistance. The recovery time may be reduced if turve translocations are successfully undertaken as at South Morecambe.
- Low-mid marsh – vegetation dominated by *Puccinellia maritima i.e.* SM13a is likely to recover in the Short- to Medium-term (10-20 years), while areas dominated by *Atriplex portulacoides* which is not tolerant of trampling and is slower growing, is likely to take longer *i.e.* the Long-term (25-40 years).

- Pioneer marsh – the variability of the pioneer zone in terms of cover of the key species *Salicornia* agg. and *Spartina anglica* mean that even small quantities of these species are indicative of the zone. Both SM6 and SM8 are likely to be recognisable as pioneer marsh within the Short-term *i.e.* approximately 10 years. However, SM9 and SM11 which develop as the marsh matures is expected to take longer *i.e.* Medium-Long-term (25-40 years). Secondary pioneer marsh (with scattered *Salicornia* agg.) that develops after construction in compacted and low-lying areas (developing in any of the vegetation zones) should establishes itself within the Short-term (5-10 years).

Table 44 – Summary of the potential recovery times of the main vegetation communities in each of the saltmarsh vegetation zones.

Vegetation zone	NVC community	Key species	Recovery times
Driftline	SM24 *Elymus pycnanthus* salt-marsh community	*Elytrigia atherica* dominated sward	Short-term *i.e.* after minor damage (c. 10 years)
Driftline	SM24 *Elymus pycnanthus* salt-marsh community	*Elytrigia atherica* dominated sward	Medium-term (20-25 years) for establishment of typical community assemblage after more severe damage
Mid-upper marsh	SM13a *Puccinellia maritima* salt-marsh community, sub-community with *Puccinellia maritima* dominant (species-poor examples)	*Puccinellia maritima* dominated sward	Short-term (c. 10 years) not a mid-upper marsh community, but a likely intermediate vegetation type
	SM13 *Puccinellia maritima* salt-marsh community – sub-communities 13b-d	*Puccinellia maritima* with characteristic species *i.e. Armeria maritima*, *Glaux maritima*, *Limonium vulgare*, *Plantago maritima*	Long-term (>35 years) for establishment of typical community assemblage
	SM16 *Festuca rubra* salt-marsh community	*Festuca rubra, Juncus gerardii*	Medium to Long-term (20-30 years)
	SM18 *Juncus maritimus* salt-marsh community	*Juncus maritimus*	Medium to Long-term (20-30 years)
	S21 *Scirpus maritimus* swamp	*Bolboschoenus maritimus*	May not re-establish naturally without assistance
Low-mid marsh	SM13a *Puccinellia maritima* salt-marsh community, sub-community with *Puccinellia maritima* dominant	*Puccinellia maritima* dominated sward	Short to Medium-term (10-20 years)
	SM10 Transitional low-marsh vegetation with *Puccinellia maritima*, annual *Salicornia* species and *Suaeda maritima*	*Puccinellia maritima*, *Salicornia* agg., *Suaeda maritima*	Potentially within the Short-term (c. 10 years)

Vegetation zone	NVC community	Key species	Recovery times
	SM14 *Halimione portulacoides* salt-marsh community	*Atriplex portulacoides*	Long-term (25-40) years
Pioneer marsh	SM6 *Spartina anglica* salt-marsh community	*Spartina anglica*	Short-term (c. 10 years)
	SM8 Annual *Salicornia* salt-marsh community	*Salicornia* agg.	Short-term (c. 10 years)
	SM9 *Suaeda maritima* salt-marsh community	*Suaeda maritima*	Long-term (c. 40 years)
	SM11 *Aster tripolium* var. *discoideus* salt-marsh community /SM12 Rayed *Aster tripolium* on salt-marshes	*Aster tripolium*	Long-term (c. 50 years)
Secondary pioneer marsh	SM8	Scattered *Salicornia* agg.	Short-term (5-10 years)

7.3.2 Sand Dunes

Sand dunes:

- Embryo/ mobile dunes – the lack of data in the embryo/ mobile dunes make predicting recovery times more difficult. However, considering the study sites vegetation referable to the key NVC types *i.e.* SD4, SD5, and SD6 were present within the Short- to Medium-term (*i.e.* 10-25 years). Species-poor examples of the communities may establish in the Short-term (5-10 years).
- Fixed dunes – in the fixed dunes the main vegetation SD7 showed recovery of its key species *i.e. Ammophila arenaria* and *Festuca arenaria/ Festuca rubra* within the Short-term (5-10 years), although this was after planting of *Ammophila arenaria*. A natural vegetation structure was achieved within the Short -Medium-term (*i.e.* 10-25 years). Where planting is not undertaken the establishment of *Ammophila arenaria* is likely to take longer. Without subsequent management succession may result in the development of scrub or SD9.
- Dune grassland – key graminoid species from species-poor examples of SD9 *i.e. Arrhenatherum elatius*, *Dactylis glomerata* and *Holcus lanatus* were recorded in the sward within the Short-term (5-10 years) after construction; but full recovery in terms of the sward developing a closed, tussocky structure is likely to take longer *i.e.* Medium-term (10-20 years). Species-rich examples of SD8 also developed after construction, where appropriate management *i.e.* grazing occurred; with recovery of this community type expected in the Medium to Long-term *i.e.* 15-35 years. In the Long-term, where there is a lack of management (*i.e.* grazing or cutting) SD9 is likely to develop to a dune form of MG1 where *Arrhenatherum elatius* is dominant or to one of the scrub communities *i.e.* W24

Rubus fruticosus-Holcus lanatus underscrub, W21 *Crataegus monogyna-Hedera helix* scrub or SD18 *Hippophae rhamnoides* dune scrub.

- Dune slacks – in the dune slacks the recovery time frames is dependent on the successional stage required. For example, early successional dune slacks *e.g.* SD13 may establish within the Medium-term (15-25 years), but other more mature communities *i.e.* SD14-SD16 is likely to take longer *i.e.* 25 to 50 years.

Table 45 - Summary of the potential recovery times of the main vegetation communities in each of the sand dune vegetation zones.

Vegetation zone	NVC community	Key species	Recovery times
Embryo/ mobile dunes	SD4 *Elymus farctus* ssp. *boreali-atlanticus* foredune community	*Elytrigia juncea, Honckenya peploides Cakile maritima, Atriplex prostrata*	Probably Medium-term (10-25 years)[103]. Species-poor examples may establish in the Short-term (5-10 years).
	SD5 *Leymus arenarius* mobile dune community	*Leymus arenarius* dominant with *Elytrigia juncea*, *Festuca rubra* depending on sub-community	
	SD6 *Ammophila arenaria* mobile dune community	*Ammophila arenaria* dominant with *Carex arenaria, Elytrigia juncea, Festuca arenaria*, *Poa humilis*	
Fixed dunes	SD7 *Ammophila arenaria* - *Festuca rubra* semi-fixed dune community	*Ammophila arenaria*, *Carex arenaria, Festuca arenaria/ Festuca rubra, Poa humilis*	Short -term (5-10 years) after planting of *Ammophila arenaria.* Natural vegetation structure should be achieved within Short - Medium-term (*i.e.* 10-25 years)
	SD7c *Ammophila arenaria-Festuca rubra* semi-fixed dune community, *Ononis repens* sub-community	*Ammophila arenaria*, *Carex arenaria*, *Festuca arenaria/ Festuca rubra, Poa humilis,* with *Ononis repens*	
Dune grassland	SD9 *Ammophila arenaria-Arrhenatherum elatius* dune grassland	*Ammophila arenaria*, *Arrhenatherum elatius, Dactylis glomerata*, *Festuca rubra*, *Holcus lanatus*	Recognisable community developing in Short-term (5-10 years); but typical vegetation structure taking longer to develop *i.e.* Medium-term (10-20 years)
	MG1 *Arrhenatherum elatius* grassland (dune-form)	*Arrhenatherum elatius, Dactylis glomerata*, *Holcus lanatus* with *Heracleum sphondylium* and other ruderal species	Medium-Long-term (20-30 years).
	SD8 *Festuca rubra-Galium verum* fixed dune grassland	*Festuca arenaria/ Festuca rubra Galium verum*, *Lotus corniculatus*, with rarities such as *Astragalus danicus* [104]. *Agrostis stolonifera* is more frequent in transitions to dune slacks	Developing where grazed[105]. SD8 swards develop in the Medium to Long-term (15-35 years)

[103] Although difficult to predict with my small dataset
[104] As recorded at Coatham Common
[105] *I.e.* by rabbits maintain a short, closed sward

Vegetation zone	NVC community	Key species	Recovery times
Dune slacks - various communities recorded depending on successional stage of development	SD13b *Sagina nodosa-Bryum pseudotriquetrum* dune-slack community, *Holcus lanatus-Festuca rubra* sub-community –	*Agrostis stolonifera*, *Carex flacca, Holcus lanatus, Festuca rubra Leontodon hispidus, Salix repens, Bryum pseudotriquetrum*	Early successional dune slack vegetation potentially establishing in the Medium-term (15-25 years)
	SD14 *Salix repens-Campylium stellatum* dune-slack community	*Agrostis stolonifera, Mentha aquatica, Salix repens, Calliergon cuspidatum*	Long-term (25-50 years)
	SD15 *Salix repens-Calliergon cuspidatum* dune-slack community, (SD15c recorded at Redcar)	*Agrostis stolonifera, Carex flacca, Eupatorium cannabinum, Mentha aquatica, Pulicaria dysenterica, Salix repens*, *Calliergon cuspidatum*	Long-term (25-50 years)
	SD16 *Salix repens-Holcus lanatus* dune-slack community (both SD16b&d recorded at Redcar & Talacre Warren)	*Agrostis stolonifera*, *Festuca rubra*, *Festuca rubra*, *Rubus caesius, Salix repens*,	Long-term (25-50 years) – developing in drier, mature dune slacks
	Dune grassland communities *i.e.* SD7, SD8, SD9, MG1	As described above	No true recovery *i.e.* where there is a shift in the community from dune slacks to dune grasslands due to hydrological change.

These recovery timeframes can form the basis for developing a monitoring strategy. However, as noted in *Section 6.3.2*, there is a difference between monitoring to determine full recovery and showing that the vegetation is recovering. Therefore, the requirement for monitoring should aim to show that vegetation recovery is proceeding along the required trajectory.

An element of caution is required when predicting recovery time frames, as recently highlighted in a paper by Rydgren et al. (2018) which found that linear models (such as I used with the species response curves) were too optimistic in predicting the time to recovery. One of the main issues in using linear models is the implication that succession is also linear and the rate of plant compositional change with time is constant. Whereas, typically the rate of succession decreases with time. The paper suggests using asymptotic model which can provide more precise predictions.

7.4 Theme 3 – Outcomes of Recovery

The post-construction recovery outcomes of the saltmarsh and sand dune vegetation zones was considered in relation to the direction and rate of succession, and the construction and reinstatement methods.

As expected, a simple unidirectional outcome was not found for either the saltmarsh or sand dunes vegetation types following construction. In most cases, the rate and direction of succession led to multiple outcomes which depended on the severity of the construction impact and the types of reinstatement methods used.

Saltmarsh

In the driftline, the post-construction outcome in the Short-term, where impacts were minor, was the re-establishment of driftline vegetation. But, where impacts were more severe, pioneer marsh developed. By the Long-term, these areas of pioneer marsh had typically succeeded to driftline. Showing that full recovery was possible.

For mid-upper marsh, there was a clear correlation between the construction/ reinstatement method and the direction and speed of recovery. Most of the mid-upper marsh quadrats where the vegetation type was retained, came from sites where the saltmarsh turves were lifted and re-laid after construction. In contrast, where the mid-upper marsh was not restored using turves, there was a loss of this vegetation type with the establishment of pioneer marsh. This shows that consideration of suitable mitigation measures can have a long-lasting and significant effect on vegetation recovery.

In the low-mid marsh, in the Short- to Medium-term, there was a general regression of the quadrats to pioneer marsh after construction. However, by the Long-term most of these quadrats were classified as low-marsh. Interestingly, data from the Adjacent sample area also showed a regression of half of the quadrats to pioneer marsh. This may indicate that works were not always restricted to the working width resulting in direct impacts.

In the Short-term, pioneer marsh was recorded in all the quadrats (although typically vegetation cover was lower). By the Long-term, half of the quadrats were classified as low-mid marsh (which was at a slightly higher rate than in the Unaffected areas). Whether this increased rate of succession was due to construction, is difficult to determine, but as conjecture, it may be due to increased compaction caused by vehicles, resulting in firmer sediments allowing quicker vegetation establishment, and succession to low-mid marsh.

In a recent paper considering niche models of 10 saltmarsh species from managed realignment (compared to natural marshes) sites it was noted that many high marsh species occurred lower in the tidal frame, and low-marsh species occurred higher in the tidal frame. The study concluded that this effect was due to a lack of initial competition (because of the availability of bare sediment across the whole tidal frame).

Sand Dunes

In the embryo/ mobile dunes, nearly all the quadrats, in the Short-term, were classified as supporting fixed dune vegetation following construction. It is likely that this is an effect of the small sample size, and the fact that typically direct impacts on this vegetation zone are avoided. Therefore, it is likely that the change from embryo/ mobile dunes to fixed dunes is due to natural succession.

In the fixed dunes, the majority of the quadrats following construction (from the Short-term through to Long-term) retained fixed dune vegetation types.

In the dune grassland, the majority (80%) of quadrats following construction, re-established themselves with dune grassland vegetation types. However, where more open conditions were generated, fixed dune vegetation was noted in *c.* 10% of the quadrats, and these typically supported notable species such *Astragalus danicus*. A further 10% of quadrats subsequently supported dune scrapes/ dune slack vegetation, which was created as part of the post-construction restoration.

Predicting vegetation outcomes in the dune slacks is dependent on whether the original hydrology was maintained during construction. In the Short-term nearly two-thirds of the dune slack quadrats were classified as dune grassland, indicating that the water-table had been negatively affected by construction, while dune slack vegetation was retained in *c.* 20% of the quadrats. By the Long-term, dune slack vegetation and dune grassland was equally likely. In addition, dune slack vegetation was retained in the Adjacent and Unaffected sample areas, indicating that construction impacts beyond the working width were minimal. One disappointing finding was that five quadrats in this vegetation zone were completely lost, due to inappropriate positioning of a construction compound that resulted in the dune slack being infilled with hard-core.

Biodiversity Net Gain

The outcomes were also considered against delivering biodiversity gain (CIEEM, 2016b). Four scenarios were considered No Net Loss, Acceptable Net Loss, Net Positive Impact and Unacceptable Net Loss.

For saltmarsh vegetation zones, in most instances the best achievable result was No Net Loss, with several outcomes resulting in an Unacceptable Net Loss. A Net Positive Impact was only recorded in a few quadrats *e.g.* where driftline or low-mid marsh succeeded to mid-upper marsh in the Long-term. This outcome was probably not due to restoration activities, but due to natural succession.

For sand dunes vegetation zones, there was a greater opportunity of achieving a Net Positive Impact. For example, where construction disturbance of dune grassland resulted in areas of bare sand (supporting early successional dune species), or where the water-table was raised (or topography lowered) allowing the creation of dune slacks, or temporary dune scrapes. However, as described the loss of dune slacks to dune grassland (or complete vegetation loss) is considered an Unacceptable Net Loss. Similarly, the increase in mesotrophic grassland would be considered an Unacceptable Net Loss.

7.5 Theme 4 – Construction and Restoration

Theme 4 focused on methods used to avoid, minimise and compensate for construction on saltmarsh and sand dune sites. The theme considered how implementing the mitigation hierarchy successfully should result in achieving projects with a No Net Loss, and provide opportunities for Biodiversity Net Gain (CIEEM, 2016a, 2016b).

As outlined in Themes 2 and 3, construction and reinstatement methods can strongly influence the overall speed and direction of vegetation recovery. While, avoiding areas of saltmarsh and sand dunes would be the best option from a nature conservation perspective, in reality, locating sites in less sensitive areas, is not always an option. Therefore, it is important that standard guidance is followed, for example with the environment impact assessment process, so that all the options are considered.

Chapter 5 considered the main construction methods used, when installing pipelines/ cables (including HDD, open-cut trenching, and alternative techniques). HDD methods have the potential to avoid much of the on-the ground impacts, and as such should be the first construction option. However, frequently HDD is not suitable, therefore, alternative construction methods need to be identified and assessed with reference to nearby projects where they have been undertaken, with similar physical and biological characters. Alternative techniques to open-cut trenching, have the potential to minimise impacts, but often their innovative design means that there is little information to support the impact assessment. Therefore, in such situations, if a project is given the go-ahead, it is critical that the baseline assessment and post-construction monitoring (Theme 5) are completed with vigour; and that all stages of the construction process are documented, so that future projects can learn from the project outcomes.

During construction, many impacts can be avoided or minimised, by employing an ECoW. The ECoW needs to have a thorough knowledge of the environment that they are overseeing in terms of its ecology, but also on the construction methods being used. Their role is vital in making on the spot decisions as to the likely impacts of individual construction actions, *e.g.* halting work on site during wet weather, after high tides or restricting vehicle movements. When correctly implemented these individual decisions can significantly minimise impacts.

For both saltmarsh and sand dunes, restoration options following construction, need to be flexible in their design, as often there will be impacts that were either underestimated or not predicted. Many of the restoration techniques set out in *Chapter 5* have been developed based on published outcomes from conservation management (*e.g.* recent work on dynamic dunes and managed realignment).

7.6 Theme 5 - Monitoring

Theme 5 (*Chapter 6*) considered suitable approaches for recording the baseline condition, as well as techniques for pre- and post-construction monitoring.

One of the key messages is that botanical surveys taken during the assessment process, need to be fit-for-purpose. The baseline survey is required as part of planning to inform the decision-making process (*i.e.* route options) and to identify ecological features that may be affected by construction. This survey should be of a sufficient extent, accuracy and detail, so that changes to the construction design, which will inevitably occur as a project evolves, can be thoroughly assessed.

Due to the likely time frames between the baseline surveys being completed, and the subsequent project start, it is likely and appropriate that a separate and tailored pre-construction survey is undertaken (based on the results of the baseline survey). The pre- and post-construction surveys should be designed to document vegetation change. Therefore, they should follow scientifically valid sampling techniques and consider data analysis prior to field work. Success criteria should be clearly set out using measurable attributes against which the effects of post-construction recovery can be monitored. Without using such criteria, it is impossible to generate early warnings and intervene when recovery is not heading in the required direction.

The length of time required for monitoring needs to be sufficient to show that vegetation change is progressing towards the unaffected vegetation condition. For both habitats, historically monitoring has not continued for long enough to determine these changes. It is recommended that a minimum monitoring period of 10-15 years is used, although in the mid-upper marsh and the dune slacks if impacts are severe then monitoring may need to extend beyond this.

Much data is generated as part of the EIA process, but the outcomes and conclusions of each project are rarely published and therefore lessons learned are not widely circulated. A central (freely-accessible) depository of Environmental Statements and their associated supporting information, including the baseline survey, the 'as-built' construction methods and the pre- and post-construction survey reports needs to be developed. In addition, it would be valuable, if, for each construction project, summary information, setting out the key findings of the scheme and lessons to be learned (in terms of construction methods and monitoring results) are published.

7.7 Saltmarshes or Sand Dunes

One question I have been asked frequently during my study is "*which habitat responds more favourably to restoration following pipeline or cable installation?*". Or asking it another way "*if there was a choice of between crossing an area of saltmarsh or sand dunes, which would be preferable*?". I shall attempt to answer this below.

If there is any alternative to crossing an area of saltmarsh or sand dunes this should always be taken as the first priority. This follows the mitigation hierarchy approach of avoidance and would be far more cost-effective both in time[106] and financial resources than attempting to cross the habitats and then trying to restore them.

In many cases, sand dune ecosystems appear to be more resilient to pipeline and cable installation than saltmarsh ecosystems. This is mainly due to the difference in sediment *i.e.* sand being more freely drained, and less susceptible to compaction by installation vehicles. But also, in part due to the dynamic nature of sand dunes, with species that have evolved to respond to disturbance episodes. This is supported in my study by the diversity of specialist species that established following construction (including several rarities), the recovery times for both individual species and desirable vegetation types, and the potential to interrupt/ halt succession (especially from mesotrophic grasslands to more open or wet conditions). There also appears to be a higher likelihood that recovery outcomes will either result in a No Net Loss or a Positive Net Gain scenario.

However, where there is dune slack vegetation, there is a greater chance that installation will result in the loss of wet-tolerant herbs caused by a change in the dune hydrology (which is considered an Unacceptable Net Loss). As dune slacks are often the most diverse areas of a dune system this can have serious implications on the integrity of the site. Therefore, in making pipeline and cable routing decisions, the extent of dune slack vegetation and its diversity, is a key consideration. Mitigation in these areas needs a more considered approach *e.g.* restricting the working width, lifting turves and restoring them to their original height and location after construction) and ensuring the dune slacks are not dewatered by the construction process. The requirement for monitoring should continue for many years to ensure there are no long-lasting effects.

In saltmarsh, impacts associated with construction tend to be more severe, resulting in long-lasting effects caused by compaction, changes in topography and an alteration of creeks. The resulting changes in tidal inundation result in the atypical development of early successional

[106] An expected time frame for the planning stage, construction, restoration and monitoring could easily amount to 20-years.

marsh (through the reverse of succession) and the creation of bare areas which may have a prolonged presence in the landscape (considered an Unacceptable Net Loss). These physical changes are harder to restore without causing further damage, than in sand dunes. Therefore, restoration (especially in the outer reaches of the marsh *i.e.* pioneer, and low-mid marsh) often focuses on natural regeneration, although this increases the recovery time. However, in the mid-upper marsh, as shown at South Morecambe (and at Corrib Pipeline (Neff, 2014)), impacts to this vegetation zone can be successfully minimised by lifting and reinstating turves (especially in areas dominated by *Festuca rubra*, *Juncus gerardii* or *Puccinellia maritima*). In the other vegetation zones, impacts can be reduced (but not eliminated) by employing appropriate mitigation techniques *e.g.* by following best-practice in terms of vegetation/ sediment protection measures, with works overseen by an ECoW. In this respect, I conclude that saltmarshes are less resilient to pipeline and cable installation than sand dunes.

7.8 Future Research

7.8.1 Physical Processes

My research focused on the potential impacts on saltmarsh and sand dunes habitat from a botanical perspective, whether considering the effects of construction on an individual species, a community or the habitat in general. However, both saltmarshes and sand dune ecosystems are complex; and their recovery following construction depends on the restoration of a number of factors including coastal processes, sediments, topography and hydrology.

Additional research that considers some of these factors in more detail would be particularly valuable. For example, many of the long-terms impacts noted at the study sites, centre around the damage caused to sediments through compaction, waterlogging or dewatering, changes in soil redox potentials, changes in topography and altered drainage patterns. There has been much published literature on these factors especially with regard to saltmarsh (Adnitt et al., 2007, Beeftink, 1977, Brooks et al., 2015, Davy et al., 2011, Mossman et al., 2012a, Reading et al., 2008); but also particularly relating to dune slacks (Grootjans et al., 2002, Jones et al., 2006, Soulsby et al., 1997), but little on the impacts directly associated with construction.

7.8.2 Additional Sites

One of the main restrictions with this project, was the limited availability of published Environmental Statements produced as part of the EIA process. At present, in the UK there is not a single depository of submitted Environmental Statements (and their supporting data *e.g.* the pre-construction botanical reports). The Marine Data Exchange [107] has started to collate survey

[107] Hosted by The Crown Estate - http://www.marinedataexchange.co.uk/

data and reports to promote further research and innovation in the marine environment. However, this depository is not comprehensive in its coverage and does not include historical projects. Typically, the Environmental Statement is submitted as part of the planning process to the local planning authority and stakeholders. At that time, it is made available for public review (either online or held at local libraries *etc.* but following award of planning it is typically removed from public access). Post-construction monitoring data is also not widely circulated beyond the required stakeholders. Therefore, it is difficult for any lessons-learned to be used for future schemes.

In an ideal situation (where the information was available), the study would have included additional sites/ locations which were either constructed using different installation methods, were of differing ages (*i.e.* completed in the Short, Medium and Long-term) or included a greater variety of vegetation types. With the increased reliance on renewable energies derived from our coast, and the increase in the number of offshore schemes being released for future development there is potential for these schemes to be included in any future research. Even over the course of my PhD research, several additional projects have been started, and have been completed, which could have increased the dataset used for determining future impacts.

7.8.3 Best-practice Handbook

Since the commencement of my PhD one of the key outputs I wished to produce, was a best-practice handbook, to advise on future developments focusing specifically on cable and pipeline installations. The handbook would be designed for use by developers, environmental consultants and statutory bodies, drawing upon the research outlined in this study. I envisage the handbook to consider the key stages of a project's life cycle, from its conception to the end of the post-construction monitoring. The aim would be to provide practical suggestions on the assessment process, construction and restoration phases, as well as monitoring. The document would focus on the principles of the mitigation hierarchy so as to achieve No Net Loss and Biodiversity Net Gain.

REFERENCES


Ecological Processes in Coastal Environments
edited by R.L. Jefferies A.J. Davy
Blackwell
Perrow and Davy
Handbook of Ecological Restoration
Volume 1 Principles of Restoration
CAMBRIDGE
Perrow and Davy
Handbook of Ecological Restoration
Volume 2 Restoration in Practice
CAMBRIDGE
Handbook of Biodiversity Methods
CAMBRIDGE
HOUSTON, EDMONDSON and ROONEY
Coastal Dune Management
Liverpool University Press
ADAM
SALTMARSH ECOLOGY
CAMBRIDGE
SECOND EDITION
Šmilauer Lepš
Multivariate Analysis of Ecological Data using Canoco 5
CAMBRIDGE
DOWNS AND DUNES
Their Plant Life and its Environment
SALISBURY
5
Saltmarsh
Clive Chatters
122
Vegetation of Britain and Ireland
MICHAEL PROCTOR
Collins
Rodwell
BRITISH PLANT COMMUNITIES
5
Maritime communities and vegetation of open habitats
CAMBRIDGE
13
Coastal Conservation and Management
J. Pat Doody
KAP
Restoration of Coastal Dunes
Mosses and Liverworts of Britain and Ireland
a field guide
GRASSES, SEDGES, RUSHES AND FERNS
VIKING
MARJORIE BLAMEY
CHRISTOPHER GREY-WILSON
CASSELL'S
WILD FLOWERS
CASSELL
STACE
NEW FLORA OF THE BRITISH ISLES
THIRD EDITION
CAMBRIDGE

Chapter 8 References

ABPMER 2015. The cost of undertaking managed realignment schemes in the UK (briefing note). ABP Marine Environmental Research Ltd.

ABPMER 2017. White Paper: Using dredge sediment for habitat creation and restoration: A cost benefit review, a summary of the techniques, costs and benefits associated with using fine dredge sediments to 'recharge' intertidal habitat. ABPmer Internal White Paper.

ADAM, P. 1978. Geographical variation in British salt-marsh vegetation. *Journal of Ecology,* 66**,** 339-366.

ADAM, P. 1981. Vegetation of British saltmarshes. *New Phytologist,* 88**,** 143-196.

ADAM, P. 1990. *Saltmarsh ecology,* Cambridge, Cambridge University Press.

ADNITT, C., BREW, D., COTTLE, R., HARDWICK, M., JOHN, S., LEGGETT, D. J., MCNULTY, S., MEAKINS, N. & STANILAND, R. 2007. Saltmarsh management manual. Bristol: Joint Defra / Environment Agency Flood and Coastal Erosion Risk Management R&D Programme.

AGATE, E. & BROOKS, A. 2005. *Sand dunes: a practical handbook,* Doncaster, British Trust for Conservation Volunteers.

ALLISON, S. K. 1995. Recovery from small-scale anthropogenic disturbances by Northern California salt marsh plant assemblages. *Ecological Applications,* 5**,** 693-702.

ÁLVAREZ-ROGEL, J., JIMÉNEZ-CÁRCELES, F. J., ROCA, M. J. & ORTIZ, R. 2007. Changes in soils and vegetation in a Mediterranean coastal salt marsh impacted by human activities. *Estuarine, Coastal and Shelf Science,* 73**,** 510-526.

ARENS, S. M. & GEELEN, L. H. W. T. 2006. Dune landscape rejuvenation by intended destabilisation in the Amsterdam water supply dunes. *Journal of Coastal Research,* 22**,** 1094-1107.

ASHALL, J., DUCKWORTH, J., HOLDER, C. & SMART, S. 1991. Gronant to Talacre, Delyn 1991. Site Report No 131. *Sand dune survey of Great Britain.* Peterborough: JNCC.

ATHERTON, D. M., BOSANQUET, S. D. S. & LLAWLEY, M. 2010. *Mosses and liverworts of Britain and Ireland: a field guide.*, British Ecological Society.

BAILY, B. & PEARSON, A. W. 2007. Change Detection Mapping and Analysis of Salt Marsh Areas of Central Southern England from Hurst Castle Spit to Pagham Harbour. *Journal of Coastal Research,* 23**,** 1549-1564.

BAINBRIDGE, I., BROWN, A., BURNETT, N., CORBETT, P., CORK, C., FERRIS, R., HOWE, M., MADDOCK, A., MOUNTFORD, E. & PRITCHARD, S. 2013a. Guidelines for selection of biological SSSIs. Part 1: Rationale, operational approach and criteria for site selection. Peterborough: JNCC.

BAINBRIDGE, I., BROWN, A., BURNETT, N., CORBETT, P., CORK, C., FERRIS, R., HOWE, M., MADDOCK, A., MOUNTFORD, E. & PRITCHARD, S. 2013b. Guidelines for selection of biological SSSIs. Part 2: Detailed guidelines for habitats and species. Peterborough: JNCC.

BAKKER, C., HEIKO, F. D. G., WILFRIED, H. O. E. & PETER, M. V. B. 2005. Does the seed bank contribute to the restoration of species-rich vegetation in wet dune slacks? *Applied Vegetation Science,* 8**,** 39-48.

BAKKER, J., ESSELINK, P., DIJKEMA, K., VAN DUIN, W. & DE JONG, D. 2002. Restoration of salt marshes in the Netherlands. . *Hydrobiologia,* 478**,** 29-51.

BAKKER, J. P., GROOTJANS, A. P., HERMY, M. & POSCHLOD, P. 2000. How to define targets for ecological restoration? *Applied Vegetation Science,* 3**,** 3-6.

BALESTRI, E., VALLERINI, F., CASTELLI, A. & LARDICCI, C. 2012. Application of plant growth regulators, a simple technique for improving the establishment success of plant cuttings in coastal dune restoration. *Estuarine, Coastal and Shelf Science,* 99**,** 74-84.

BARKMAN, J. J., MORAVEC, J. & RAUSCHERT, S. 1986. Code of phytosociological nomenclature. 2nd edition. *Vegetatio,* 67**,** 145-58.

BEEFTINK, W. G. The structure of salt marsh communities in relation to environmental disturbances. *In:* JEFFERIES, R. L. & DAVY, A. J., eds. 1st European Ecological Symposium and 19th Symposium of The British Ecological Society, 1977 Norwich. Blackwell Scientific Publications, 77-93.

BEKKER, R. M., LAMMERTS, E. J., SCHUTTER, A. & GROOTJANS, A. P. 1999. Vegetation development in dune slacks: The role of persistent seed banks. *Journal of Vegetation Science,* 10**,** 745-754.

BELLMER, R. J. Restoration success criteria. MTS/IEEE Oceans 2001. An Ocean Odyssey. Conference Proceedings (IEEE Cat. No.01CH37295), 2001 2001. 327-330 vol.1.

BERR 2008. Review of cabling techniques and environmental effects applicable to the offshore wind farm industry. Department for Business, Enterprise and Regulatory Reform (BERR) in association with the Department for Environment, Food and Rural Affairs (DEFRA).

BERTNESS, M. D. 1991. Interspecific interactions among high marsh perennials in a New England salt marsh. *Ecology,* 72**,** 125-137.

BIODIVERSITY REPORTING AND INFORMATION GROUP 2007. Report on the species and habitats review. Report by the Biodiversity Reporting and Information Group to the UK Biodiversity Standing Committee. Peterborough: JNCC.

BIRDLIFE INTERNATIONAL, UNEP-WCMC, RSPB, FFI & CAMBRIDGE, U. O. 2015. Strengthening implementation of the mitigation hierarchy: managing biodiversity risk for conservation gains. *A Cambridge Conservation Initiative – Collaborative Fund Project Report.*

BIRSE, E. L. 1980. Plant communities of Scotland: A preliminary phytocoenonia. Aberdeen: The Macaulay Institute for Soil Research.

BIRSE, E. L., LANDSBERG, S. Y. & GIMINGHAM, C. H. 1957. The effects of burial by sand on dune mosses. *Transactions of the British Bryological Society,* 3**,** 285-301.

BIRSE, E. L., ROBERTSON, J. S. & DURNO, S. E. 1976. Plant communities and soils of the lowland and southern upland regions of Scotland. Aberdeen: The Macaulay Institute for Soil Research.

BOARDMAN, C. & SMITH, P. H. 2016. Rates of spread of *Rosa rugosa* (Japanese Rose) determined by GIS on a coastal sand-dune system in Northwest England. *Journal of Coastal Conservation,* 20**,** 281-287.

BOND, T. E. T. 1952. *Elymus arenarius* (L.). *Journal of Ecology,* 40**,** 217-227.

BOORMAN, L. A. 1967. *Limonium Vulgare* Mill. and *L. Humile* Mill. *Journal of Ecology,* 55**,** 221-232.

BOORMAN, L. A. 2003. Saltmarsh review. An overview of coastal saltmarshes, their dynamics and sensitivity characteristics for conservation and management. *JNCC Report No. 334.* Peterborough: JNCC.

BOORMAN, L. A. 2011. The grazing of British sand dune vegetation. *Proceedings of the Royal Society of Edinburgh. Section B. Biological Sciences,* 96**,** 75-88.

BOSSUYT, B., STICHELMANS, E. & HOFFMANN, M. 2005. The importance of seed bank knowledge for the restoration of coastal plant communities – a case study of salt marshes and dune slacks at the Belgian coast. *In:* J.-L., H., MEES, J., SALMAN, A., SEYS, H., VAN NIEUWENHUYSE, H. & DOBBELAERE, I. (eds.) *Proceedings 'Dunes and Estuaries 2005' – International Conference on Nature Restoration Practices in European Coastal Habitats.* Koksijde, Belgium: VLIZ (Flanders Marine Institute) Special Publication.

BRADSHAW, A. D. 1983. The reconstruction of ecosystems. *Journal of Applied Ecology,* 20**,** 1-17.

BRADSHAW, A. D. & CHADWICK, M. J. 1980. *The restoration of land, studies in ecology,* Oxford, Blackwell Scientific

BRIDGE WATCH. 2010-2016. *Bridge Watch Sutton Bridge - Wind farms in the Greater Wash Area and the North Sea* [Online]. Available: http://www.bridgewatch.org.uk/offshore-wind-farm-news.html [Accessed 12/09/17].

BROOKE, J., LANDIN, M., MEAKINS, N. & ANITT, C. 1999. The restoration of vegetation on saltmarshes. *R&D Technical Report W208.* Swindon: Environment Agency.

BROOKS, K. L., MOSSMAN, H. L., CHITTY, J. L. & GRANT, A. 2015. Limited vegetation development on a created salt marsh associated with over-consolidated sediments and lack of topographic heterogeneity. *Estuaries and Coasts,* 38**,** 325-336.

BROWN, A. E., BUM, A. J., HOPKINS, J. J. & WAY, S. F. 1997. The Habitats Directive: selection of Special Areas of Conservation in the UK. *JNCC Report No. 270.* Peterborough: JNCC.

BU, C., ZHANG, K., ZHANG, C. & WU, S. 2015. Key factors influencing rapid development of potentially dune-stabilizing moss-dominated crusts. *PLoS ONE,* 10**,** e0134447.

BURD, F. 1989. Saltmarsh survey of Great Britain: an inventory of British saltmarshes. *Reasearch and Survey in Nature Conservation No. 17.* Peterborough: Nature Conservancy Council.

BURGESS, N. 1988. Tetney Marshes Reserve; vegetation survey, botanical site evaluation and management prescriptions. Sandy Lodge: RSPB.

BURNS, O. & JACKSON-MATTHEWS, S. 2016. Environmental Clerks of Works: Good practice guidance. Glasgow: The Association of Environmental & Ecological Clerks of Works.

CARTER ECOLOGICAL LIMITED 1999. Annual report 1998: monitoring of sand dune restorations at Talacre. Unpublished: Report to BHP Petroleum Ltd.

CARTER ECOLOGICAL LIMITED 2000. Annual report 1999: monitoring of sand dune restorations at Talacre. Unpublished: Report to BHP Petroleum Ltd.

CARTER ECOLOGICAL LIMITED 2001. Botanical monitoring of Talacre Dunes at Point of Ayr **-** annual report 2000. Unpublished: on behalf of BHP Billiton.

CENTRAL WATER PLANNING UNIT 1976. *The Wash Water Storage Scheme: report on the feasibility study,* London, HMSO.

CENTRICA ENERGY 2007. Lincs Offshore Wind Farm environmental statement: volume 1 offshore (Chapter 5). Unpublished: RPS Group PLC on behalf of Centrica Energy,.

CENTRICA ENERGY 2009. Race Bank Offshore Wind Farm environmental statement non-technical summary. Windsor.

CHANG, E. R., VEENEKLAAS, R. M., BAKKER, J. P., DANIELS, P. & ESSELINK, P. 2016. What factors determined restoration success of a salt marsh ten years after de-embankment? *Applied Vegetation Science,* 19**,** 66-77.

CHAPMAN, V. J. 1950. *Halimione portulacoides* (L.) Aell. *Journal of Ecology,* 38**,** 214-222.

CHAPMAN, V. J. 1960. *Salt marshes and salt deserts of the world,* London, Leonard Hill (Books).

CHARPENTIER, A., MESL, XE, ARD, F. & THOMPSON, J. D. 1998. The effects of rhizome severing on the clonal growth and clonal architecture of *Scirpus maritimus*. *Oikos,* 83**,** 107-116.

CIEEM 2016a. Guidelines for ecological impact assessment in the UK and Ireland, terrestrial, freshwater and coastal. 2nd ed. Windsor: Chartered Institute of Ecology and Environmental Management.

CIEEM, C., IEMA, 2016b. Biodiversity Net Gain: Good practice principles for development. Windsor: Chartered Institute of Ecology and Environmental Management.

CLEVERING, O. A. 1995. Germination and seedling emergence of *Scirpus lacustris* L. and *Scirpus maritimus* L. with special reference to the restoration of wetlands. *Aquatic Botany,* 50**,** 63-78.

COLES, S. M. 1979. Benthic microalgal populations on intertidal sediments and their role as precursors to salt marsh development. *In:* JEFFERIES, R. L. & DAVY, A. J. (eds.) *Ecological Processes in Coastal Environments.* Oxford: Blackwell Scientific Publications.

COMMITTEE ON CLIMATE CHANGE 2016. UK climate action following the Paris Agreement London: Committee on Climate Change,.

CONNOR, S. 2001. Ecologists find simple way of killing invasive coastal weed. *Independent*, 19/11/2001.

COOPER, A. 1982. The effects of salinity and waterlogging on the growth and cation uptake of saltmarsh plants. *New Phytologist,* 90**,** 263-275.

COOPER, N. J., COOPER, T. & BURD, F. 2001. 25 years of salt marsh erosion in Essex: Implications for coastal defence and nature conservation. *Journal of Coastal Conservation,* 7**,** 31-40.

CROFTS, A. & JEFFERSONS, R. G. 1999. *The lowland grassland management handbook*, English Nature and The Wildlife Trusts.

CROOKS, S., SCHUTTEN, J., SHEEN, G. D., PYE, K. & DAVY, A. J. 2002. Drainage and elevation as factors in the restoration of salt marsh in Britain. *Restoration Ecology,* 10**,** 591-602.

DARGIE, T. C. D. 1988. Morrich More SSSI Ross and Cromarty: vegetation survey 1988. Nature Conservancy Council.

DARGIE, T. C. D. 1993. *Sand dune vegetation survey of Great Britain: a national inventory part II: Scotland,* Peterborough, JNCC.

DARGIE, T. C. D. 1995. *Sand dune vegetation survey of Great Britain: a national inventory part III: Wales,* Peterborough, JNCC.

DARGIE, T. C. D. 2001a. Morrich More: SMIT land and marine review of annual monitoring: an evaluation of monitoring reports for a flowbundle pipeline facility Morrich More SSSI/cSAC/SPA, Ross-shire. Scottish Natural Heritage.

DARGIE, T. C. D. 2001b. North Lincolnshire SSSI National Vegetation Classification (NVC) survey of coastal habitats. Peterborough: English Nature.

DAVY, A. J. 2002. Establishment and manipulation of plant populations and communities in terrestrial systems. *In:* PERROW, M. R. & DAVY, A. J. (eds.) *Handbook of ecological restoration; volume 1 principles of restoration.* Cambridge: Cambridge University Press.

DAVY, A. J., BROWN, M. J. H., MOSSMAN, H. L. & GRANT, A. 2011. Colonization of a newly developing salt marsh: disentangling independent effects of elevation and redox potential on halophytes. *Journal of Ecology,* 99**,** 1350-1357.

DAVY, A. J., GROOTJANS, A. P., HISCOCK. K. & PETERSEN, J. 2006. Development of eco-hydrological guidelines for dune habitats – Phase 1. *English Nature Research Report 696. .* Peterborough: English Nature.

DE HERT, K., JACQUEMYN, H., PROVOOST, S. & HONNAY, O. 2013. Absence of recruitment limitation in restored dune slacks suggests that manual seed introduction can be a successful practice for restoring orchid populations. *Restoration ecology,* 21**,** 159-162.

DE LEEUW, J., APON, L. P., HERMAN, P. M. J., DE MUNCK, W. & BEEFTINK, W. G. 1992. Vegetation response to experimental and natural disturbance in two salt-marsh plant communities in the southwest Netherlands. *Netherlands Journal of Sea Research,* 30**,** 279-288.

DEFRA 2012. Biodiversity offsetting pilots technical paper: the metric for the biodiversity offsetting pilot in England The Stationary Office: Department for Environment, Food and Rural Affairs.

DEFRA/ ENVIRONMENT AGENCY 2004. Suitability criteria for habitat creation – Report I: Reviews of present practices and scientific literature relevant to site selection criteria. London: Defra/ Environment Agency Flood and Coastal Defence R&D Programme.

DEFRA/ ENVIRONMENT AGENCY 2007. Sand dune processes and management for flood and coastal defence. Part 4: Techniques for sand dune management. *In:* PYE, K., SAYE, S. & BLOTT, S. J. (eds.). London: Defra/ Environment Agency Flood and Coastal Defence R&D Programme.

DENNY, M. & ANDERSON, G. 1999. Effects of rotoburying *Spartina anglica* at Lindisfarne NNR, Results for plant species, two years after rotoburying. English Nature.

DEPARTMENT FOR BUSINESS, E. I. S. 2017. Energy trends September 2017. London: Department for Business, Energy & Industrial Strategy, National Statistics.

DEPARTMENT OF TRADE AND INDUSTRY 1992. *Guidelines for the environmental assessment of cross-country pipelines,* London, HMSO.

DINES, T. 2008. A vascular plant red data list for Wales. Salisbury: Plantlife International.

DONG ENERGY 2013. Walney Extension Offshore Wind Farm, Volume 1 Environmental Statement, Chapter 24: Terrestrial ecology and nature conservation. London: DONG Energy, Walney Extension.

DONG ENERGY 2016. Race Bank Offshore Wind Farm April 2016 newsletter.

DOODY, J. P. 2007. *Saltmarsh Conservation, Management and Restoration*, Springer.

DOODY, J. P. & RANDELL, R. 2003. *A guide to the management and restoration of coastal vegetated shingle,* Peterborough, English Nature.

DOODY, P. 2001. *Coastal conservation and management: an ecological perspective,* London, Kluver Academic Publishers.

ECOLOGICAL SERVICES LTD 1999. National Vegetation Classification survey of the saltmarshes of The Wash National Nature Reserve. Peterborough: English Nature.

EDF ENERGY (NORTHERN OFFSHORE WIND) LTD. 2004. Teesside Offshore Wind Farm Environmental Statement - Non-technical summary. Unpublished.

ELLIOTT, S. 2015. Coastal realignment at RSPB Nigg Bay Nature Reserve. Sandy, Bedfordshire: RSPB.

ELLISON, A. M. 1987. Effects of competition, disturbance, and herbivory on *Salicornia europaea*. *Ecology,* 68**,** 576-586.

EMERY, N., EWANCHUK, P. J. & BERTNESS, M. D. 2001. Competition and salt-marsh plant zonation: Stress tolerators may be dominant competitors. . *Ecology,* 82**,** 2471–2485.

ENTEC 2004. Teesside Offshore Wind Farm Environmental Statement. Unpublished: EDF Energy (Northern Offshore Wind) Ltd.

ENTEC 2008. Teesside Offshore Wind Farm Environmental Statement. Unpublished: EDF Energy (Northern Offshore Wind) Ltd.

ENVIRONMENT AGENCY 2008. Freiston Shore managed realignment site: Information sheet no.1 Strategic & Development Planning, Shoreline Management Group Environment Agency.

ENVIRONMENT AGENCY 2010. Protecting the plant communities and rare species of dune wetland systems: Ecohydrological guidelines for wet dune habitats Bristol: Environment Agency

ENVIRONMENTAL RESOURCES LIMITED 1990. Amoco CATS Onshore Gas Pipeline Environmental Statement. Unpublished.

ENVIRONMENTAL RESOURCES LIMITED 1993. Block 110/13 Point of Ayr Pipeline Landfall: Environmental Statement.

ENVIRONMENTAL RESOURCES MANAGEMENT 1994. Britannia Pipeline Landfall, Teesside: Environmental Statement. Unpublished.

EUROPEAN COMMISSION 2010. EU Guidance on wind energy development in accordance with the EU nature legislation. Luxembourg: European Commission,.

EUROPEAN COMMISSION 2013. Interpretation Manual of European Union Habitats - EUR28. European Commission,.

EUROPEAN COMMISSION 2017. LIFE and coastal habitats. *In:* MERCIOL, J. (ed.). Luxembourg: European Commission.

FOREY, E., CHAPELET, B., VITASSE, Y., TILQUIN, M., TOUZARD, B. & MICHALET, R. 2008. The relative importance of disturbance and environmental stress at local and regional scales in French coastal sand dunes. *Journal of Vegetation Science,* 19**,** 493-502.

FRANK, D. & KLOTZ, S. 1990. *Biologisch-ökologische Daten zur Flora der DDR.* , Wiss. Beitr. Martin Luther University, Halle-Wittenberg. .

FRENCH, J. R. & BURNINGHAM, H. 2009. Restoration of an eroded estuarine foreshore using cohesive dredge material, Orwell Estuary, UK. *Journal of Coastal Research***,** 1444-1448.

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

FRID, C. L. J., CHANDRASEKARA, W. U. & DAVEY, P. 1999. The restoration of mud flats invaded by common cord-grass (*Spartina anglica*, CE Hubbard) using mechanical disturbance and its effects on the macrobenthic fauna. *Aquatic Conservation: Marine and Freshwater Ecosystems,* 9**,** 47-61.

GARBUTT, A. & WOLTERS, M. 2008. The natural regeneration of salt marsh on formerly reclaimed land. *Applied Vegetation Science,* 11**,** 335-344.

GARBUTT, R. A., READING, C. J., WOLTERS, M., GRAY, A. J. & ROTHERY, P. 2006. Monitoring the development of intertidal habitats on former agricultural land after the managed realignment of coastal defence at Tollesbury, Essex, UK. *Marine Pollution Bulletin,* 53**,** 155-164.

GEORGE, J. D., TITTLEY, I., WARBRICK, S., EVANS, N. J., MUIR, A. I., CHIMONIDES, P. J. & SPURRIER, C. J. 1992. North Morecambe Project, baseline ecological survey 1991/1992; Volumes 1 and 2. A report for British Gas Exploration and Production Ltd. London: The Natural History Museum, and The British Trust for Ornithology.

GIMINGHAM, C. H. 1964. Maritime and sub-maritime communities. *In:* BURNETT, J. H. (ed.) *The vegetation of Scotland.* Edinburgh: Oliver & Boyd.

GLEN, E., PRICE, E. A. C., CAPORN, S. J. M., CARROLL, J. A., JONES, L. M. & SCOTT, R. 2017. Evaluation of topsoil inversion in UK habitat creation and restoration schemes. *Restoration Ecology,* 25**,** 72-81.

GOSDEN, E. 2017. Keeping UK connected to europe - just as it leaves. *The Times*, 15 April 2017, p.50.

GOUDIE, A. 2013. Characterising the distribution and morphology of creeks and pans on salt marshes in England and Wales using Google Earth. *Estuarine, Coastal and Shelf Science,* 129**,** 112-123.

GRAFEN, A. & HALLS, R. 2002. *Modern statistics for the life sciences. Learn to analyse your own data,* Oxford, Oxford University Press.

GRAY, A. J. 1985. *Poole Harbour ecological sensitivity analysis of the shoreline: a report prepared for BP Petroleum Development Ltd.,* Huntingdon, Institute of Terrestrial Ecology.

GRAY, A. J. 1986. Saltmarsh restoration a review: with special reference to the impact of pipeline construction on the Poole Harbour saltmarshes. Huntingdon: Institute of Terrestrial Ecology (Natural Environment Research Council).

GRAY, A. J. & BENHAM, P. E. M. 1986. Biological monitoring of Wytch Farm Outfall (saltmarsh vegetation). Huntingdon: Institute of Terrestrial Ecology (Natural Environment Research Council).

GRAY, A. J. & SCOTT, R. 1977a. The ecology of Morecambe Bay. VII. The Distribution of *Puccinellia maritima, Festuca rubra* and *Agrostis stolonifera* in the salt marshes. *Journal of Applied Ecology,* 14**,** 229-241.

GRAY, A. J. & SCOTT, R. 1977b. *Puccinellia maritima* (Huds.) Parl.: (*Poa Maritima* Huds.; *Glyceria Maritima* (Huds.) Wahlb.). *Journal of Ecology,* 65**,** 699-716.

GREIPSSON, S. 2002. Coastal dunes. *In:* PERROW, M. R. & DAVY, A. J. (eds.) *Handbook of ecological restoration volume 2 restoration in practice.* Cambridge: Cambridge University Press.

GREIPSSON, S. & DAVY, A. J. 1996. Sand accretion and salinity as constraints on the establishment of *Leymus arenarius* for land reclamation in Iceland. *Annals of Botany,* 78**,** 611-618.

GRIME, J. P. 2001. *Plant strategies, vegetation processes, and ecosystem properties,* Chichester, Wiley.

GRIME, J. P., HODGSON, J. G. & HUNT, R. 1988. *Comparative plant ecology: a functional approach to common British species,* London, Unwin Hyman.

GROOTJANS, A. P., GEELEN, H. W. T., JANSEN, A. J. M. & LAMMERTS, E. J. 2002. Restoration of coastal dune slacks in the Netherlands. *Hydrobiologia,* 478**,** 181-203.

HANCOCK, C. 2016. Vegetation Trend Analysis (VTA). 2.01 ed.: Vegetation Trend Analysis.

HANDA, I. T. & JEFFERIES, R. L. 2000. Assisted revegetation trials in degraded salt-marshes. *Journal of Applied Ecology,* 37**,** 944-958.

HARRIS, D. & DAVY, A. J. 1986. Regenerative potential of *Elymus farctus* from rhizome fragments and seed. *Journal of Ecology,* 74**,** 1057-1067.

HARRIS, D. & DAVY, A. J. 1987. Seedling growth in *Elymus farctus* after episodes of burial with sand. *Annals of Botany,* 60**,** 587-593.

HAYNES, T. 2016. Scottish saltmarsh survey national report. Inverness: Scottish Natural Heritage, .

HESP, P., SCHMUTZ, P., MARTINEZ, M. L., DRISKELL, L., ORGERA, R., RENKEN, K., REVELO, N. A. R. & OROCIO, O. A. J. 2010. The effect on coastal vegetation of trampling on a parabolic dune. *Aeolian Research,* 2**,** 105-111.

HEWETT, D. G. 1970. The Colonization of sand dunes after stabilization with Marram Grass (*Ammophila arenaria*). *Journal of Ecology,* 58**,** 653-668.

HEWETT, D. G. 1985. Grazing and mowing as management tools on dunes. *Vegetatio,* 62**,** 441-447.

HILL, D., FASHAM, M., TUCKER, G., SHEWRT, M. & SHAW, P. 2005. *Handbook of biodiversity methods survey, evaluation and monitoring,* Cambridge, Cambridge University Press.

HILL, M. 1988. Saltmarsh vegetation of The Wash: an assessment of change from 1971 to 1985. *Research and Survey in Nature Conservation.* Peterborough: Nature Conservancy Council.

HILL, M., PRESTON, C. D. & ROY, D. B. 2004. *PLANTATT. Attributes of British and Irish plants: Status, size, life history, geography and habitats* Cambridgeshire, Natural Environment Research Council

HILL, M. O., MOUNTFORD, J. O., ROY, D. B. & BUNCE, R. G. H. 1999. Ellenberg's indicator values for British plants: Ecofact Volume 2, Technical Annex. . ITE Monkswood & ITE Grange-over-Sands. : Centre for Ecology & Hydrology and Natural Environment Research Council.

HILL, M. O., PRESTON, C. D., BOSANQUET, S. D. S. & ROY, D. B. 2007. *BRYOATT Attributes of British and Irish mosses, liverworts and hornworts,* Huntingdon, Centre for Ecology and Hydrology.

HM GOVERNMENT 2011. The natural choice: securing the value of nature. London.

HOBBS, R. J., GIMINGHAM, C. H. & BAND, W. T. 1983. The effects of planting technique on the growth of *Ammophila arenaria* (L.) Link and *Lymus arenarius* (L.) Hochst. *Journal of Applied Ecology,* 20**,** 659-672.

HOBBS, R. J. & NORTON, D. A. 1996. Towards a conceptual framework for restoration ecology. *Restoration Ecology,* 4**,** 93-110.

HOLL, K. & CAIRNS, J. 2002. Monitoring and appraisal. *In:* PERROW, M. R. & DAVY, A. J. (eds.) *Handbook of ecological restoration; volume 1 principles of restoration.* Cambridge: Cambridge University Press.

HOUSTON, J. A. 1997. Conservation management practice on British dune systems. *British Wildlife,* 8**,** 297-307.

HUBBARD, J. C. E. 1954. *Grasses,* Middlesex, Penguin Books.

HUGHES, R. G., FLETCHER, P. W. & HARDY, M. J. 2009. Successional development of saltmarsh in two managed realignment areas in SE England, and prospects for saltmarsh restoration. *Marine Ecology Progress Series,* 384**,** 13-22.

HUGHES, R. G. & PARAMOR, O. A. L. 2004. On the loss of saltmarshes in south-east England and methods for their restoration. *Journal of Applied Ecology,* 41**,** 440-448.

HUISKES, A. H. L. 1979. *Ammophila arenaria* (L.) Link (*Psamma arenaria* (L.) Roem. et Schult.; *Calamgrostis arenaria* (L.) Roth). *Journal of Ecology,* 67**,** 363-382.

HUTCHINGS, M. J. & RUSSELL, P. J. 1989. The seed regeneration dynamics of an emergent salt marsh. *Journal of Ecology,* 77**,** 615-637.

IEEM 2010. Guidelines for ecological impact assessment in Britain and Ireland: Marine and coastal. Windsor: Institute of Ecology and Environmental Management.

IPCC 2013. Summary for Policymakers. *In:* STOCKER, T. F., QIN, D., PLATTNER, G. K., TIGNOR, M., ALLEN, S. K., BOSCHUNG, J., NAUELS, A., XIA, Y., BEX, V. & MIDGLEY, P. M. (eds.) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* Cambridge and New York: Cambridge University Press.

ISERMANN, M. 2008. Expansion of *Rosa rugosa* and *Hippophaë rhamnoides* in coastal grey dunes: Effects at different spatial scales. *Flora,* 203**,** 273-280.

ISERMANN, M., DIEKMANN, M. & HEEMANN, S. 2007. Effects of the expansion by *Hippophae rhamnoides* on plant species richness in coastal dunes *Applied Vegetation Science,* 10**,** 33-42.

ISERMANN, M. & ROONEY, P. 2014. Biological Flora of the British Isles: *Eryngium maritimum*. *Journal of Ecology,* 102**,** 789-821.

JENKINS, G. J., MURPHY, J. M., SEXTON, D. M. H., LOWE, J. A., JONES, P. & KILSBY, C. G. 2009. UK Climate Projections: Briefing report. Exeter: Met Office Hadley Centre.

JENNINGS, M., LOUCKS, O., PEET, R., FABER-LANGENDOEN, D., GLENN-LEWIN, D., GROSSMAN, D., DAMMAN, A., BARBOUR, M., PFISTER, R., WALKER, M., TALBOT, S., WALKER, J., HARTSHORN, G., WAGGONER, G., ARBAMS, M., HILL, A., ROBERTS, D., TART, D. & REJMANEK, M. 2003. Guidelines for describing associations and alliances of the U.S. national vegetation classification. Washington: The Ecological Society of America Vegetation Classification Panel,.

JENSEN, A. 1985. The effect of cattle and sheep grazing on salt-marsh vegetation at Skallingen, Denmark. *Vegetatio,* 60**,** 37-48.

JERLING, L. 1988. Population dynamics of *Glauxa maritima* (L.) along a distributional cline. *Vegetatio,* 74**,** 161-170.

JERMY, A. C., SIMPSON, D. A., FOLEY, M. J. Y. & PORTER, M. S. 2007. *Sedges of the British Isles,* London, Botanical Society of Britain and Ireland.

JNCC 2004a. *Common standards monitoring guidance for saltmarsh habitats,* Peterborough, JNCC.

JNCC 2004b. *Common standards monitoring guidance for sand dune habitats,* Peterborough, JNCC.

JNCC 2013a. Guidelines for the selection of biological SSSIs: Part 1: rationale, operational approach and criteria for site selection. Peterborough: JNCC.

JNCC 2013b. Guidelines for the selection of biological SSSIs: Part 2: Detailed guidelines for habitats and species - 1a Coastlands. Peterborough: JNCC.

JNCC 2016. Conservation designations for UK taxa. Peterborough: JNCC.

JOHN, S. A., MEAKINS, N., BASFORD, K., CRAVEN, H. & CHARLES, P. 2015. *Coastal and marine environment site guide* London, CIRIA.

JOHN, S. A., MEAKINS, N., BASFORD, K., CRAVEN, H. & CHARLES, P. 2016. Coastal and marine environmental pocket book. London: CIRIA.

JONES, L., ANGUS, S., COOPER, A., DOODY, J. P., EVERARD, M., GARBUTT, R. A., GILHURST, P., HANSOM, J., NICHOLLS, R., PYE, K., RAVENSCROFT, N., REES, S., RHIND, P. & WHITEHOUSE, A. 2011. Coastal margins. *UK National Ecosystem Assessment.* Cambridge: United Nations Environment Programme.

JONES, M. L. M., NORMAN, K. & RHIND, P. M. 2010a. Topsoil inversion as a restoration measure in sand dunes, early results from a UK field-trial. *Journal of Coastal Conservation,* 14**,** 139-151.

JONES, M. L. M., REYNOLDS, B., BRITTAIN, S. A., NORRIS, D. A., RHIND, P. M. & JONES, R. E. 2006. Complex hydrological controls on wet dune slacks: The importance of local variability. *Science of the Total Environment,* 372**,** 266-277.

JONES, M. L. M., SOWERBY, A. & RHIND, P. M. 2010b. Factors affecting vegetation establishment and development in a sand dune chronosequence at Newborough Warren, North Wales. *Journal of Coastal Conservation,* 14**,** 127-137.

JONES, M. L. M., WALLACE, H. L., NORRIS, D., BRITTAIN, S. A., HARIA, S., JONES, R. E., RHIND, P. M., REYNOLDS, B. R. & EMMETT, B. A. 2004. Changes in vegetation and soil characteristics in coastal sand dunes along a gradient of atmospheric nitrogen deposition. *Plant Biology,* 6**,** 598-605.

KENTULA, M. E. 2000. Perspectives on setting success criteria for wetland restoration. *Ecological Engineering,* 15**,** 199-209.

KIM, D., CAIRNS, D. M. & BARTHOLDY, J. 2013. Tidal creek morphology and sediment type influence spatial trends in salt marsh vegetation. *The Professional Geographer,* 65**,** 544-560.

KNOTT, D. M., WENNER, E. L. & WENDT, P. H. 1997. Effects of pipeline construction on the vegetation and macrofauna of two South Carolina, USA salt marshes. *Wetlands,* 17**,** 65-81.

LACAMBRA, C., CUTTS, N., ALLEN, J., BURD, F. & ELLIOTT, M. 2004. *Spartina anglica*: a review of its status, dynamics and management. *English Nature Research Reports.* Peterborough: English Nature.

LAMMERTS, E. J., PEGTEL, D. M., GROOTJANS, A. P. & VAN DER VEEN, A. 1999. Nutrient limitation and vegetation changes in a coastal dune slack. *Journal of Vegetation Science,* 10**,** 111-122.

LAUGHLIN, D. C., STRAHAN, R. T., MOORE, M. M., FULÉ, P. Z., HUFFMAN, D. W. & COVINGTON, W. W. 2017. The hierarchy of predictability in ecological restoration: are vegetation structure and functional diversity more predictable than community composition? *Journal of Applied Ecology,* 54**,** 1058-1069.

LAWRENCE, P. J., SMITH, G., SULLIVAN, M. J. P. & MOSSMAN, H. L. 2018. Restored saltmarshes lack the topographic diversity found in natural habitat. *Ecological Engineering,* 115**,** 58-66.

LAWTON, J. 2010. Making space for nature: A review of England's wildlife sites and ecological network The Stationary Office: Department for Environment, Food and Rural Affairs.

LITHGOW, D., MARTÍNEZ, M. L., GALLEGO-FERNÁNDEZ, J. B., HESP, P. A., FLORES, P., GACHUZ, S., RODRÍGUEZ-REVELO, N., JIMÉNEZ-OROCIO, O., MENDOZA-GONZÁLEZ, G. & ÁLVAREZ-MOLINA, L. L. 2013. Linking restoration ecology with coastal dune restoration. *Geomorphology,* 199**,** 214-224.

LOCKWOOD, J. L. & PIMM, S. L. 1999. When does restoration succeed? *In:* WEIHER, E. & KEDDY, P. (eds.) *Ecological Assembly Rules: Perspectives, Advances, Retreats.* Cambridge: Cambridge University Press.

LOWE, S. 2012. Lymington Harbour habitat replenishment scheme: summary of works. *Marine Estate Research Report.* London: The Crown Estates.

LOWE, S. 2013. Lymington Harbour habitat replenishment scheme - phase II summary of works.

LUDLOW, D. 2015. Dune rejuvenation management in Wales: Merthyr Mawr Warren NNR, Kenfig NNR, Newborough Warren NNR. *Dynamic Dunes 2015: daring solutions for 'Natura 2000 challenges'.* Amsterdam, Netherlands: PWN, Natuurmonumenten, Waternet.

LUSH, M., HAYNES, T. & LUSH, C. 2016. *Spartina anglica* and its management in estuarine Natura 2000 sites: an update of its status and monitoring future change in England. Natural England.

MAGURRAN, A. E. 2004. *Measuring biological diversity,* Oxford, Blackwell Publishing.

MAGURRAN, A. E. & MCGILL, B. 2011. *Biological diversity frontiers in measurement and assessment,* Oxford, Oxford University Press.

MALDON ECOLOGICAL CONSULTANTS 1997. Annual report 1996: monitoring of sand dune restorations at Talacre Unpublished: Report to BHP Petroleum Ltd.

MALDON ECOLOGICAL CONSULTANTS 1998. Annual report 1997: monitoring of sand dune restorations at Talacre. Unpublished: Report to BHP Petroleum Ltd.

MARKS, T. C. & TRUSCOTT, A. J. 1985. Variation in seed production and germination of *Spartina Anglica* within a zoned saltmarsh. *Journal of Ecology,* 73**,** 695-705.

MARTIN, D. M. 2017. Ecological restoration should be redefined for the twenty-first century. *Restoration Ecology***,** n/a-n/a.

MARTIN, J. P., DAVEY, A. J., GRANT, A. & MOSSMAN, H. L. 2018. Is saltmarsh success constrained by matching natural environments or altered succession? A test using niche models. *Journal of Applied Ecology,* 55**,** 1207-1217.

MATTHEWS, J. W. & ENDRESS, A. G. 2008. Performance criteria, compliance success, and vegetation development in compensatory mitigation wetlands. *Environmental Management,* 41**,** 130-141.

MCDONALD, T., GANN, G., JONSON, J. & DIXON, K. 2016. International standards for the practice of ecological restoration – including principles and key concepts. Washington, D.C.: Society for Ecological Restoration.

MCGRATH, T. & JENKINS, L. 2014. WWT Steart Marshes - a coastal wetland that works for people and wildlife. *Spring Conference 2015: 'Managing Change in Coastal Habitats'.* Bristol: Chartered Institute of Ecology and Environmental Management.

MILLETT, J. & EDMONDSON, S. 2013. The impact of 36 years of grazing management on vegetation dynamics in dune slacks. *Journal of Applied Ecology,* 50**,** 1367-1376.

MINISTRY OF HOUSING, C. L. G. 2012. National Planning Policy Framework. *In:* LEGISLATION.GOV.UK (ed.). London,: HMSO.

MITSCH, W. J. & WILSON, R. F. 1996. Improving the success of wetland creation and restoration with know-how, time, and self-design. *Ecological Applications,* 6**,** 77-83.

MORRISON, L. W. 2016. Observer error in vegetation surveys: a review. *Journal of Plant Ecology,* 9**,** 367-379.

MOSSMAN, H. L., BROWN, M. J. H., DAVY, A. J. & GRANT, A. 2012a. Constraints on salt marsh development following managed coastal realignment: dispersal limitation of environmental tolerance? *Restoration Ecology,* 20**,** 65-75.

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

MOSSMAN, H. L., GRANT, A. & DAVY, A. 2013. Implications of climate change for coastal and inter-tidal habitats in the UK. Terrestrial biodiversity climate change impacts report card technical paper. Biodiversity Report Card paper 10. Norwich: University of East Anglia.

MURTAGH, P. 2015. Corrib gas: Keeping ecological eye on restoration at Leenamore. *The Irish Times*, 29/06/15.

NATIONAL ACADEMIES OF SCIENCES, E., MEDICINE. 2017. *Effective monitoring to evaluate ecological restoration in the Gulf of Mexico,* Washington, DC, The National Academies Press.

NATURAL CAPITAL COMMITTEE 2015. The state of natural capital protecting and improving natural capital for prosperity and wellbeing. UK: Natural Capital Committee.

NATURAL ENGLAND & RSPB 2014. Climate change adaptation manual: Evidence to support nature conservation in a changing climate (NE546). Natural England.

NATURE CONSERVATION COUNCIL 1989. Guidelines for the selection of SSSIs. Peterborough: Nature Conservation Council, .

NATUURMONUMENTEN 2015a. Dutch dune revival in Zuid-Kennemerland: de Noordwesr Natuurken en Levend Duin layman's report. *In:* NATUURMONUMENTEN (ed.). The Netherlands: Natuurmonumenten and PWN.

NATUURMONUMENTEN 2015b. Dutch dune revival Voorn & Goeree layman's report. *In:* NATUURMONUMENTEN (ed.). The Netherlands: Natuurmonumenten.

NEFF, J. 2014. Habitat reinstatement, restoration and creation on the Corrib Gas Onshore Pipeline in Co Mayo, Ireland - challenges and solutions *Progress in Effective Habitat Restoration, Translocation and Creation.* The University of Edinburgh, Edinburgh: Chartered Institute of Ecology and Environmental Management.

NEMO LINK. 2012. *Nemo Link - Cable Route* [Online]. Available: http://www.nemo-link.com/the-project/selecting-the-cable-route/ [Accessed 12/09/17].

NOBLE, J. C. 1982. *Carex arenaria* (L.). *Journal of Ecology,* 70**,** 867-886.

NOTTAGE, A. & ROBERTSON, P. 2005. *The saltmarsh creation handbook: a project manager's guide to the creation of saltmarsh and intertidal mudflat,* Sandy, Bedfordshire, The RSPB.

O'REILLY, J. 2015. Design of a vegetation monitoring scheme for the Border mires. *Improvement Programme for England's Natura 2000 sites (IPENS).* Natural England.

O'SULLIVAN, S. 2010. Report on certain aspects of the application for approval under Section 182C of the Planning and Development Acts 2000-2006 for the onshore upstream gas pipeline facility relating to the Corrib Gas Field Project, Co Mayo, as modified in response to the letter issued to the applicant by An Bord Pleanála on 2nd November 2009 and described in the Environmental Impact Statement submitted to the board on 31st May 2010. An Bord Pleanála.

OLFF, H., DE LEEUW, J., BAKKER, J. P., PLATERINK, R. J. & VAN WIJNEN, H. J. 1997. Vegetation succession and herbivory in a salt marsh: Changes induced by sea level rise and silt deposition along an elevational gradient. *Journal of Ecology,* 85**,** 799-814.

OLSSON, P. A. & ÖDMAN, A. M. 2014. Natural establishment of specialist plant species after topsoil removal and soil perturbation in degraded calcareous sandy grassland. *Restoration Ecology,* 22**,** 49-56.

OSPAR 2017. Guidelines on best environmental practice (BEP) in Cable laying and operation (Revised in 2017). Agreement 2012-2. London: OSPAR Commission,.

PACKHAM, J. R. & LIDDLE, M. J. 1970. The Cefni salt marsh Anglesey, and its recent development. *Field Studies,* 3**,** 331-356.

PACKHAM, J. R. & WILLIS, A. J. 1997. *Ecology of dunes, salt marsh, and shingle,* London; New York, Chapman & Hall.

PAGE, R. R., VINHA, S. G. D. & AGNEW, A. D. Q. 1985. The reaction of some sand-dune plant species to experimentally imposed environmental change: A reductionist approach to stability. *Vegetatio,* 61**,** 105-114.

PEARSALL, W. 1934. North Lancashire sand dunes. *Naturalist,* 1934**,** 201-2015.

PEARSON, M. C. & ROGERS, J. A. 1962. Biological Flora of the British Isles: *Hippophae rhaminoides*. *Journal of Ecology,* 50**,** 501-513.

PERROW, M. R. & DAVY, A. J. 2002. *Handbook of ecological restoration; volume 1 principles of restoration,* Cambridge, Cambridge University Press.

PETHICK, J. S. 1974. The distribution of salt pans on tidal marshes. *Journal of Biogeography,* 1**,** 57-62.

PETHICK, J. S. 1981. Long term accretion rates on tidal saltmarshes. *Journal of Sedimentary Petrology,* 51**,** 571-577.

PHELAN, N., SHAW, A. & BAYLIS, A. 2011. The extent of saltmarsh in England and Wales: 2006–2009 Bristol: Environment Agency.

PLASSMANN, K., BROWN, N., JONES, M. L. M. & EDWARDS-JONES, G. 2009. Can soil seed banks contribute to the restoration of dune slacks under conservation management? *Applied Vegetation Science,* 12**,** 199-210.

PLASSMANN, K., JONES, M. L. M. & EDWARDS-JONES, G. 2010. Effects of long-term grazing management on sand dune vegetation of high conservation interest. *Applied Vegetation Science,* 13**,** 100-112.

PROCTOR, M. C. F. 2013. *Vegetation of Britain and Ireland,* London, HarperCollins.

PYE, K. & BLOTT, S. J. 2012. A geomorphological survey of Welsh dune systems to determine best methods of dune rejuvenation. Bangor: Countryside Council for Wales.

PYE, K., BLOTT, S. J. & HOWE, M. A. 2014. Coastal dune stabilization in Wales and requirements for rejuvenation. *Journal of Coastal Conservation,* 18**,** 27-54.

PYE, K., SAYE, S. & BLOTT, S. J. 2007. Sand dune processes and management for flood and coastal defence: Part 1: project overview and recommendations. London: Joint Defra/EA Flood and Coastal Erosion Risk Management R&D Programme.

RADLEY, G. P. 1994. *Sand dune vegetation survey of Great Britain: a national inventory part I: England,* Peterborough, JNCC.

RAE, P. A. S. 1981. The pipeline crossing of Walney Island, Barrow-in-Furness: a preliminary ecological survey of Wylock Marsh. Unpublished: British Gas.

RAE, P. A. S. 1983. Pipeline crossing of Walney Island, Barrow-in-Furness: interim report on the progress of reinstatement with an assessment of methods for revegetation Unpublished: British Gas.

RAE, P. A. S. 1984a. Pipeline crossing of Walney Island, Barrow-in-Furness: interim report No. 3 on the progress of reinstatement. Unpublished: British Gas.

RAE, P. A. S. 1984b. Pipeline crossing of Walney Island, Barrow-in-Furness: interim report No. 4 survey of Wylock Marsh to assess quality of trench backfilling and surface reinstatement. Unpublished: British Gas.

RAE, P. A. S. 1984c. Pipeline crossing of Walney Island, Barrow-in-Furness: interim report No. 5 on the progress of reinstatement. Unpublished: British Gas.

RANDERSON, P. F. 1975. The saltmarshes of The Wash. The Wash feasibility study ecological report. Scientific Study D. Unpublished.

RANWELL, D. S. 1959. Newborough Warren, Anglesey. I. The dune system and dune-slack habitat. *Journal of Ecology,* 47**,** 571-601.

RANWELL, D. S. 1960a. Newborough Warren, Anglesey. II. Plant associes and succession cycles of the sand-dune and dune-slack vegetation. *Journal of Ecology,* 48**,** 117-141.

RANWELL, D. S. 1960b. Newborough Warren, Anglesey. III. Changes in the vegetation on parts of the dune system after the loss of rabbits by myxomatosis. *Journal of Ecology,* 48**,** 385-395.

RANWELL, D. S. 1972. *Ecology of salt marshes and sand dunes,* London, Chapman and Hall.

RANWELL, D. S., BIRD, E. C. F., HUBBARD, J. C. E. & STEBBINGS, R. E. 1964. *Spartina* salt marshes in Southern England: V. Tidal submergence and chlorinity in Poole Harbour. *Journal of Ecology,* 52**,** 627-641.

RANWELL, D. S. & BOAR, R. 1986. *Coastal dune management guide,* Abbots Rippon, Huntingdon, Institute of Terrestrial Ecology.

RATCLIFFE, D. 1977. *A nature conservation review: the selection of biological sites of national importance to nature conservation in Britain,* Cambridge, Cambridge University Press.

READING, C. J., GARBUTT, R. A., WATTS, C. W., ROTHERY, P., TURK, A., YATES, M., BOFFEY, C., SAUNDERS, J. & WOLTERS, M. 2008. Managed realignment at Tollesbury. *Joint Defra/ EA Flood and Coastal Erosion Risk Management R&D Programme.* London: Defra.

REED, D. J., SPENCER, T., MURRAY, A. L., FRENCH, J. R. & LEONARD, L. 1999. Marsh surface sediment deposition and the role of tidal creeks: implications for created and managed coastal marshes. *Journal of Coastal Conservation,* 5**,** 81-90.

RHIND, P. M. & JONES, P. S. 1999. The floristics and conservation status of sand-dune communities in Wales. *Journal of Coastal Conservation,* 5**,** 31-42.

RHIND, P. M., JONES, R. & JONES, L. 2013. The impact of dune stabilization on the conservation status of sand dune systems in Wales. *In:* MARTÍNEZ, L. M., GALLEGO-FERNÁNDEZ, J. B. & HESP, P. A. (eds.) *Restoration of Coastal Dunes.* Berlin: Springer.

RHYMES, J., WALLACE, H., FENNER, N. & JONES, L. 2014. Evidence for sensitivity of dune wetlands to groundwater nutrients. *Science of The Total Environment,* 490**,** 106-113.

RICH, T. C. G. 2012. *Taraxacum* Section *Erythrosperma*. *In:* RICH, T. C. G. & CLEAL, H. B. R. (eds.) *Plant Crib 3.* London: Botanical Society of the British Isles.

RICHARDS, E. G. & BURNINGHAM, H. 2011. *Hippophae rhamnoides* on a coastal dune system: a thorny issue? *Journal of Coastal Conservation,* 15**,** 73-85.

RITCHIE, W. 1980. Environmental aspects of oil and gas pipeline landfalls in northeast Scotland. *Coastal Engineering Proceedings,* 1**,** 2938-2954.

RITCHIE, W. & GIMINGHAM, C. H. 1989. Restoration of coastal dunes breached by pipeline landfalls in North-east Scotland. *Proceedings of the Royal Society of Edinburgh,* 96B**,** 231-245.

RODWELL, J. S. 1991. *British plant communities volume 1: woodlands and scrub,* Cambridge, Cambridge University Press.

RODWELL, J. S. 1992. *British plant communities volume 3: grassland and montane communities,* Cambridge, Cambridge University Press.

RODWELL, J. S. 2000. *British plant communities volume 5: maritime communities and vegetation of open habitats,* Cambridge, Cambridge University Press.

RODWELL, J. S. 2006. *National Vegetation Classification: Users' handbook,* Peterborough, JNCC.

RODWELL, J. S., DRING, J. C., AVERIS, A. B. G., PROCTOR, M. C. F., MALLOCH, A. J. C., SCHAMINÉE, J. H. J. & DARGIE, T. C. D. 2000. Review of coverage of the National Vegetation Classification. *JNCC Report No. 302.* Peterborough: JNCC.

ROHANI, S., DULLO, B., WOUDWIJK, W., DE HOOP, P., KOOIJMAN, A. & GROOTJANS, A. P. 2014. Accumulation rates of soil organic matter in wet dune slacks on the Dutch Wadden Sea islands. *Plant Soil,* 380**,** 181-191.

ROONEY, P. 2010. Changing perspectives in coastal dune management. *Journal of Coastal Conservation,* 14**,** 71-73.

ROYAL HASKONING 2005a. Thanet Offshore Wind Farm Environmental Statement Royal Haskoning on behalf Warwick Energy and Thanet Offshore Wind Ltd

ROYAL HASKONING 2005b. Thanet Offshore Wind Farm Environmental Statement non-technical summary. Royal Haskoning on behalf Warwick Energy and Thanet Offshore Wind Ltd.

ROYAL HASKONING 2010. Thanet Offshore Wind Farm: saltmarsh recovery monitoring survey. Unpublished.

ROYAL HASKONING 2011. Thanet Offshore Wind Farm: saltmarsh recovery monitoring survey 2011. Unpublished.

RSK CARTER ECOLOGICAL 2009. Project Breagh botany report. Unpublished.

RUIZ-JAEN, M. C. & AIDE, T. M. 2005. Restoration success: How is it being measured? *Restoration Ecology,* 13**,** 569-577.

RWE GROUP 2010. Breagh Pipeline Project Environmental Statement. Unpublished.

RYDGREN, K., HALVORSEN, R., TOPPER, J. P., AUESTAD, I., NORUNN HAMRE, L., JONGEJANS, E. & SULAVIK, J. 2018. Advancing restoration ecology: A new approach to predict time to recovery. *Journal of Applied Ecology,* 00**,** 1-10.

SALISBURY, E. 1922. The soils of Blakeney Point: a study of soil reaction and succession in relation to plant covering. *Annals of Botany,* 36**,** 391-431.

SANTORO, R., JUCKER, T., PRISCO, I., CARBONI, M., BATTISTI, C. & ACOSTA, A. T. 2012. Effects of trampling limitation on coastal dune plant communities. . *Environmental Management,* 49**,** 534-542.

SCHOLTEN, M. & ROZEMA, J. 1990. The competitive ability of *Spartina anglica* on Dutch salt marshes. *In:* GRAY, A. J. & BENHAM, P. E. M. (eds.) *Spartina anglica - a research review.* London: Institute of Terrestrial Ecology, Natural Environment Research Council.

SCOTTISH NATURAL HERITAGE 2000. A guide to managing coastal erosion in beach/dune systems. Scottish Natural Heritage.

SMILAUER, P. & LEPS, J. 2014. *Multivariate analysis of ecological data using CANOCO 5,* Cambridge, Cambridge University Press.

SMITH, W. G. 1913. Raunkiaer's "life-forms" and statistical methods. *Journal of Ecology,* 1**,** 16-26.

SOCIETY FOR ECOLOGICAL RESTORATION INTERNATIONAL 2004. The SER International primer on ecological restoration. . Tuscon, Arizona: Society for Ecological Restoration International.

SOULSBY, C., HANNAH, D., MALCOLM, R., MAIZELS, J. K. & GARD, R. 1997. Hydrogeology of a restored coastal dune system in Northeastern Scotland. *Journal of Coastal Conservation,* 3**,** 143-154.

SPARKS, E. L., CEBRIANA, J., BIBERC, P. B., SHEEHAND, K. L. & TOBIAS, C. R. 2013. Cost-effectiveness of two small-scale salt marsh restoration designs. *Ecological Engineering,* 53**,** 250-256.

SPENCER ECA. 2014. *Export cable installation for Thanet wind energy project – February 2010* [Online]. Available: http://www.spencereca.com/thanetcasestudy.html [Accessed 06/02/14].

STACE, C. A. 2010. *New Flora of the British Isles,* Cambridge, Cambridge University Press.

STEWART, A., PEARMAN, D. A. & PRESTON, C. D. 1994. *Scarce Plants in Britain,* Peterborough, JNCC.

STROH, P. A., LEACH, S. J., AUGUST, T. A., WALKER, K. J., PEARMAN, D. A., RUMSEY, F. J., HARROWER, C. A., FAY, M. F., MARTIN, J. P., PANKHURST, T., PRESTON, C. D. & TAYLOR, I. 2014. A vascular plant red list for England. Bristol: Botanical Society of Britain and Ireland.

SUTHERLAND, W. J. & FRECKLETON, R. P. 2012. Making predictive ecology more relevant to policy makers and practitioners. *Philosophical Transactions of the Royal Society: Biological Sciences,* 367**,** 322–330.

SUTHERLAND, W. J., MITCHELL, R. & PRIOR, S. V. 2012. The role of 'Conservation Evidence' in improving conservation management. *Conservation Evidence,* 9**,** 1-2.

TANSLEY, A. G. 1939. *The British Islands and their Vegetation,* Cambridge, Cambridge University Press.

TEP 2013. Effect on integrity of European nature conservation interests - Applicants submission. Prepared for National Grid Nemo Link Ltd.

TER BRAAK, C. J. F. & SMILAUER, P. 2012. *Canoco reference manual and user's guide: Software for ordination (Version 5.0),* Ithaca, Microcomputer Power.

THE BBC. 2017. *Offshore wind power cheaper than new nuclear* [Online]. Available: http://www.bbc.co.uk/news/business-41220948 [Accessed 03/10/17].

THE CROWN ESTATE. 2017a. *The Crown Estate to consider new leasing for offshore wind projects* [Online]. Available: https://www.thecrownestate.co.uk/en-gb/media-and-insights/news/2017-the-crown-estate-to-consider-new-leasing-for-offshore-wind-projects/ [Accessed 23/11/17].

THE CROWN ESTATE 2017b. Offshore wind operational report. January – December 2016. London: The Crown Estate.

THE ENVIRONMENT BANK 2015. Investing in natural capital: saltmarsh restoration on the Deben Estuary. The Environment Bank.

THE ENVIRONMENT BANK. Unknown. *Biodiversity offsets and habitat banking in the UK and some comments on opportunities in Norway* [Online]. Available: http://www.nina.no/Portals/0/Innholdssider/økosystemtjenester/Duke-%20biodiversity%20offsets%20in%20the%20UK.pdf [Accessed 20/10/17].

THE GUARDIAN. 2016. *World's largest offshore windfarm to be built off Yorkshire coast* [Online]. Available: https://www.theguardian.com/environment/2016/feb/03/worlds-largest-offshore-windfarm-to-be-built-off-yorkshire-coast [Accessed 03/10/17].

THE GUARDIAN. 2017. *Wild is the wind: the resource that could power the world* [Online]. Available: https://www.theguardian.com/environment/2017/oct/15/wild-is-the-wind-the-resource-that-could-power-the-world [Accessed 16/10/17].

THE INDEPENDENT. 2017. *Britain powered 24 hours without coal for first time in 135 years in watershed moment* [Online]. Available: http://www.independent.co.uk/news/uk/home-news/day-without-coal-uk-135-years-energy-mix-happen-more-frequently-national-grid-a7696611.html [Accessed 03/10/17].

THE TIMES. 2017. *Record-breaking Hornsea Two wind farm will cut cost of green energy* [Online]. Available: https://www.thetimes.co.uk/article/record-breaking-wind-farm-will-cut-cost-of-green-energy-dong-energy-renewable-uk-hinkley-point-xfs0j893k [Accessed 03/10/17].

THOMSON, A. 2004. Match version 4 for Windows NT/95/98/2000/XP. Version 4 ed. Unit of Vegetation Science University of Lancaster University of Lancaster

TURNER, K., SCHAAFSMA, M., ELLIOTT, M., BURDON, D., ATKINS, J., JICKELLS, T., TETT, P., MEE, L., VAN LEEUWEN, S., BARNARD, S., LUISETTI, T., PALTRIGUERA, L., PALMIERI, G. & ANDREWS, J. 2014. UK National Ecosystem Assessment follow-on work package report 4: coastal and marine ecosystem services: principles and practice. UK: United Nations Environment Programme, World Conservation Monitoring Centre, Living With Environmental Change

TUTIN, T. G., HEYWOOD, V. H., BURGES, N. A., VALENTINE, D. H., WALTERS, S. M. & WEBB, D. A. 1964. *Flora Europaea, Volume 1. Lycopodiaceae to Platanaceae.,* Cambridge, Cambridge University Press.

VAN DER HAGEN, H. J., GEELEN, L. & DE VRIES, C. N. 2008. Dune slack restoration in Dutch mainland coastal dunes. *Journal for Nature Conservation,* 16**,** 1-11.

VAN DER MEULEN, F. & VAN DER MAAREL, E. 1989. Coastal defence alternatives and nature development perspectives. *Perspectives in coastal dune management.* The Hague: SPB Academic Publishing.

VAN DER PUTTEN, W. H. 1990. Establishment of *Ammophila arenaria* (Marram Grass) from culms, seeds and rhizomes. *Journal of Applied Ecology,* 27**,** 188-199.

VAN DIJK, H. 1992. Grazing domestic livestock in Dutch coastal dunes: experiments, experiences and perspectives. *In:* CARTER, R. W. G., CURTIS, T. G. F. & SHEEHY-SKEFFINGTON, M. (eds.) *Coastal dunes.* Rotterdam: A.A. Balkema.

VAN LOON-STEENSMA, J. M., VAN DOBBEN, H. F., SLIM, P. A., HUISKES, H. P. J. & DIRKSE, G. M. 2015. Does vegetation in restored salt marshes equal naturally developed vegetation? *Applied Vegetation Science,* 18**,** 674-682.

VAN TIL, M. & KOOIJMAN, A. 2007. Rapid improvement of grey dunes after shallow sod cutting. *In:* ISERMANN, M. & KIEHL, K. (eds.) *Coastline Reports: Restoration of Coastal Ecosystems.* Leiden: EUCC – The Coastal Union.

VERCRUYSSE, W. & FITZSIMONS, M. 2006. Landfall and shore approach of the new Langeled Pipeline at Easington, UK. *Terra et Aqua,* 102**,** 12-18.

WALKER, K. J., STROH, P. A. & ELLIS, R. W. 2017. *Threatened plants in Britain and Ireland,* Bristol, Botanical Society of Britain and Ireland.

WALMSLEY, C. A. & DAVY, A. J. 1997. The restoration of coastal shingle vegetation: effects of substrate composition on the establishment of seedlings. *Journal of Applied Ecology,,* 34**,** 143-153.

WARTON, D. I. & HUI, F. K. C. 2011. The arcsine is asinine: the analysis of proportions in ecology. *Ecology,* 92**,** 3-10.

WATERNET, NATUURMONUMENTEN & PWN. Dynamic Dunes 2015 - Daring solutions for Natura 2000 challenges. *In:* GEELEN, L., SALMAN, A. & KUIPERS, M., eds. Dynamic Dunes 2015 - Daring solutions for Natura 2000 challenges, 2015 Zandvoort and Rockanje, Netherlands. Waternet.

WATSON, E. V. 1980. *British mosses and liverworts,* Cambridge, Cambridge University Press.

WEINSTEIN, M. P., BALLETTO, J. H., TEAL, J. M. & LUDWIG, D. F. 1996. Success criteria and adaptive management for a large-scale wetland restoration project. *Wetlands Ecology and Management,* 4**,** 111-127.

WESTHOFF, V. & VAN DER MAAREL, E. 1973. The Braun-Blanquet Approach. *In:* WHITTAKER, P. J. (ed.) *Ordination and Classification of Vegetation. Handbook of Vegetation Science Part V. .* Junk, The Hague.

WIGGINGTON, M. J. 1999. *British red data books: 1 Vascular plants,* Peterborough, JNCC.

WILLIS, A. J., FOLKES, B. F., J.K., H.-S. & YEMM, E. W. 1959. Braunton Burrows: the dune system and its vegetation. Part 1 and 2. *Journal of Ecology,* 47**,** 1-24; 249-288.

WOODELL, S. R. J. & DALE, A. 1993. *Armeria maritima* (Mill.) Willd. (Statice Armeria L.; S. Maritima Mill.). *Journal of Ecology,* 81**,** 573-588.

WOODWORTH, P. L., TEFERLE, F. N., BINGLEY, R. M., SHENNAN, I. & WILLIAMS, S. D. P. 2009. Trends in UK mean sea level revisited. *Geophysical Journal International,* 176**,** 19-30.

WORKING GROUP ON NO NET LOSS OF ECOSYSTEMS AND THEIR SERVICES 2013. Development of operational principles of any proposed EU no net loss initiative. European Commission,.

ZEDLER, J. B. & ADAM, P. 2002. Saltmarshes. *In:* PERROW, M. R. & DAVY, A. J. (eds.) *Handbook of ecological restoration volume 2 restoration in practice.* Cambridge: Cambridge University Press.

ZEDLER, J. B. & CALLAWAY, J. C. 2000. Evaluating the progress of engineered tidal wetlands. *Ecological Engineering,* 15**,** 211-225.

APPENDICES


recovery
vegetation
dunes
saltmarsh
construction
sand
monitoring
species
impacts
successional
impact
provide
frames
time
early
Species
projects
slacks
resulting
often
likely
using
Past
best
used
areas
bare
long
dune
botanical
development
Linear
associated
allowing
baseline
data
Model
advisable
decision-making
wet-tolerant
different
Analysis
informed
pipelines
drier
energy
although might
Canonical
Recovery
habitat
restored
attributes
cover
zones
environmental
resilient
opportunities
coastal
completed
Curves
tended
pipeline
aid
open
exclusively
atypical
subject
indicators
herbs
typically
zone
reflect
compaction
marsh
standard
findings
current
analysed
original
evidence
process
creeks
Generalised
found
installation
initially
reliance
unaffected
severe
compare
assessment
adjacent
change
positive
surveys
record
varied
show
exception
following
off-shore
creating
post-construction
cables
Response
generally
research
plant
just
outcomes
survey
aim
subsequent
Central
renewable
Detailed
study
focuses
sensitive
supporting
habitats
became
Correspondence
depending
determining
loss
modification
determine
overall
focus

Appendix 1 Supporting Information

Appendix Table 1 - Extent (ha) of sand dune and saltmarsh habitat listed on Annex I of the EU Habitat Directive in the UK – taken from the JNCC webpage[1].

EU Habitats Directive Annex I types	England (ha)	Scotland (ha)	Wales (ha)	Northern Ireland (ha)	UK (ha)
Sand Dune Habitats					
H2130 Fixed dunes with herbaceous vegetation ('grey dunes')	3,900	14,800	2,700	1,000	22,400
H2120 Shifting dunes along the shoreline with *Ammophila arenaria* ('white dunes')	780	910	480	15	2,185
H2190 Humid dune slacks	200	1,184	390	22	1,796
H2150 Decalcified fixed dunes with *Empetrum nigrum*	190	550	40	120	900
H2170 Dunes with *Salix repens* ssp. *argentea* (*Salicion arenariae*)	230	170	230	12	642
H2140 Decalcified fixed dunes with *Empetrum nigrum*	–	322	–	–	322
H2110 Embryonic shifting dunes	100	90	100	5	295
H2160 Dunes with *Hippophae rhamnoides*	235	–	–	–	235
H2250 Coastal dunes with *Juniperus* spp.	–	8	–	–	8
H21A0 Machairs	–	14,500	–	–	14,500
Saltmarsh Habitats					
H1330 Atlantic salt meadows (*Glauco-Puccinellietalia maritimae)*	21,000	2,105	7,128	230	30,463
H1310 *Salicornia* and other annuals colonising mud and sand	1,620	300	210	10	2,140
H1320 *Spartina* swards (*Spartinion maritimae*)	100	–	–	–	100
H1420 Mediterranean and thermo-Atlantic halophilous scrubs (*Sarcocornetea fruticosi*)	100	–	7	–	107

[1] Assessed 01/10/17 http://jncc.defra.gov.uk/page-5379 page updated 27/01/16

Appendix Table 2 – Potential climate change impacts on saltmarsh habitats taken from Natural England and RSPB (2014) pages 200-201.

Cause	Consequence	Potential Impacts
Sea level rise (taking account of isostatic changes)	Altered coastal dynamics and changes to the amount of sediment supplied	▪ The area of saltmarsh is likely to be reduced or lost. ▪ Where sediment loading is sufficient, rates of vertical accretion can keep pace with sea level rise (Hughes 2004; Mossman et al. 2013) ▪ Where space exists inland migration of saltmarsh can also take place, but this is restricted in many parts of England by hard sea defences.
	Increased frequency of inundation and water-logging	▪ Inundation and water-logging can result in an increased area of exposed mud, leading to greater susceptibility to invasive plants and erosion; increased water logging at low-tide; and potential impacts on soil processes and community composition (Davy et al. 2011).
	Increased erosion	▪ Erosion at seaward margin, with no sediment transfer higher into the marsh, can cause plants to die back. ▪ A steepening of the marsh and foreshore profile, which could lead to more wave energy reaching the saltmarsh (Mossman et al. 2013). ▪ A reduction in the area of saltmarsh where accretion is at a slower rate than sea level rise. ▪ Increased fragmentation and internal dissection as creeks erode.
	Potential construction of new sea defence, and existing hard defences maintained to higher standards	▪ A rise in flood defence standards could result in an existing sea wall being enlarged and encroaching directly on saltmarsh, while new defences could result in changes to sediment dynamics and lead to the accumulated destruction of marshes. The loss of fronting marsh will increase the wave energy reaching sea walls, with impacts on maintenance costs.
Increased annual average temperatures	Changes in the relative climate space available to saltmarsh species	▪ Changes to community composition with an increase in graminoid species over forbs (Gedan & Bertness, 2009). ▪ Potential loss of suitable climate space for some key saltmarsh species *e.g. Atriplex portulacoides, Puccinellia maritima* and *Suaeda maritima* (Holman & Loveland, 2001). ▪ *Frankenia laevis, Limonium vulgare, Limonium humile,* and *Spartina anglica* have the potential to expand from their current southerly distribution (Holman & Loveland, 2001; Mossman et al. 2013). ▪ *Atriplex portulacoides* is potentially the physiognomic dominant of saltmarsh and has been found to rapidly dominate some newly created managed realignments (Mossman, Davy & Grant, 2012). Expansion of this potentially dominant species may lead to a shift in community structure.
Hotter summers	Increased evaporation	▪ Increased salinity in the upper zones of marshes could result in changes to community composition and vegetative dieback (McKee et al. 2014).
Drier summers	Drought	▪ Drier conditions could lead to vegetative dieback in upper marshes, and changes in community composition due to competition from grassy species (Ewanchuk & Bertness, 2004).
In combination	Increased nutrient loading due to increased erosion and run-off from adjacent agricultural land	▪ Increased nutrient loading could lead to an increase in late-successional species and the dominance of graminoid species, such as *Elytrigia atherica* (van Wijen & Bakker, 1999; Bobbink & Hettelingh, 2011; Mossman et al. 2013)

Appendix Table 3 – Potential climate change impacts on sand dune habitats taken from Natural England and RSPB (2014) page 194.

Cause	Consequence	Potential Impacts
Sea level rise	Altered coastal dynamics	▪ Changes to the amount of sediment being supplied and removed from dunes.
Increased frequency of storms	Increased erosion	▪ Beach lowering and steepening of the foreshore. ▪ Changes in dune hydrology can affect the flow of water from dune slacks. ▪ Changes in shoreline position and dune system area are likely to affect sand stability, dune mobility, and groundwater levels and flow patterns, which in turn will affect the ecology of dune habitats. ▪ If beach plains are narrower or wetter there is likely to be less wind-blown sand. ▪ Species assemblages will change, affecting bird and mammal food sources. ▪ In combination with hard sea defences, coastal dynamics will change, with loss of sediment exchange between the beach plain and dune system; and a lowering of beach levels. This leads to increased wave energy causing more erosion to the dune face and net loss of habitat.
Higher annual average temperatures	Longer growing season	▪ Dune systems may become more stable due to warmer temperatures favouring growth of dune grasses and exacerbated by Nitrogen deposition (Mossman et al. 2013; Jones et al. 2008) increasing the rate of successional change. ▪ Increased stabilization of dune systems and soil development (Rees et al. 2010).
Drier summers	Drought	▪ Lower dune water-tables (Clarke & Sanitwong, 2010). The associated drying out of dune slacks would lead to the loss of specialist species. ▪ Increased drying of sand may lead to more wind-blown sand, leading to dune expansion, the creation of new blow-outs, and more early successional stage habitat.
Wetter winters	Wetter winters	▪ Wetter conditions could prevent beach plains from drying out. Wet sand is less likely to be moved by the wind which can affect dune processes and hence vegetation.

Appendix 2 Case Studies

Saltmarsh Sites

Appendix Table 4 - South Morecambe, Walney Island.

Site name:	South Morecambe	**County:**	Cumbria	**OS Grid Ref:**	SD19776464
Designations:	Morecambe Bay SAC, SPA & Ramsar; and South Walney and Piel Channel Flats SSSI				
Effected habitat:	Saltmarsh	**Length of affected habitat:**	600m	**Construction:**	1982-1983
Summary:	A gas pipeline installed using open trench techniques with the pipe buried to 2-3m. A causeway was built alongside the trench for vehicle access. Turves in the upper marsh were lifted and then were reinstated in June 1983 with turves from Silverdale Marshes. An EIA[2] was not undertaken, but planning conditions required a preliminary ecological survey of the site to be carried out and stipulated that the upper marsh should be returned to its former condition. No requirements were required to reinstate the lower marsh.				
Baseline	Pre-construction survey data was collected in 1981 (Rae, 1981). The survey used a grid sampling system across the upper marsh. 50 quadrats were sampled in upper saltmarsh (note the planning condition did not require sampling of lower saltmarsh). Vegetation cover was recorded as percentages along with cover of standing water and bare ground.				
Post-construction	A qualitative assessment of the progress of restoration was undertaken (Rae, 1983, Rae, 1984b, Rae, 1984c, Rae, 1984a). In addition, project notes were sourced from the Cumbria Area Team of Natural England. Vegetation recovery for South Morecambe pipeline is mentioned in North Morecambe documents.				

Appendix Table 5 - North Morecambe, Walney Island.

Site name:	North Morecambe	**County:**	Cumbria	**OS Grid Ref:**	SD20256397
Designations:	Morecambe Bay SAC, SPA & Ramsar; and South Walney and Piel Channel Flats SSSI				
Effected habitat:	Saltmarsh	**Length of affected habitat:**	615m	**Construction:**	1992-1993
Summary:	A gas pipeline connecting an offshore platform in the North Morecambe gas field with a new onshore terminal. Installation methods as South Morecambe. Turves were lifted prior to trenching and stored in an area of *Spartina*. These were reinstated after construction. Additional reinstatement of vehicle ruts was undertaken in 1992.				
Baseline	An EIA was undertaken in 1992 and included a baseline vegetation survey of the saltmarsh (George et al., 1992). These surveys covered the proposed 150m wide working width, and used three transects, each with seven quadrats) positioned in upper and lower saltmarsh. The % vegetation cover was recorded with notes on topography, presence of pools and standing water. The information is provided in baseline survey report (George et al., 1992).				
Post-construction	The original survey was repeated over 5 years following pipeline installation. This is reported in (Tittley and Huxley, 1998, Tittley et al., 1997, George et al., 1996, George et al., 1995, George et al., 1994)				

[2] Environmental Impact Assessment

Appendix Table 6 - Rivers Field Development, Walney Island.

Site name:	Rivers Field Development	**County:**	Cumbria	**OS Grid Ref:**	SD20856394
Designations:	Morecambe Bay SAC, SPA & Ramsar; and South Walney and Piel Channel Flats SSSI				
Effected habitat:	Saltmarsh	**Length of affected habitat:**	450m	**Construction:**	2003
Summary:	A gas pipeline connecting the gas terminal at Barrow-in-Furness with offshore gas fields in the eastern Irish Sea. The Environmental Statement notes that the position of the pipeline route was chosen to limit the amount of saltmarsh that would need to be removed during construction (*i.e.* the narrowest width) and that it encompassed an area of saltmarsh already partially degraded by an existing track. Installation methods followed those used for North Morecambe. Turves were lifted prior to trenching and were reinstated in 2003 after construction.				
Baseline	An EIA was submitted in 2002 (Burlington Resources (Irish Sea) Limited, 2002) and included an intertidal survey of the saltmarsh. A similar survey approach (as North Morecambe) was undertaken. Sixty quadrats were taken on grid system in upper, middle and lower saltmarsh communities and along the foot of the sea wall. Vegetation cover was recorded as percentages. The information is provided in baseline survey report (Bamber et al., 2002).				
Post-construction	The original survey was repeated over 2 years following pipeline installation. This is reported in (Evans et al., 2008, Evans et al., 2006).				

Appendix Table 7 - Thanet Offshore Wind Farm, Pegwell Bay, Thanet.

Site name:	Thanet Offshore Wind Farm	**County:**	Kent	**OS Grid Ref:**	TR34506380
Designations:	Thanet Coast and Sandwich Bay SPA and Ramsar, the Sandwich Bay SAC, the Sandwich Bay and Pegwell Bay National Nature Reserve (NNR) and the Sandwich Bay and Hacklinge Marshes SSSI.				
Effected habitat:	Saltmarsh	**Length of affected habitat:**	225m	**Construction:**	2010
Summary:	Thanet Offshore Wind Farm makes landfall at Pegwell Bay with two electricity cables crossing saltmarsh. Construction started in early 2010 following six years of planning and site investigations to inform the EIA. Several options for the cable lay process were assessed (Royal Haskoning, 2009), including open-cut trenching with turves lifted and then replaced and the use of a piece of trenching kit called the SpiderPlow.				
Baseline	In 2005, a Phase 1 Habitat survey was undertaken by Royal Haskoning of the onshore cable route. At this time the landfall was positioned further to the north (approximately 750m away). Consequently, no pre-construction data is available other than target notes describing the saltmarsh.				
Post-construction	Quadrats were undertaken in 2010 immediately after the installation of the cable (March 2010), with the surveys continuing monthly until August 2010. This information is not fully reported in the monitoring report (Royal Haskoning, 2010), but is summarised and photographs of each quadrat are provided. In August 2011 the survey was repeated (Royal Haskoning, 2011). This survey divided the area into four vegetation zones with a quadrat undertaken in each zone in affected areas and in the adjacent undisturbed areas. The report describes the difference in vegetation.				

Appendix Table 8 - Tetney Sealine Pipeline, Tetney Marshes, Lincolnshire.

Site name:	Tetney Sealine Pipe	**County:**	Lincolnshire	**OS Grid Ref:**	TA35160331
Designations:	Tetney Marshes forms part of the much larger Humber Estuary SAC, SPA and SSSI.				
Effected habitat:	Saltmarsh & sand dune	**Length of affected habitat:**	1250m	**Construction:**	1971
Summary:	In 1971, a crude oil pipeline was commissioned to run from an offshore mooring buoy in the Humber Estuary to an Oil Transfer Terminal at Tetney in Lincolnshire. The pipeline was the first offshore mooring pipelines to be constructed in the UK as reported in the Maritime Reporter at the time (Maritime Reporter and Engineering News, 1969). The pipeline crossed an area of saltmarsh and was constructed from a raised stone causeway built across the sand dunes. In 2013 permission was granted to replace the original pipeline (which had an original design life of 25 years) by Horizontal Direct Drilling under sand dunes situated 1.2km to the east (RPS, 2013). The new pipeline was installed in 2015 (and is not considered here). However, the original 1970's pipeline has been left in-situ along with the construction causeway, so to avoid damage to the saltmarsh and sand dunes which have established around it.				
Baseline	No information is available regarding the construction or assessment process.				
Post-construction	As far as it is understood, there was no specific surveys of the post-construction area. However, the RSPB undertook a survey in 1988 to inform site management (Burgess, 1988)and subsequently a detailed NVC survey was undertaken by Dargie in 2000 (Dargie, 2001).				

Appendix Table 9 - Inner Trial Bank, The Wash.

Site name:	Inner Trial Bank	**County:**	Norfolk	**OS Grid Ref:**	TF54282637
Designations:	The Wash and North Norfolk Coast SAC; three separate SPA's known as The Wash, North Norfolk Coast, and Gibraltar Point and The Wash SSSI & NNR				
Effected habitat:	Saltmarsh	Length of affected habitat:	615m	**Construction:**	1974-1975
Summary:	In 1971, the Government commissioned a study known as The Wash Storage Scheme to assess the feasibility of building a tidal barrage to capture freshwater across half of The Wash (Central Water Planning Unit, 1976). The idea was to capture freshwater from four rivers (the River Witham, the River Welland, the River Nene and the Great Ouse) to build a freshwater reservoir. This feasibility study was one of four similar assessments with the others at Morecambe Bay, the Solway Firth and the Dee Estuary (Corlett, 1978). As part of the feasibility study, approval to build two artificial islands (known as Outer and Inner Trial bank) approximately 3.2km off the Lincolnshire coast and 0.65km off the North Norfolk coast were given consent in November 1974 and construction started the following year. The results of the trial proved the scheme was financially unfeasible (costing £3 million at the time), and that the freshwater was too close to the tidal estuary to ensure low salinity and minimal silt levels. The trial was soon abandoned and the plans for the scheme shelved, however both the Inner and Outer Trail Bank reservoirs were left in-situ.				
Baseline	A number of ecology studies were undertaken by NERC[3] between 1972 and 1975 to assess the implications of the scheme (Natural Environment Research Council, 1976). A vegetation map was produced by examining aerial photographs, and surveys included 12 line transects along which vegetation and sediment accretion data was taken (Randerson (1975) reported in Hill (1988). In 1988, the survey was repeated as part of a wider survey of The Wash (Hill 1988).				
Post-construction	Hill (1988) undertook surveys across saltmarsh in The Wash. Survey area S6 provides a vegetation map of Inner Trial Bank; and survey point 39 records species along a transect (every 100m) near to the causeway. The data in the report is presented as habitat types *i.e.* with frequency/abundance data. Royal Haskoning (2003) repeated the Hill survey recording vegetation along transect N0D4 close to the causeway. Data is in the form of target notes, with no specific quadrat data. In 2012 RSK repeated both Hill and Royal Haskoning transects for NE (RSK, 2013b).				

Appendix Table 10 - Wytch Farm, Wareham, Poole, Dorset.

Site name:	Wytch Farm	**County:**	Dorset	**OS Grid Refs:**	See below

[3] Natural Environment Research Council

Designations:	Poole Harbour SPA and Ramsar and SSSI; and lies adjacent to the Dorset Heathlands SPA and Ramsar and Dorset Heaths (Purbeck and Wareham) Studland Dunes SAC				
Effected habitat:	Saltmarsh	**Length of affected habitat:**	355m across three sites	**Construction:**	1987-1988
Summary:	Three infield oil flowlines at Cleavel Point (SZ00258605), Shotover Moor (SY99388564), and Wytch Moor (SY98228547). Construction used open trench techniques, with turves lifted before trenching and matting used to protect sediment surface. Lifted turves were reinstated and planting of *Spartina* was used to minimise erosion.				
Baseline	An EIA was not undertaken, although the Institute of Terrestrial Ecology and Wytch Farm commissioned several studies to examine the impacts of pipeline construction across the Poole Harbour saltmarshes (Gray and Benham, 1986) and (Gray, 1985, Gray, 1986). These studies set out the baseline conditions and provided qualitative information as to the success of the reinstatement. As part of a recent EIA for pipeline reinstatement works (BP Exploration Operating Company Ltd, 2007) survey data was collected for the surrounding area including along the 1980s pipe.				
Post-construction	No post-construction survey data available for the three areas. However, as part of a recent application to replace sections of the pipeline across Wytch Moor, the vegetation either side of the causeway was subject to a NVC survey (Cook, 2012). The results of the survey were used to inform the Environmental Statement (Perenco UK, 2012).				

Sand Dunes

Appendix Table 11 - BP CATS, Redcar.

Site name:	BP (AMCO) CATS	**County:**	Teesside	**OS Grid Ref:**	NZ574025294
Designations:	Teesmouth & Cleveland Coast SPA & Ramsar; and South Gare & Coatham Common SSSI				
Effected habitat:	Sand dunes	**Length of affected habitat:**	560m	**Construction:**	1990-1991
Summary:	The Central Area Transmission System (CATS) gas pipeline links a gas platform in the Central North Sea with a processing terminal at Teesside.				
Baseline	As part of the ES[4] detailed botanical surveys (Appendix C: Terrestrial Ecology) were undertaken (Environmental Resources Limited, 1990). This included a general survey of the dune system at South Gare to determine the range of habitats and plant species present in the wider area; and a detailed survey of the dune system at Coatham Common lying within 50m of the proposed pipeline route. The detailed survey included 165 quadrats taken on a grid system across entire dunes in proposed pipeline corridor. Species abundance data was collected using the Domin-scale.				
Post-construction	The area was resurveyed in 1994 as part of a pipeline project that was not completed (Environmental Resources Management, 1994) and in 2010 as part of the Project Breagh project (RSK Carter Ecological, 2009). The 2010 survey used the NVC survey methods. Quadrat data was taken to support NVC mapping. Quadrats were taken in foredunes, dune crest, dune ridges, dune grassland, rough grassland and marshy grassland.				

[4] Environmental Statement

Appendix Table 12 - Project Breagh, Redcar.

Site name:	Project Breagh	**County:**	Teesside	**OS Grid Ref:**	NZ57502522
Designations:	Teesmouth & Cleveland Coast SPA & Ramsar; and South Gare & Coatham Common SSSI				
Effected habitat:	Sand dunes	**Length of affected habitat:**	560m	**Construction:**	2011-2012
Summary:	A gas pipeline installed across sand dunes using open cut techniques. The working width was constrained by the adjacent BP CATS pipeline and areas of dune slacks which were to be avoided. Plants were collected (in the form of seeds and plants) prior to work to be used to aid vegetation recovery, and these were sown/ replanted following works.				
Baseline	In 2009, a NVC survey was undertaken of the dune system (which also recorded habitats in the adjacent BP CATS pipeline). Quadrat data was taken to support NVC mapping. Quadrats taken in foredunes, dune crest, dune ridges, dune grassland, rough grassland and marshy grassland. The information is provided in baseline survey report (RSK Carter Ecological, 2009).				
Post-construction	Post-construction monitoring is available for 2012 (year 1), 2013 and 2014 (RSK 2012). Quadrat sampling using a survey grid was undertaken in the cable corridor and construction compound. For each quadrat (total 164 quadrats) an estimation of species abundance using the Domin-scale is provided.				

Appendix Table 13 - Teesside Offshore Wind Farm, Redcar

Site name:	Teesside Offshore Wind Farm	**County:**	Teesside	**OS Grid Ref:**	NZ57432588
Designations:	Teesmouth & Cleveland Coast SPA & Ramsar; and South Gare & Coatham Common SSSI				
Effected habitat:	Sand dunes	**Area of affected habitat:**	50m^2	**Construction:**	2012-2013
Summary:	Electricity cables were installed across sand dunes as part of an offshore wind farm. The cable was installed between 2012 and 2013 using HDD techniques as to avoid impacts on the dunes but a work compound was situated in an area of dune slacks. No restoration works were undertaken.				
Baseline	The ES for the project was originally submitted in 2004 (Entec, 2004a) and again in 2008 (Entec, 2008). The vegetation survey (Entec, 2004b) included a Phase 1 Habitat survey and NVC survey of the yellow and grey dunes, dune slacks and areas of slag from the adjacent steel works. This survey included quadrat sampling of the area surrounding the compound. This included 8 quadrat sample points where species were recorded along with Domin values. The previous Project Breagh surveys ((RSK Carter Ecological, 2009) also provide some quadrat data (10 sample points) from the vicinity of the compound, again these record species with Domin values.				
Post-construction	No post-construction survey data is available.				

Appendix Table 14 - Point of Ayr Pipeline, Talacre, Flintshire.

Site name:	Point of Ayr Pipeline Landfall	**County:**	Flintshire	**OS Grid Ref:**	SJ11088478
Designations:	The Dee Estuary Special Area of Conservation, Liverpool Bay Special Protection Area and Ramsar; and Gronant Dunes and Talacre Warren SSSI				
Effected habitat:	Sand dunes	**Length of affected habitat:**	460m	**Construction:**	1994
Summary:	Four parallel gas pipelines were installed linking gas reserves in Liverpool Bay with a processing terminal at Point of Ayr. The pipelines were buried to a depth of 2m. The pipeline construction used conventional trenching and pipe laying techniques *i.e.* a trench was dug, and the pipeline was winched offshore. The trench was backfilled, and the dune system reinstated *i.e.* the contours and vegetation. Following reinstatement, the dunes were subject to ongoing management as mitigation.				
Documents	This was followed by annual post construction monitoring completed between 1996 and 1999 ((Maldon Ecological Consultants, 1997, Maldon Ecological Consultants, 1998, Carter Ecological Limited, 1999, Carter Ecological Limited, 2000).				
Baseline	The ES was submitted in June 1993 (Environmental Resources Limited, 1993) and included a detailed botanical assessment of the dunes known as The Warren. The survey covered a larger area than was finally used to allow for route selection. This larger area was subject to species-listing with estimates of abundance using Dafors. This survey focused on 5 fore dune areas and 10 dune ridges areas. The fore dunes have since eroded and therefore the original data for this area cannot be used, but 7 of the dune ridge species-lists areas lie within/along the pipeline route. The dune grassland was surveyed using 20 quadrats and abundance data was collected using the Domin-scale.				
Post-construction	Quadrat sampling was undertaken across dune system in affected areas. The site was divided into three main areas - the Dune Ridge (with 8 sample blocks), the Dune Grassland (with 4 sample blocks) and the Sand Storage Area (with 9 line transects). The Dune Ridge and the Dune Grassland was surveyed in 1996, 1997 and 1999, whilst the Sand Storage Area was surveyed in 1999. Quadrat data was collected with a measure of frequency (1-9) using a sub-divided quadrat (Carter Ecological Limited, 2000, Carter Ecological Limited, 1999, Maldon Ecological Consultants, 1998, Maldon Ecological Consultants, 1997). The whole dune system was subject quadrat sampling in 2000 as part of a NVC survey, 278 quadrats were taken with Domin-values, but the locations of these quadrats is unknown.				

Appendix 3 Saltmarsh Supporting Data

Driftline

Appendix Table 15 - Results of General Linear Model, with sample area (factor) and distance from pipe (covariate) for driftline species.

Response	Factor	DF	F-Value	P-Value	Statistically Significant	Covariate	DF	F-Value	P-Value	Statistically Significant
Elytrigia atherica	Area	2	1.22	0.302	Not significant	Distance from Pipe	1	0.46	0.499	Not significant
Puccinellia maritima	Area	2	1.99	0.146	Not significant	Distance from Pipe	1	0.01	0.942	Not significant
Spartina anglica	Area	2	0.35	0.703	Not significant	Distance from Pipe	1	1.81	0.184	Not significant
Aster tripolium	Area	2	1.13	0.329	Not significant	Distance from Pipe	1	3.57	0.064	Not significant
Atriplex littoralis	Area	2	1.17	0.318	Not significant	Distance from Pipe	1	0.14	0.713	Not significant
Atriplex patula	Area	2	1.04	0.360	Not significant	Distance from Pipe	1	0.04	0.844	Not significant
Atriplex portulacoides	Area	2	1.82	0.171	Not significant	Distance from Pipe	1	0.28	0.602	Not significant
Atriplex prostrata	Area	2	0.73	0.486	Not significant	Distance from Pipe	1	0.39	0.535	Not significant
Cochlearia officinalis	Area	2	3.43	0.039	Significant	Distance from Pipe	1	0.93	0.339	Not significant
Limonium vulgare	Area	2	3.42	0.039	Significant	Distance from Pipe	1	0.00	0.944	Not significant
Plantago maritima	Area	2	2.57	0.085	Not significant	Distance from Pipe	1	0.21	0.652	Not significant
Salicornia agg.	Area	2	0.79	0.458	Not significant	Distance from Pipe	1	0.80	0.376	Not significant
Spergularia media	Area	2	0.99	0.377	Not significant	Distance from Pipe	1	2.36	0.130	Not significant
Suaeda maritima	Area	2	0.25	0.779	Not significant	Distance from Pipe	1	0.02	0.894	Not significant
Triglochin maritima	Area	2	4.02	0.023	Significant	Distance from Pipe	1	0.16	0.689	Not significant
Vegetation cover	Area	2	2.05	0.138	Not significant	Distance from Pipe	1	8.04	0.006	Significant
Cover of bare ground	Area	2	4.19	0.020	Significant	Distance from Pipe	1	9.12	0.004	Significant
Graminoid cover	Area	2	0.83	0.442	Not significant	Distance from Pipe	1	0.52	0.472	Not significant
Herb cover	Area	2	0.38	0.684	Not significant	Distance from Pipe	1	0.21	0.649	Not significant
Perennial cover	Area	2	9.68	0.002	Significant	Distance from Pipe	1	3.9	0.022	Significant
Annual/biennial cover	Area	2	1.92	0.150	Not significant	Distance from Pipe	1	5.17	0.024	Significant
Number of species	Area	2	2.21	0.120	Not significant	Distance from Pipe	1	0.17	0.680	Not significant
Simpsons Diversity Index	Area	2	0.30	0.742	Not significant	Distance from Pipe	1	0.03	0.866	Not significant
Shannon Diversity Index	Area	2	0.70	0.499	Not significant	Distance from Pipe	1	0.02	0.878	Not significant

Shannon Evenness	Area	2	0.22	0.802	Not significant	Distance from Pipe	1	0.03	0.867	Not significant
Margalef Diversity Index	Area	2	2.22	0.118	Not significant	Distance from Pipe	1	0.19	0.666	Not significant
Berger-Parker Dominance Index	Area	2	0.29	0.750	Not significant	Distance from Pipe	1	0.15	0.701	Not significant

Appendix Table 16 – Tukey Pairwise Comparison for significant driftline species using sample area.

Response	Sample Area	Difference of means	SE of difference	Simultaneous 95% CI		T-value	Adjusted P-value	Statistically Significant
Cochlearia officinalis	On-Off	0.1045	0.0485	-0.0122	0.2212	2.15	0.088	Not significant
Limonium vulgare	On-Off	0.221	0.123	-0.075	0.518	1.80	0.180	Not significant
Triglochin maritima	On-Off	0.303	0.179	-0.129	0.734	1.69	0.219	Not significant
Cover of bare ground	On-Off	0.572	0.249	-0.028	1.172	2.29	0.065	Not significant
Perennial cover	On-Off	-58.2	22	-110.2	-6.2	-2.65	0.024	Significant

Appendix Table 17 – Results of General Linear Model, with age class (factor) and distance from pipe (covariate) for driftline species.

Response	Factor	DF	F-Value	P-Value	Statistically Significant	Covariate	DF	F-Value	P-Value	Statistically Significant
Elytrigia atherica	Age Class	2	1.22	0.301	Not significant	Distance from Pipe	1	1.33	0.254	Not significant
Atriplex littoralis	Age Class	2	1.40	0.255	Not significant	Distance from Pipe	1	0.39	0.534	Not significant
Atriplex patula	Age Class	2	1.40	0.256	Not significant	Distance from Pipe	1	0.55	0.460	Not significant
Atriplex prostrata	Age Class	2	8.99	0.000	Significant	Distance from Pipe	1	0.27	0.608	Not significant
Cochlearia officinalis	Age Class	2	3.66	0.032	Significant	Distance from Pipe	1	1.39	0.244	Not significant
Lepidium latifolium	Age Class	2	0.85	0.431	Not significant	Distance from Pipe	1	0.13	0.720	Not significant
Triglochin maritima	Age Class	2	3.91	0.026	Significant	Distance from Pipe	1	0.02	0.885	Not significant
Vegetation cover	Age Class	2	9.18	0.000	Significant	Distance from Pipe	1	3.35	0.073	Not significant
Cover of bare ground	Age Class	2	23.23	0.000	Significant	Distance from Pipe	1	2.20	0.143	Not significant
Graminoid cover	Age Class	2	0.48	0.619	Not significant	Distance from Pipe	1	0.07	0.788	Not significant
Herb cover	Age Class	2	1.45	0.243	Not significant	Distance from Pipe	1	0.01	0.940	Not significant
Perennial cover	Age Class	3	1.76	0.157	Not significant	Distance from Pipe	1	7.67	0.006	Significant
Annual/biennial cover	Age Class	3	38.90	0.000	Significant	Distance from Pipe	1	25.97	0.000	Significant
Number of species	Age Class	3	2.78	0.070	Not significant	Distance from Pipe	1	0.41	0.525	Not significant
Simpsons Diversity Index	Age Class	3	4.38	0.017	Significant	Distance from Pipe	1	0.02	0.885	Not significant
Shannon Diversity Index	Age Class	3	3.46	0.038	Significant	Distance from Pipe	1	0.00	0.985	Not significant
Shannon Evenness	Age Class	3	4.11	0.021	Significant	Distance from Pipe	1	0.22	0.637	Not significant
Margalef Diversity Index	Age Class	3	2.84	0.067	Not significant	Distance from Pipe	1	0.44	0.511	Not significant

Berger-Parker Dominance Index	Age Class	3	5.25	0.008	Significant	Distance from Pipe	1	0.01	0.907	Not significant

Appendix Table 18 - Tukey Pairwise Comparison for driftline using age class.

Response	Difference of Age Class	Difference of means	SE of difference	Simultaneous 95% CI		T-value	Adjusted P-value	Statistically Significant
Atriplex prostrata	Short-Unaffected	0.202	0.144	-0.144	0.548	1.40	0.346	Not significant
Atriplex prostrata	Short-Long	-0.3109	0.0734	-0.4874	-0.1344	-4.23	0.000	Significant
Cochlearia officinalis	Short-Unaffected	0.1147	0.0428	0.0118	0.2177	2.68	0.026	Significant
Cochlearia officinalis	Long-Unaffected	0.1005	0.0401	0.0041	0.1968	2.51	0.039	Significant
Triglochin maritima	Short-Unaffected	0.443	0.159	0.06	0.825	2.78	0.020	Significant
Triglochin maritima	Long-Unaffected	0.378	0.149	0.02	0.737	2.54	0.036	Significant
Perennial cover	Short-Unaffected	86.9	11.4	57.3	116.4	7.63	0.000	Significant
Perennial cover	Medium-Unaffected	49.8	14.6	12.1	87.6	3.42	0.000	Significant
Perennial cover	Long-Unaffected	20.72	9.94	-5.07	46.52	2.08	0.162	Not significant
Annual/biennial cover	Short-Unaffected	-12.21	7.69	-32.18	7.76	-1.59	0.389	Not significant

Mid-upper Marsh

Appendix Table 19 - Results of General Linear Model, with sample area (factor) and distance from pipe (covariate) for mid-upper marsh species.

Response	Factor	DF	F-Value	P-Value	Statistically Significant	Covariate	DF	F-Value	P-Value	Statistically Significant
Agrostis stolonifera	Area	2	0.43	0.653	Not significant	Distance from Pipe	1	1.49	0.224	Not significant
Bolboschoenus maritimus	Area	2	5.45	0.005	Significant	Distance from Pipe	1	4.67	0.033	Significant
Elytrigia atherica	Area	2	2.08	0.130	Not significant	Distance from Pipe	1	0.09	0.765	Not significant
Festuca rubra	Area	2	4.34	0.015	Significant	Distance from Pipe	1	5.89	0.017	Significant
Juncus gerardii	Area	2	4.82	0.010	Significant	Distance from Pipe	1	23.15	0.000	Significant
Juncus maritimus	Area	2	1.14	0.324	Not significant	Distance from Pipe	1	8.84	0.004	Significant
Phragmites australis	Area	2	0.76	0.471	Not significant	Distance from Pipe	1	0.31	0.576	Not significant
Puccinellia maritima	Area	2	1.79	0.172	Not significant	Distance from Pipe	1	0.65	0.421	Not significant
Spartina anglica	Area	2	2.24	0.111	Not significant	Distance from Pipe	1	1.37	0.244	Not significant
Armeria maritima	Area	2	2.55	0.083	Not significant	Distance from Pipe	1	0.05	0.831	Not significant

Response	**Factor**	**DF**	**F-Value**	**P-Value**	**Statistically Significant**	**Covariate**	**DF**	**F-Value**	**P-Value**	**Statistically Significant**
Aster tripolium	Area	2	2.44	0.092	Not significant	Distance from Pipe	1	0.00	0.990	Not significant
Atriplex portulacoides	Area	2	1.89	0.155	Not significant	Distance from Pipe	1	3.85	0.052	Not significant
Atriplex prostrata	Area	2	0.18	0.834	Not significant	Distance from Pipe	1	0.68	0.412	Not significant
Cochlearia officinalis	Area	2	2.99	0.054	Not significant	Distance from Pipe	1	22.89	0.000	Significant
Limonium vulgare	Area	2	0.96	0.387	Not significant	Distance from Pipe	1	2.49	0.117	Not significant
Oenanthe lachenalii	Area	2	0.31	0.737	Not significant	Distance from Pipe	1	0.82	0.368	Not significant
Plantago maritima	Area	2	1.03	0.359	Not significant	Distance from Pipe	1	0.15	0.701	Not significant
Potentilla anserina	Area	2	0.28	0.759	Not significant	Distance from Pipe	1	1.67	0.199	Not significant
Salicornia agg.	Area	2	4.84	0.010	Significant	Distance from Pipe	1	0.18	0.675	Not significant
Spergularia media	Area	2	1.22	0.299	Not significant	Distance from Pipe	1	0.68	0.412	Not significant
Suaeda maritima	Area	2	0.75	0.473	Not significant	Distance from Pipe	1	1.87	0.174	Not significant
Triglochin maritima	Area	2	0.61	0.546	Not significant	Distance from Pipe	1	0.34	0.559	Not significant
Cover of Algae	Area	2	1.32	0.270	Not significant	Distance from Pipe	1	0.00	0.997	Not significant
Vegetation cover	Area	2	8.98	0.000	Significant	Distance from Pipe	1	8.71	0.004	Significant
Cover of bare ground	Area	2	12.84	0.000	Significant	Distance from Pipe	1	14.75	0.000	Significant
Graminoid cover	Area	2	0.09	0.916	Not significant	Distance from Pipe	1	2.71	0.102	Not significant
Herb cover	Area	2	0.60	0.549	Not significant	Distance from Pipe	1	0.42	0.516	Not significant
Perennial cover	Area	2	10.63	0.000	Significant	Distance from Pipe	1	4.63	0.033	Significant
Annual/biennial cover	Area	2	0.82	0.444	Not significant	Distance from Pipe	1	36.35	0.000	Significant
Number of species	Area	2	2.36	0.099	Not significant	Distance from Pipe	1	0.66	0.419	Not significant
Simpsons Diversity Index	Area	2	1.69	0.189	Not significant	Distance from Pipe	1	0.91	0.341	Not significant
Shannon Diversity Index	Area	2	1.63	0.200	Not significant	Distance from Pipe	1	0.27	0.603	Not significant
Shannon Evenness	Area	2	0.84	0.434	Not significant	Distance from Pipe	1	0.26	0.609	Not significant
Margalef Diversity Index	Area	2	2.85	0.062	Not significant	Distance from Pipe	1	0.16	0.690	Not significant
Berger-Parker Dominance Index	Area	2	2.82	0.064	Not significant	Distance from Pipe	1	2.95	0.089	Not significant

Appendix Table 20 - Tukey Pairwise Comparison for mid-upper marsh using sample area.

Response	Sample Area	Difference of means	SE of difference	Simultaneous 95% CI		T-value	Adjusted P-value	Statistically Significant
Bolboschoenus maritimus	On-Off	0.513	0.17	0.109	0.916	3.02	0.009	Significant
Festuca rubra	On-Off	-0.733	0.285	-1.409	-0.056	-2.57	0.030	Significant
Juncus gerardii	On-Off	-0.611	0.236	-1.171	-0.051	-2.59	0.029	Significant
Cochlearia officinalis	On-Off	-0.1669	0.0684	-0.3294	-0.0045	-2.44	0.042	Significant
Vegetation cover	On-Off	-0.0407	0.0302	-0.1125	0.0311	-1.35	0.372	Not significant
Cover of bare ground	On-Off	0.408	0.222	-0.119	0.935	1.84	0.620	Not significant
Perennial cover	On-Off	0.82	6.58	-14.81	16.45	0.13	0.991	Not significant

Appendix Table 21 - Results of General Linear Model, with age class (factor) and distance from pipe (covariate) for mid-upper marsh species.

Response	Factor	DF	F-Value	P-Value	Statistically Significant	Covariate	DF	F-Value	P-Value	Statistically Significant
Agrostis stolonifera	Age Class	3	2.66	0.051	Not significant	Distance from Pipe	1	1.42	0.236	Not significant
Bolboschoenus maritimus	Age Class	3	3.29	0.023	Significant	Distance from Pipe	1	3.74	0.056	Not significant
Festuca rubra	Age Class	3	7.09	0.000	Significant	Distance from Pipe	1	2.60	0.110	Not significant
Juncus gerardii	Age Class	3	0.55	0.648	Not significant	Distance from Pipe	1	14.06	0.000	Significant
Juncus maritimus	Age Class	3	0.53	0.665	Not significant	Distance from Pipe	1	6.79	0.010	Significant
Puccinellia maritima	Age Class	3	16.75	0.000	Significant	Distance from Pipe	1	0.00	0.981	Not significant
Spartina anglica	Age Class	3	5.98	0.001	Significant	Distance from Pipe	1	0.07	0.790	Not significant
Armeria maritima	Age Class	3	3.37	0.021	Significant	Distance from Pipe	1	2.07	0.153	Not significant
Aster tripolium	Age Class	3	25.51	0.000	Significant	Distance from Pipe	1	0.00	0.975	Not significant
Atriplex portulacoides	Age Class	3	8.16	0.000	Significant	Distance from Pipe	1	2.13	0.147	Not significant
Cochlearia officinalis	Age Class	3	1.47	0.225	Not significant	Distance from Pipe	1	21.29	0.000	Significant
Glaux maritima	Age Class	3	2.36	0.076	Not significant	Distance from Pipe	1	0.16	0.691	Not significant
Limonium vulgare	Age Class	3	7.20	0.000	Significant	Distance from Pipe	1	8.37	0.005	Significant
Plantago coronopus	Age Class	3	1.20	0.313	Not significant	Distance from Pipe	1	1.10	0.296	Not significant
Plantago maritima	Age Class	3	2.09	0.105	Not significant	Distance from Pipe	1	0.00	0.950	Not significant
Salicornia agg.	Age Class	3	6.78	0.000	Significant	Distance from Pipe	1	3.92	0.050	Significant
Spergularia media	Age Class	3	11.41	0.000	Significant	Distance from Pipe	1	4.79	0.031	Significant
Triglochin maritima	Age Class	3	12.28	0.000	Significant	Distance from Pipe	1	0.58	0.447	Not significant

Response	Factor	DF	F-Value	P-Value	Statistically Significant	Covariate	DF	F-Value	P-Value	Statistically Significant
Vegetation cover	Age Class	3	6.65	0.000	Significant	Distance from Pipe	1	17.61	0.000	Significant
Cover of bare ground	Age Class	3	6.60	0.000	Significant	Distance from Pipe	1	27.12	0.000	Significant
Graminoid cover	Age Class	3	6.40	0.000	Significant	Distance from Pipe	1	5.44	0.021	Significant
Herb cover	Age Class	3	4.35	0.006	Significant	Distance from Pipe	1	2.77	0.099	Not significant
Perennial cover	Age Class	3	7.04	0.000	Significant	Distance from Pipe	1	15.74	0.000	Significant
Annual/biennial cover	Age Class	3	5.07	0.002	Significant	Distance from Pipe	1	50.79	0.000	Significant
Number of species	Age Class	3	2.16	0.096	Not significant	Distance from Pipe	1	0.18	0.674	Not significant
Simpsons Diversity Index	Age Class	3	0..60	0.614	Not significant	Distance from Pipe	1	0.06	0.815	Not significant
Shannon Diversity Index	Age Class	3	1.02	0.386	Not significant	Distance from Pipe	1	0.08	0.783	Not significant
Shannon Evenness	Age Class	3	3.32	0.022	Not significant	Distance from Pipe	1	0.02	0.902	Not significant
Margalef Diversity Index	Age Class	3	1.94	0.128	Not significant	Distance from Pipe	1	0.91	0.343	Not significant
Berger-Parker Dominance Index	Age Class	3	4.19	0.008	Not significant	Distance from Pipe	1	0.44	0.507	Not significant

Appendix Table 22 - Tukey Pairwise Comparison for mid-upper marsh using age class.

Response	Difference of Age Class	Difference of means	SE of difference	Simultaneous 95% CI		T-value	Adjusted P-value	Statistically Significant
Bolboschoenus maritimus	Short-Unaffected	0.414	0.156	0.007	0.822	2.65	0.044	Significant
Bolboschoenus maritimus	Medium-Unaffected	0.39	0.152	-0.006	0.787	2.57	0.055	Not significant
Bolboschoenus maritimus	Long-Unaffected	0.414	0.14	0.0048	0.78	2.95	0.020	Significant
Puccinellia maritima	Short-Unaffected	-1.109	0.261	-1.79	-0.427	-4.25	0.000	Significant
Spartina anglica	Short-Unaffected	-0.376	0.159	-0.791	0.04	-2.36	0.091	Not significant
Armeria maritima	Short-Unaffected	0.267	0.139	-0.096	0.631	1.92	0.227	Not significant
Aster tripolium	Short-Unaffected	-0.364	0.13	-0.702	-0.026	-2.81	0.030	Significant
Aster tripolium	Medium-Unaffected	-0.707	0.126	-1.036	-0.378	-5.61	0.000	Significant
Atriplex portulacoides	Short-Unaffected	-0.041	0.195	-0.551	0.468	-0.21	0.997	Not significant
Atriplex portulacoides	Medium-Unaffected	-0.759	0.19	-1.254	-0.263	-3.99	0.001	Significant
Cochlearia officinalis	Short-Unaffected	-0.1138	0.063	-0.2782	0.0506	-1.81	0.276	Not significant
Limonium vulgare	Short-Unaffected	0.577	0.197	0.065	1.09	2.94	0.021	Significant
Salicornia agg.	Short-Unaffected	-0.332	0.135	-0.684	0.02	-2.46	0.071	Not significant
Spergularia media	Short-Unaffected	-0.1374	0.0696	-0.0319	0.0443	-1.97	0.204	Not significant
Spergularia media	Medium-Unaffected	-0.1752	0.0677	-0.352	0.0015	-2.59	0.053	Not significant
Triglochin maritima	Short-Unaffected	0.333	0.218	-0.236	0.902	1.53	0.424	Not significant
Triglochin maritima	Medium-Unaffected	-0.697	0.212	-1.25	-0.143	-3.29	0.007	Significant

Response	Difference of Age Class	Difference of means	SE of difference	Simultaneous 95% CI		T-value	Adjusted P-value	Statistically Significant
Vegetation cover	Short-Unaffected	-0.0447	0.0275	-0.1163	0.027	-1.63	0.368	Not significant
Vegetation cover	Medium-Unaffected	-0.1032	0.0267	-0.1728	-0.0335	-3.86	0.001	Significant
Vegetation cover	Long-Unaffected	-0.0882	0.0246	-0.1525	-0.0239	-3.58	0.003	Significant
Cover of bare ground	Short-Unaffected	0.672	0.207	0.13	1.213	3.24	0.008	Significant
Cover of bare ground	Medium-Unaffected	0.832	0.202	0.305	1.359	4.12	0.000	Significant
Cover of bare ground	Long-Unaffected	0.735	0.186	0.249	1.221	3.95	0.001	Significant
Graminoid cover	Short-Unaffected	-0.464	0.196	-0.976	0.048	-2.37	0.090	Not significant
Perennial cover	Short-Unaffected	-4.49	6.04	-20.25	11.26	-0.74	0.879	Not significant
Perennial cover	Medium-Unaffected	-19.5	5.46	-33.75	-5.24	-3.57	0.003	Significant
Perennial cover	Long-Unaffected	-17.47	5.79	-32.59	-2.36	-3.02	0.016	Significant
Annual/biennial cover	Short-Unaffected	22.99	9.02	-0.54	46.52	2.55	0.058	Not significant

Low-mid Marsh

Appendix Table 23 - Results of General Linear Model, with sample area (factor) and distance from pipe (covariate) for low-mid marsh species.

Response	Factor	DF	F-Value	P-Value	Statistically Significant	Covariate	DF	F-Value	P-Value	Statistically Significant
Elytrigia atherica	Area	2	1.86	0.158	Not significant	Distance from Pipe	1	2.48	0.116	Not significant
Puccinellia maritima	Area	2	0.87	0.418	Not significant	Distance from Pipe	1	0.15	0.698	Not significant
Spartina anglica	Area	2	7.52	0.001	Significant	Distance from Pipe	1	22.65	0.000	Significant
Aster tripolium	Area	2	4.55	0.011	Significant	Distance from Pipe	1	10.73	0.001	Significant
Atriplex portulacoides	Area	2	9.82	0.000	Significant	Distance from Pipe	1	10.41	0.000	Significant
Atriplex prostrata	Area	2	1.14	0.320	Not significant	Distance from Pipe	1	2.50	0.115	Not significant
Cochlearia officinalis	Area	2	3.31	0.038	Significant	Distance from Pipe	1	6.97	0.009	Significant
Limonium vulgare	Area	2	1.76	0.174	Not significant	Distance from Pipe	1	4.81	0.029	Significant
Plantago maritima	Area	2	1.61	0.202	Not significant	Distance from Pipe	1	0.13	0.724	Not significant
Salicornia agg.	Area	2	3.22	0.041	Significant	Distance from Pipe	1	2.19	0.140	Not significant
Spergularia media	Area	2	0.34	0.712	Not significant	Distance from Pipe	1	0.64	0.424	Not significant
Suaeda maritima	Area	2	0.82	0.440	Not significant	Distance from Pipe	1	1.53	0.217	Not significant
Triglochin maritima	Area	2	2.50	0.084	Not significant	Distance from Pipe	1	12.07	0.001	Significant

Response	Factor	DF	F-Value	P-Value	Statistically Significant	Covariate	DF	F-Value	P-Value	Statistically Significant
Cover of Algae	Area	2	8.20	0.000	Significant	Distance from Pipe	1	4.16	0.042	Significant
Vegetation cover	Area	2	1.52	0.221	Not significant	Distance from Pipe	1	0.03	0.856	Not significant
Cover of bare ground	Area	2	14.90	0.000	Significant	Distance from Pipe	1	19.03	0.000	Significant
Graminoid cover	Area	2	0.31	0.736	Not significant	Distance from Pipe	1	4.83	0.029	Significant
Herb cover	Area	2	4.16	0.017	Significant	Distance from Pipe	1	5.87	0.016	Significant
Perennial cover	Area	2	6.01	0.003	Significant	Distance from Pipe	1	1.21	0.272	Not significant
Annual/biennial cover	Area	2	1.90	0.151	Not significant	Distance from Pipe	1	381.18	0.000	Significant
Number of species	Area	2	0.71	0.495	Not significant	Distance from Pipe	1	1.20	0.273	Not significant
Simpsons Diversity Index	Area	2	1.98	0.140	Not significant	Distance from Pipe	1	2.29	0.131	Not significant
Shannon Diversity Index	Area	2	1.69	0.185	Not significant	Distance from Pipe	1	2.40	0.122	Not significant
Shannon Evenness	Area	2	2.51	0.083	Not significant	Distance from Pipe	1	1.98	0.160	Not significant
Margalef Diversity Index	Area	2	0.58	0.558	Not significant	Distance from Pipe	1	1.11	0.292	Not significant
Berger-Parker Dominance Index	Area	2	1.62	0.199	Not significant	Distance from Pipe	1	1.98	0.160	Not significant

Appendix Table 24 - Tukey Pairwise Comparison for low-mid marsh using sample area.

Response	Sample Area	Difference of means	SE of difference	Simultaneous 95% CI		T-value	Adjusted P-value	Statistically Significant
Spartina anglica	On-Off	-0.936	0.243	-1.505	-0.366	-3.85	0.000	Significant
Aster tripolium	On-Off	0.419	0.141	0.09	0.748	2.98	0.008	Significant
Atriplex portulacoides	On-Off	1.081	0.254	0.486	1.676	4.25	0.000	Significant
Cochlearia officinalis	On-Off	-0.1182	0.0509	-0.2372	0.0009	-2.32	0.053	Not significant
Salicornia agg.	On-Off	-0.519	0.205	-1	-0.039	-2.53	0.030	Significant
Cover of Algae	On-Off	-0.52	0.158	-0.889	-0.15	-3.29	0.003	Significant
Cover of bare ground	On-Off	-1.296	0.239	-1.855	-0.737	-5.43	0.000	Significant
Herb cover	On-Off	0.511	0.212	0.016	1.006	2.42	0.042	Significant
Perennial cover	On-Off	-41.3	12.3	-70.2	-12.5	-3.35	0.000	Significant

Appendix Table 25 - Results of General Linear Model, with age class (factor) and distance from pipe (covariate) for low-mid marsh species.

Response	Factor	DF	F-Value	P-Value	Statistically Significant	Covariate	DF	F-Value	P-Value	Statistically Significant
Puccinellia maritima	Age Class	3	3.61	0.014	Significant	Distance from Pipe	1	0.16	0.687	Not significant
Spartina anglica	Age Class	3	37.17	0.000	Significant	Distance from Pipe	1	10.03	0.002	Significant
Aster tripolium	Age Class	3	10.00	0.000	Significant	Distance from Pipe	1	1.46	0.228	Not significant
Atriplex portulacoides	Age Class	3	6.77	0.000	Significant	Distance from Pipe	1	0.43	0.513	Not significant
Atriplex prostrata	Age Class	3	6.40	0.000	Significant	Distance from Pipe	1	0.58	0.447	Not significant
Cochlearia officinalis	Age Class	3	3.01	0.031	Significant	Distance from Pipe	1	1.52	0.219	Not significant
Limonium vulgare	Age Class	3	7.34	0.000	Significant	Distance from Pipe	1	2.17	0.141	Not significant
Plantago maritima	Age Class	3	1.60	0.189	Not significant	Distance from Pipe	1	0.39	0.535	Not significant
Salicornia agg.	Age Class	3	18.46	0.000	Significant	Distance from Pipe	1	0.22	0.641	Not significant
Spergularia media	Age Class	3	4.72	0.003	Significant	Distance from Pipe	1	0.86	0.354	Not significant
Suaeda maritima	Age Class	3	6.08	0.000	Significant	Distance from Pipe	1	0.79	0.374	Not significant
Cover of Algae	Age Class	3	9.46	0.000	Significant	Distance from Pipe	1	3.29	0.070	Not significant
Vegetation cover	Age Class	3	17.03	0.000	Significant	Distance from Pipe	1	0.90	0.345	Not significant
Cover of bare ground	Age Class	3	22.12	0.000	Significant	Distance from Pipe	1	2.44	0.119	Not significant
Graminoid cover	Age Class	3	9.80	0.000	Significant	Distance from Pipe	1	2.45	0.118	Not significant
Herb cover	Age Class	3	2.29	0.078	Not significant	Distance from Pipe	1	0.15	0.695	Not significant
Perennial cover	Age Class	3	23.64	0.000	Significant	Distance from Pipe	1	1.06	0.305	Not significant
Annual/biennial cover	Age Class	3	2.37	0.071	Not significant	Distance from Pipe	1	546.93	0.000	Significant
Number of species	Age Class	3	1.12	0.343	Not significant	Distance from Pipe	1	3.55	0.06	Not significant
Simpsons Diversity Index	Age Class	3	3.29	0.021	Significant	Distance from Pipe	1	3.13	0.078	Not significant
Shannon Diversity Index	Age Class	3	2.05	0.107	Not significant	Distance from Pipe	1	3.68	0.056	Not significant
Shannon Evenness	Age Class	3	4.55	0.004	Significant	Distance from Pipe	1	2.22	0.137	Not significant
Margalef Diversity Index	Age Class	3	0.71	0.548	Not significant	Distance from Pipe	1	2.09	0.150	Not significant
Berger-Parker Dominance Index	Age Class	3	3.06	0.028	Not significant	Distance from Pipe	1	2.49	0.116	Not significant

Appendix Table 26 - Tukey Pairwise Comparison for low-mid marsh using age class.

Response	Difference of Age Class	Difference of means	SE of difference	Simultaneous 95% CI		T-value	Adjusted P-value	Statistically Significant
Spartina anglica	Short-Unaffected	-0.229	0.156	-0.63	0.172	-1.47	0.457	Not significant

Spartina anglica	Medium-Unaffected	-0.728	0.137	-1.079	-0.377	-5.33	0.000	Significant
Aster tripolium	Short-Unaffected	-0.1404	0.0992	-0.3951	0.1143	-1.42	0.490	Not significant
Atriplex portulacoides	Short-Unaffected	0.458	0.184	-0.015	0.931	2.49	0.062	Not significant
Atriplex portulacoides	Medium-Unaffected	0.392	0.161	-0.021	0.805	2.43	0.071	Not significant
Limonium vulgare	Short-Unaffected	0.0411	0.0815	-0.1681	0.2502	0.50	0.958	Not significant
Limonium vulgare	Medium-Unaffected	-0.1984	0.0713	-0.3813	-0.0155	-2.78	0.028	Significant
Salicornia agg.	Short-Unaffected	-0.526	0.139	-0.883	-0.168	-3.78	0.001	Significant
Salicornia agg.	Medium-Unaffected	-0.338	0.122	-0.65	-0.025	-2.78	0.028	Significant
Cover of Algae	Short-Unaffected	0.284	0.113	-0.005	0.573	2.52	0.057	Not significant
Perennial cover	Short-Unaffected	33.36	8.28	12.11	54.61	4.03	0.000	Significant
Perennial cover	Medium-Unaffected	18.96	7.1	0.73	37.18	2.67	0.038	Significant
Perennial cover	Long-Unaffected	-14.71	7.66	-34.37	4.94	-1.92	0.219	Not significant
Annual/biennial cover	Short-Unaffected	-1.69	2.81	-8.92	5.53	-0.60	0.931	Not significant

Pioneer Marsh

Appendix Table 27 - Results of General Linear Model, with sample area (factor) and distance from pipe (covariate) for pioneer species.

Response	**Factor**	**DF**	**F-Value**	**P-Value**	**Statistically Significant**	**Covariate**	**DF**	**F-Value**	**P-Value**	**Statistically Significant**
Puccinellia maritima	Area	2	1.04	0.357	Not significant	Distance from Pipe	1	0.18	0.671	Not significant
Spartina anglica	Area	2	1.54	0.218	Not significant	Distance from Pipe	1	1.26	0.263	Not significant
Aster tripolium	Area	2	0.98	0.377	Not significant	Distance from Pipe	1	0.76	0.386	Not significant
Atriplex portulacoides	Area	2	0.56	0.572	Not significant	Distance from Pipe	1	0.05	0.830	Not significant
Limonium vulgare	Area	2	2.79	0.065	Not significant	Distance from Pipe	1	2.10	0.149	Not significant
Salicornia agg.	Area	2	5.64	0.004	Significant	Distance from Pipe	1	19.35	0.000	Significant
Suaeda maritima	Area	2	3.64	0.029	Significant	Distance from Pipe	1	5.37	0.022	Significant
Cover of Algae	Area	2	1.69	0.188	Not significant	Distance from Pipe	1	1.81	0.180	Not significant
Vegetation cover	Area	2	0.55	0.579	Not significant	Distance from Pipe	1	0.38	0.540	Not significant
Cover of bare ground	Area	2	2.83	0.062	Not significant	Distance from Pipe	1	5.51	0.020	Significant
Graminoid cover	Area	2	2.33	0.101	Not significant	Distance from Pipe	1	2.75	0.099	Not significant
Herb cover	Area	2	3.91	0.022	Significant	Distance from Pipe	1	8.33	0.004	Significant

Perennial cover	Area	2	2.04	0.139	Not significant	Distance from Pipe	1	2.37	0.129	Not significant
Annual/biennial cover	Area	2	0.98	0.383	Not significant	Distance from Pipe	1	0.01	0.813	Not significant
Number of species	Area	2	3.82	0.024	Significant	Distance from Pipe	1	6.98	0.009	Significant
Simpsons Diversity Index	Area	2	5.48	0.005	Significant	Distance from Pipe	1	13.55	0.000	Significant
Shannon Diversity Index	Area	2	5.86	0.003	Significant	Distance from Pipe	1	12.30	0.001	Significant
Shannon Evenness	Area	2	3.20	0.043	Significant	Distance from Pipe	1	11.72	0.001	Significant
Berger-Parker Dominance Index	Area	2	5.08	0.007	Significant	Distance from Pipe	1	8.53	0.004	Significant

Appendix Table 28 - Tukey Pairwise Comparison for pioneer marsh using sample area.

Response	Sample Area	Difference of means	SE of difference	Simultaneous 95% CI		T-value	Adjusted P-value	Statistically Significant
Salicornia agg.	On-Off	-1.116	0.343	-1.929	-0.304	-3.26	0.004	Significant
Suaeda maritima	On-Off	-0.477	0.251	-1.072	0.117	-1.90	0.141	Not significant
Cover of bare ground	On-Off	-0.922	0.387	-1.839	-0.004	-2.38	0.048	Significant
Herb cover	On-Off	-0.848	0.413	-1.826	0.131	-2.05	0.103	Not significant
Number of species	On-Off	-2.23	1.02	-4.64	0.19	-2.19	0.077	Not significant
Simpsons Diversity Index	On-Off	-0.387	0.156	-0.758	-0.017	-2.47	0.038	Significant
Shannon Diversity Index	On-Off	-0.654	0.259	-1.267	-0.040	-2.52	0.034	Significant
Shannon Evenness	On-Off	-0.399	0.190	-0.850	0.051	-2.10	0.093	Not significant
Berger-Parker Dominance Index	On-Off	0.222	0.118	-0.058	0.502	1.88	0.148	Not significant

Appendix Table 29 - Results of General Linear Model, with age class (factor) and distance from pipe (covariate) for pioneer species.

Response	Factor	DF	F-Value	P-Value	Statistically Significant	Covariate	DF	F-Value	P-Value	Statistically Significant
Puccinellia maritima	Age Class	2	12.83	0.000	Significant	Distance from Pipe	1	1.77	0.185	Not significant
Spartina anglica	Age Class	2	13.74	0.000	Significant	Distance from Pipe	1	8.11	0.005	Significant
Aster tripolium	Age Class	2	1.04	0.356	Not significant	Distance from Pipe	1	0.02	0.875	Not significant
Salicornia agg.	Age Class	2	4.63	0.011	Significant	Distance from Pipe	1	18.79	0.000	Significant
Suaeda maritima	Age Class	2	13.85	0.000	Significant	Distance from Pipe	1	7.33	0.007	Significant
Cover of Algae	Age Class	2	0.99	0.373	Not significant	Distance from Pipe	1	0.28	0.598	Not significant
Vegetation cover	Age Class	2	70.68	0.000	Significant	Distance from Pipe	1	5.84	0.017	Significant
Cover of bare ground	Age Class	2	15.88	0.000	Significant	Distance from Pipe	1	4.11	0.044	Significant
Graminoid cover	Age Class	2	43.81	0.000	Significant	Distance from Pipe	1	15.79	0.000	Significant

Response	Factor	DF	F-Value	P-Value	Statistically Significant	Covariate	DF	F-Value	P-Value	Statistically Significant
Herb cover	Age Class	2	8.22	0.000	Significant	Distance from Pipe	1	10.29	0.002	Significant
Perennial cover	Age Class	2	4.76	0.012	Significant	Distance from Pipe	1	0.07	0.789	Not significant
Annual/biennial cover	Age Class	2	1.01	0.372	Not significant	Distance from Pipe	1	0.3	0.584	Not significant
Number of species	Age Class	2	22.70	0.000	Significant	Distance from Pipe	1	7.50	0.007	Significant
Simpsons Diversity Index	Age Class	2	5.86	0.003	Significant	Distance from Pipe	1	19.53	0.000	Significant
Shannon Diversity Index	Age Class	2	10.98	0.000	Significant	Distance from Pipe	1	17.03	0.000	Significant
Shannon Evenness	Age Class	2	2.94	0.056	Not significant	Distance from Pipe	1	14.17	0.000	Significant
Margalef Diversity Index	Age Class	2	12.19	0.000	Significant	Distance from Pipe	1	17.68	0.000	Significant
Berger-Parker Dominance Index	Age Class	2	8.81	0.000	Significant	Distance from Pipe	1	9.28	0.003	Significant

Appendix Table 30 - Tukey Pairwise Comparison for pioneer marsh using age class.

Response	Difference of Age Class	Difference of means	SE of difference	Simultaneous 95% CI		T-value	Adjusted P-value	Statistically Significant
Puccinellia maritima	Short-Unaffected	0.276	0.242	-0.298	0.851	1.14	0.491	Not significant
Puccinellia maritima	Short-Long	-0.655	0.134	-0.972	-0.337	-4.89	0.000	Significant
Spartina anglica	Short-Unaffected	0.965	0.258	0.354	1.577	3.74	0.001	Significant
Spartina anglica	Short-Long	0.965	0.258	0.354	1.577	3.74	0.001	Significant
Salicornia agg.	Short-Unaffected	-0.672	0.221	-1.196	-0.149	-3.04	0.008	Significant
Salicornia agg.	Long-Unaffected	-0.496	0.196	-0.96	-0.033	-2.54	0.032	Significant
Suaeda maritima	Short-Unaffected	-0.073	0.15	-0.43	0.283	-0.49	0.878	Not significant
Suaeda maritima	Long-Unaffected	-0.438	0.133	-0.754	-0.123	-3.29	0.004	Significant
Vegetation cover	Short-Unaffected	1.252	0.181	0.823	1.681	6.91	0.000	Significant
Cover of bare ground	Short-Unaffected	-0.937	0.235	-1.494	-0.38	-3.99	0.000	Significant
Graminoid cover	Short-Unaffected	1.502	0.228	0.963	2.041	6.60	0.000	Significant
Herb cover	Short-Unaffected	-0.208	0.26	-0.825	0.409	-0.80	0.705	Not significant
Herb cover	Long-Unaffected	-0.658	0.231	-1.204	-0.112	-2.85	0.014	Significant
Perennial cover	Short-Unaffected	7.52	5.06	-4.63	19.68	1.49	0.304	Not significant
Annual/biennial cover	Short-Unaffected	-5.46	4.87	-17.17	6.24	-1.120	0.504	Not significant
Number of species	Short-Long	-1.968	0.325	-2.739	-1.197	-6.05	0.000	Significant
Number of species	Short-Unaffected	0.135	0.589	-1.261	1.531	0.23	0.972	Not significant
Simpsons Diversity Index	Short-Long	-0.074	0.055	-0.205	0.056	-1.35	0.369	Not significant
Simpsons Diversity Index	Short-Unaffected	-0.213	0.099	-0.449	0.023	-2.14	0.086	Not significant

Response	Difference of Age Class	Difference of means	SE of difference	Simultaneous 95% CI		T-value	Adjusted P-value	Statistically Significant
Shannon Diversity Index	Short-Long	-0.288	0.088	-0.498	-0.077	-3.24	0.004	Significant
Shannon Diversity Index	Short-Unaffected	-0.234	0.161	-0.615	0.147	-1.45	0.316	Not significant
Shannon Evenness	Short-Long	-0.077	0.067	-2.384	0.829	-1.15	0.487	Not significant
Shannon Evenness	Short-Unaffected	-0.165	0.123	-0.456	0.126	-1.34	0.374	Not significant
Margalef Diversity Index	Short-Long	-0.250	0.078	-0.435	-0.066	-3.21	0.005	Significant
Margalef Diversity Index	Short-Unaffected	-0.253	0.141	-0.588	0.082	-1.79	0.176	Not significant
Berger-Parker Dominance Index	Short-Long	-0.174	0.053	-0.300	-0.048	-3.28	0.004	Significant
Berger-Parker Dominance Index	Short-Unaffected	0.370	0.096	0.143	0.598	3.85	0.000	Significant

Appendix 4 Sand Dunes Supporting Data

Embryo/ Mobile Dunes

Appendix Table 31 - Results of General Linear Model, with sample area (factor) and distance from pipe (covariate) for embryo/ mobile dune species.

Response	Factor	DF	F-Value	P-Value	Statistically Significant	Covariate	DF	F-Value	P-Value	Statistically Significant
Agrostis stolonifera	Area	2	0.06	0.946	Not significant	Distance from Pipe	1	0.23	0.635	Not significant
Ammophila arenaria	Area	2	1.74	0.196	Not significant	Distance from Pipe	1	3.94	0.058	Not significant
Arrhenatherum elatius	Area	2	0.36	0.701	Not significant	Distance from Pipe	1	0.50	0.485	Not significant
Carex arenaria	Area	2	1.26	0.302	Not significant	Distance from Pipe	1	0.70	0.412	Not significant
Elytrigia juncea	Area	2	0.71	0.503	Not significant	Distance from Pipe	1	2.56	0.122	Not significant
Festuca arenaria	Area	2	1.18	0.324	Not significant	Distance from Pipe	1	0.06	0.812	Not significant
Festuca rubra	Area	2	0.38	0.685	Not significant	Distance from Pipe	1	0.11	0.738	Not significant
Holcus lanatus	Area	2	5.99	0.008	Significant	Distance from Pipe	1	0.69	0.413	Not significant
Leymus arenarius	Area	2	1.08	0.354	Not significant	Distance from Pipe	1	0.30	0.586	Not significant
Phleum arenarium	Area	2	1.42	0.260	Not significant	Distance from Pipe	1	4.57	0.042	Significant
Poa humilis	Area	2	3.89	0.034	Significant	Distance from Pipe	1	0.02	0.884	Not significant
Anacamptis pyramidalis	Area	2	0.25	0.784	Not significant	Distance from Pipe	1	0.01	0.905	Not significant
Cerastium fontanum	Area	2	2.72	0.085	Not significant	Distance from Pipe	1	3.74	0.065	Not significant
Cirsium arvense	Area	2	1.06	0.360	Not significant	Distance from Pipe	1	0.01	0.922	Not significant
Equisetum arvense	Area	2	0.70	0.506	Not significant	Distance from Pipe	1	0.02	0.879	Not significant
Euphorbia portlandica	Area	2	0.84	0.443	Not significant	Distance from Pipe	1	2.48	0.128	Not significant
Galium verum	Area	2	1.19	0.320	Not significant	Distance from Pipe	1	1.82	0.189	Not significant
Hieracium sp.	Area	2	0.78	0.468	Not significant	Distance from Pipe	1	0.81	0.375	Not significant
Hypochaeris radicata	Area	2	0.37	0.691	Not significant	Distance from Pipe	1	2.28	0.144	Not significant
Linaria vulgaris	Area	2	0.72	0.497	Not significant	Distance from Pipe	1	2.07	0.162	Not significant
Ononis repens	Area	2	0.05	0.956	Not significant	Distance from Pipe	1	0.00	0.981	Not significant
Rubus fruticosus agg.	Area	2	2.12	0.141	Not significant	Distance from Pipe	1	4.08	0.054	Not significant
Senecio erucifolius	Area	2	0.05	0.950	Not significant	Distance from Pipe	1	0.64	0.431	Not significant
Senecio jacobaea	Area	2	0.64	0.535	Not significant	Distance from Pipe	1	1.51	0.231	Not significant

Response	Factor	DF	F-Value	P-Value	Statistically Significant	Covariate	DF	F-Value	P-Value	Statistically Significant
Sonchus asper	Area	2	0.34	0.716	Not significant	Distance from Pipe	1	0.05	0.827	Not significant
Sonchus oleraceus	Area	2	0.46	0.635	Not significant	Distance from Pipe	1	0.07	0.801	Not significant
Solidago canadensis	Area	2	2.16	0.136	Not significant	Distance from Pipe	1	0.08	0.776	Not significant
Taraxacum sp.	Area	2	1.31	0.287	Not significant	Distance from Pipe	1	1.50	0.233	Not significant
Vicia hirsuta	Area	2	0.26	0.772	Not significant	Distance from Pipe	1	0.13	0.725	Not significant
Calliergonella cuspidata	Area	2	0.06	0.946	Not significant	Distance from Pipe	1	0.23	0.635	Not significant
Ceratodon purpureus	Area	2	1.74	0.196	Not significant	Distance from Pipe	1	3.94	0.058	Not significant
Hylocomium splendens	Area	2	0.36	0.701	Not significant	Distance from Pipe	1	0.50	0.485	Not significant
Oxyrrhynchium hians	Area	2	1.26	0.302	Not significant	Distance from Pipe	1	0.70	0.412	Not significant
Vegetation cover	Area	2	0.97	0.395	Not significant	Distance from Pipe	1	1.88	0.182	Not significant
Cover of bare ground	Area	2	0.41	0.671	Not significant	Distance from Pipe	1	0.43	0.517	Not significant
Graminoid cover	Area	2	1.77	0.190	Not significant	Distance from Pipe	1	3.03	0.094	Not significant
Herb cover	Area	2	0.04	0.965	Not significant	Distance from Pipe	1	0.02	0.877	Not significant
Moss cover	Area	2	0.63	0.541	Not significant	Distance from Pipe	1	0.75	0.394	Not significant
Annual cover	Area	2	0.08	0.924	Not significant	Distance from Pipe	1	0.46	0.504	Not significant
Perennial cover	Area	2	1.06	0.313	Not significant	Distance from Pipe	1	0.59	0.560	Not significant

Appendix Table 32 - Results of General Linear Model, with age class (factor) and distance from pipe (covariate) for embryo/ mobile dune species.

Response	Factor	DF	F-Value	P-Value	Statistically Significant	Covariate	DF	F-Value	P-Value	Statistically Significant
Agrostis stolonifera	Age Class	2	1.53	0.237	Not significant	Distance from Pipe	1	0.21	0.649	Not significant
Ammophila arenaria	Age Class	2	10.74	0.000	Significant	Distance from Pipe	1	4.04	0.055	Not significant
Arrhenatherum elatius	Age Class	2	9.78	0.001	Significant	Distance from Pipe	1	4.14	0.000	Significant
Carex arenaria	Age Class	2	1.50	0.242	Not significant	Distance from Pipe	1	0.28	0.599	Not significant
Elytrigia juncea	Age Class	2	23.38	0.000	Significant	Distance from Pipe	1	3.27	0.001	Significant
Festuca arenaria	Age Class	2	0.89	0.423	Not significant	Distance from Pipe	1	1.53	0.228	Not significant
Holcus lanatus	Age Class	2	5.42	0.011	Significant	Distance from Pipe	1	9.12	0.006	Significant
Leymus arenarius	Age Class	2	3.92	0.033	Significant	Distance from Pipe	1	1.06	0.313	Not significant
Poa humilis	Age Class	2	3.25	0.056	Not significant	Distance from Pipe	1	6.75	0.016	Significant

Response	Factor	DF	F-Value	P-Value	Statistically Significant	Covariate	DF	F-Value	P-Value	Statistically Significant
Anacamptis pyramidalis	Age Class	2	0.30	0.745	Not significant	Distance from Pipe	1	0.34	0.567	Not significant
Cirsium arvense	Age Class	2	1.06	0.361	Not significant	Distance from Pipe	1	0.00	0.949	Not significant
Equisetum arvense	Age Class	2	1.84	0.180	Not significant	Distance from Pipe	1	1.57	0.222	Not significant
Euphorbia portlandica	Age Class	2	0.62	0.546	Not significant	Distance from Pipe	1	1.32	0.262	Not significant
Linaria vulgaris	Age Class	2	0.76	0.477	Not significant	Distance from Pipe	1	2.33	0.140	Not significant
Ononis repens	Age Class	2	15.45	0.000	Significant	Distance from Pipe	1	0.24	0.625	Not significant
Rubus fruticosus agg.	Age Class	2	1.69	0.205	Not significant	Distance from Pipe	1	2.41	0.133	Not significant
Senecio erucifolius	Age Class	2	0.07	0.936	Not significant	Distance from Pipe	1	0.73	0.402	Not significant
Senecio jacobaea	Age Class	2	2.16	0.136	Not significant	Distance from Pipe	1	2.76	0.109	Not significant
Sonchus asper	Age Class	2	10.64	0.000	Significant	Distance from Pipe	1	0.93	0.344	Not significant
Sonchus oleraceus	Age Class	2	0.07	0.930	Not significant	Distance from Pipe	1	0.47	0.498	Not significant
Solidago canadensis	Age Class	2	2.25	0.126	Not significant	Distance from Pipe	1	0.87	0.359	Not significant
Taraxacum sp.	Age Class	2	1.16	0.330	Not significant	Distance from Pipe	1	0.14	0.710	Not significant
Vicia hirsuta	Age Class	2	0.18	0.840	Not significant	Distance from Pipe	1	0.01	0.937	Not significant
Ceratodon purpureus	Age Class	2	10.74	0.000	Significant	Distance from Pipe	1	4.04	0.055	Not significant
Hylocomium splendens	Age Class	2	9.87	0.001	Significant	Distance from Pipe	1	7.37	0.012	Significant
Oxyrrhynchium hians	Age Class	2	1.50	0.242	Not significant	Distance from Pipe	1	0.28	0.599	Not significant
Vegetation cover	Age Class	2	6.54	0.005	Significant	Distance from Pipe	1	0.26	0.613	Not significant
Cover of bare ground	Age Class	2	17.74	0.000	Significant	Distance from Pipe	1	0.18	0.676	Not significant
Graminoid cover	Age Class	2	1.92	0.167	Not significant	Distance from Pipe	1	0.25	0.620	Not significant
Herb cover	Age Class	2	32.73	0.000	Significant	Distance from Pipe	1	0.01	0.904	Not significant
Moss cover	Age Class	2	17.60	0.000	Significant	Distance from Pipe	1	1.08	0.309	Not significant
Annual cover	Age Class	2	1.23	0.310	Not significant	Distance from Pipe	1	0.80	0.381	Not significant
Perennial cover	Age Class	2	7.62	0.003	Significant	Distance from Pipe	1	0.27	0.611	Not significant

Appendix Table 33 - Tukey Pairwise Comparison for embryo/mobile dunes using age class.

Response	Difference of Age Class	Difference of means	SE of difference	Simultaneous 95% CI		T-value	Adjusted P-value	Statistically Significant
Ammophila arenaria	Medium-Unaffected	-0.891	0.367	-1.804	0.021	-2.43	0.057	Not significant
Arrhenatherum elatius	Medium-Unaffected	0.008	0.232	-0.57	0.586	0.03	0.999	Not significant
Elytrigia juncea	Medium-Unaffected	0.381	0.197	-0.109	0.872	1.94	0.149	Not significant

Response	Difference of Age Class	Difference of means	SE of difference	Simultaneous 95% CI		T-value	Adjusted P-value	Statistically Significant
Holcus lanatus	Medium-Unaffected	0.764	0.265	0.104	1.424	2.88	0.021	Significant
Ononis repens	Medium-Unaffected	-0.312	0.275	-0.966	0.373	-1.13	0.503	Not significant
Sonchus asper	Medium-Unaffected	-0.05	0.102	-0.305	0.205	-0.49	0.879	Not significant
Ceratodon purpureus	Medium-Unaffected	-0.891	0.367	-1.804	0.021	-2.43	0.057	Not significant
Hylocomium splendens	Medium-Unaffected	0.008	0.232	-0.57	0.586	0.03	0.999	Not significant
Vegetation cover	Medium-Unaffected	-0.104	0.106	-0.369	0.16	-0.98	0.595	Not significant
Cover of bare ground	Medium-Unaffected	0.721	0.376	-0.214	1.656	1.92	0.154	Not significant
Herb cover	Medium-Unaffected	-0.086	0.153	-0.468	0.292	-0.56	0.842	Not significant
Moss cover	Medium-Unaffected	113.6	49.1	-8.6	235.7	2.31	0.072	Not significant

Fixed Dunes

Appendix Table 34 - Results of General Linear Model, with sample area (factor) and distance from pipe (covariate) for fixed dune species.

Response	Factor	DF	F-Value	P-Value	Statistically Significant	Covariate	DF	F-Value	P-Value	Statistically Significant
Agrostis stolonifera	Area	2	2.17	0.115	Not significant	Distance from Pipe	1	23.49	0.000	Significant
Ammophila arenaria	Area	2	32.29	0.000	Significant	Distance from Pipe	1	6.78	0.010	Significant
Arrhenatherum elatius	Area	2	39.61	0.000	Significant	Distance from Pipe	1	27.48	0.000	Significant
Carex arenaria	Area	2	12.09	0.000	Significant	Distance from Pipe	1	21.10	0.000	Significant
Dactylis glomerata	Area	2	2.32	0.099	Not significant	Distance from Pipe	1	5.95	0.015	Significant
Elytrigia juncea	Area	2	0.83	0.435	Not significant	Distance from Pipe	1	17.90	0.000	Significant
Festuca arenaria	Area	2	17.25	0.000	Significant	Distance from Pipe	1	22.82	0.000	Significant
Festuca rubra	Area	2	62.82	0.000	Significant	Distance from Pipe	1	22.02	0.000	Significant
Holcus lanatus	Area	2	15.87	0.000	Significant	Distance from Pipe	1	44.00	0.000	Significant
Leymus arenarius	Area	2	15.09	0.000	Significant	Distance from Pipe	1	69.15	0.000	Significant
Phleum arenarium	Area	2	2.67	0.070	Not significant	Distance from Pipe	1	1.65	0.200	Not significant
Poa humilis	Area	2	1.98	0.139	Not significant	Distance from Pipe	1	5.90	0.015	Significant
Achillea millefolium	Area	2	0.98	0.375	Not significant	Distance from Pipe	1	19.17	0.000	Significant
Anthyllis vulneraria	Area	2	33.67	0.000	Significant	Distance from Pipe	1	5.44	0.020	Significant

Response	Factor	DF	F-Value	P-Value	Statistically Significant	Covariate	DF	F-Value	P-Value	Statistically Significant
Cerastium fontanum	Area	2	4.83	0.008	Significant	Distance from Pipe	1	7.68	0.006	Significant
Diplotaxis tenuifolia	Area	2	35.62	0.000	Significant	Distance from Pipe	1	20.41	0.000	Significant
Equisetum arvense	Area	2	2.49	0.840	Not significant	Distance from Pipe	1	24.50	0.000	Significant
Erodium cicutarium	Area	2	0.12	0.888	Not significant	Distance from Pipe	1	6.74	0.009	Significant
Galium verum	Area	2	4.00	0.019	Significant	Distance from Pipe	1	4.44	0.036	Significant
Heracleum sphondylium	Area	2	7.23	0.001	Significant	Distance from Pipe	1	1.90	0.169	Not significant
Hieracium sp.	Area	2	6.62	0.001	Significant	Distance from Pipe	1	9.88	0.002	Significant
Hypochaeris radicata	Area	2	13.66	0.000	Significant	Distance from Pipe	1	0.41	0.524	Not significant
Leontodon saxatilis	Area	2	2.68	0.070	Not significant	Distance from Pipe	1	2.46	0.117	Not significant
Linaria vulgaris	Area	2	3.12	0.045	Not significant	Distance from Pipe	1	0.07	0.792	Not significant
Linum catharticum	Area	2	0.57	0.566	Not significant	Distance from Pipe	1	0.84	0.361	Not significant
Lotus corniculatus	Area	2	3.05	0.048	Significant	Distance from Pipe	1	8.70	0.003	Significant
Medicago lupulina	Area	2	0.95	0.388	Not significant	Distance from Pipe	1	5.35	0.021	Significant
Ononis repens	Area	2	17.95	0.000	Significant	Distance from Pipe	1	11.75	0.001	Significant
Plantago coronopus	Area	2	0.32	0.725	Not significant	Distance from Pipe	1	3.27	0.071	Not significant
Plantago lanceolata	Area	2	6.31	0.002	Significant	Distance from Pipe	1	34.06	0.000	Significant
Potentilla reptans	Area	2	22.76	0.000	Significant	Distance from Pipe	1	6.87	0.009	Significant
Rhinanthus minor	Area	2	38.79	0.000	Significant	Distance from Pipe	1	2.70	0.101	Not significant
Rubus fruticosus agg.	Area	2	45.89	0.000	Significant	Distance from Pipe	1	5.55	0.019	Significant
Senecio erucifolius	Area	2	38.33	0.000	Significant	Distance from Pipe	1	2.84	0.093	Not significant
Taraxacum sp.	Area	2	6.65	0.001	Significant	Distance from Pipe	1	7.53	0.006	Significant
Trifolium pratense	Area	2	2.34	0.097	Not significant	Distance from Pipe	1	26.80	0.000	Significant
Trifolium repens	Area	2	1.08	0.339	Not significant	Distance from Pipe	1	13.68	0.000	Significant
Brachythecium albicans	Area	2	28.26	0.000	Significant	Distance from Pipe	1	1.59	0.208	Not significant
Calliergonella cuspidata	Area	2	2.17	0.115	Not significant	Distance from Pipe	1	23.49	0.000	Significant
Ceratodon purpureus	Area	2	32.29	0.000	Significant	Distance from Pipe	1	6.78	0.010	Significant
Hylocomium splendens	Area	2	39.61	0.000	Significant	Distance from Pipe	1	27.48	0.000	Significant
Oxyrrhynchium hians	Area	2	12.09	0.000	Significant	Distance from Pipe	1	21.10	0.000	Significant

Response	Factor	DF	F-Value	P-Value	Statistically Significant	Covariate	DF	F-Value	P-Value	Statistically Significant
Vegetation cover	Area	2	46.61	0.000	Significant	Distance from Pipe	1	22.48	0.000	Significant
Cover of bare ground	Area	2	53.19	0.000	Significant	Distance from Pipe	1	23.96	0.000	Significant
Graminoid cover	Area	2	45.27	0.000	Significant	Distance from Pipe	1	8.80	0.003	Significant
Herb cover	Area	2	7.73	0.000	Significant	Distance from Pipe	1	16.26	0.000	Significant
Moss cover	Area	2	108.54	0.000	Significant	Distance from Pipe	1	5.05	0.025	Significant
Annual cover	Area	2	15.60	0.000	Significant	Distance from Pipe	1	2.02	0.156	Not significant
Perennial cover	Area	2	62.05	0.000	Significant	Distance from Pipe	1	24.69	0.000	Significant

Appendix Table 35 - Tukey Pairwise Comparison for fixed dune species using sample area.

Response	Sample Area	Difference of means	SE of difference	Simultaneous 95% CI		T-value	Adjusted P-value	Statistically Significant
Ammophila arenaria	On-Off	0.637	0.119	0.358	0.916	5.34	0.000	Significant
Ammophila arenaria	On-Adjacent	-0.641	0.085	-0.841	-0.441	-7.51	0.000	Significant
Arrhenatherum elatius	On-Off	0.797	0.095	0.574	1.019	8.37	0.000	Significant
Arrhenatherum elatius	On-Adjacent	-0.395	0.068	-0.551	-0.235	-5.80	0.000	Significant
Carex arenaria	On-Off	0.222	0.059	0.084	0.360	3.77	0.000	Significant
Carex arenaria	On-Adjacent	-0.181	0.042	-0.279	-0.082	-4.29	0.000	Significant
Festuca arenaria	On-Off	-0.698	0.124	-0.989	-0.407	-5.61	0.000	Significant
Festuca arenaria	On-Adjacent	0.322	0.089	0.113	0.530	3.62	0.001	Significant
Festuca rubra	On-Off	0.897	0.104	0.651	1.140	8.64	0.000	Significant
Festuca rubra	On-Adjacent	-0.724	0.074	-0.897	-0.550	-9.74	0.000	Significant
Holcus lanatus	On-Off	0.541	0.101	0.303	0.778	5.33	0.000	Significant
Holcus lanatus	On-Adjacent	-0.261	0.073	-0.431	-0.091	-3.60	0.001	Significant
Leymus arenarius	On-Off	-0.314	0.058	-0.448	-0.179	-5.45	0.000	Significant
Leymus arenarius	On-Adjacent	0.108	0.041	0.011	0.204	2.61	0.025	Significant
Anthyllis vulneraria	On-Off	-0.772	0.126	-1.066	-0.477	-6.14	0.000	Significant
Anthyllis vulneraria	On-Adjacent	0.654	0.090	0.443	0.864	7.27	0.000	Significant
Cerastium fontanum	On-Off	0.078	0.042	-0.021	0.176	1.84	0.157	Not significant
Cerastium fontanum	On-Adjacent	-0.091	0.030	-0.161	-0.020	-3.00	0.000	Significant
Diplotaxis tenuifolia	On-Off	-0.532	0.077	-0.712	-0.351	-6.89	0.000	Significant
Diplotaxis tenuifolia	On-Adjacent	0.387	0.055	0.258	0.516	7.01	0.000	Significant

Response	Sample Area	Difference of means	SE of difference	Simultaneous 95% CI		T-value	Adjusted P-value	Statistically Significant
Galium verum	On-Off	0.079	0.045	-0.025	0.183	1.78	0.175	Not significant
Galium verum	On-Adjacent	-0.086	0.032	-0.160	-0.011	-2.69	0.020	Significant
Hieracium sp.	On-Off	0.040	0.041	-0.057	0.137	0.98	0.592	Not significant
Hieracium sp.	On-Adjacent	-0.107	0.030	-0.177	-0.038	-3.62	0.001	Significant
Lotus corniculatus	On-Off	0.072	0.080	-0.116	0.259	0.90	0.643	Not significant
Lotus corniculatus	On-Adjacent	-0.141	0.057	-0.275	-0.007	-2.47	0.036	Significant
Ononis repens	On-Off	0.045	0.101	0.212	0.683	4.45	0.000	Significant
Ononis repens	On-Adjacent	-0.384	0.072	-0.552	-0.215	-5.33	0.000	Significant
Plantago lanceolata	On-Off	-0.215	0.061	-0.358	-0.072	-3.51	0.001	Significant
Plantago lanceolata	On-Adjacent	0.032	0.044	-0.071	0.134	0.72	0.751	Not significant
Potentilla reptans	On-Off	0.133	0.026	0.073	0.194	5.15	0.000	Significant
Potentilla reptans	On-Adjacent	-0.109	0.019	-0.153	-0.066	-5.91	0.000	Significant
Rubus fruticosus agg.	On-Off	0.366	0.044	0.263	0.470	8.27	0.000	Significant
Rubus fruticosus agg.	On-Adjacent	-0.236	0.032	-0.311	-0.162	-7.46	0.000	Significant
Taraxacum sp.	On-Off	0.134	0.037	0.047	0.221	3.60	0.001	Significant
Taraxacum sp.	On-Adjacent	-0.049	0.027	-0.111	0.013	-1.84	0.158	Not significant
Ceratodon purpureus	On-Off	0.637	0.119	0.358	0.916	5.34	0.000	Significant
Ceratodon purpureus	On-Adjacent	-0.641	0.085	-0.841	-0.441	-7.51	0.000	Significant
Hylocomium splendens	On-Off	0.797	0.095	0.574	1.019	8.37	0.000	Significant
Hylocomium splendens	On-Adjacent	-0.395	0.068	-0.554	-0.235	-5.80	0.000	Significant
Oxyrrhynchium hians	On-Off	0.222	0.059	0.008	0.360	3.77	0.000	Significant
Oxyrrhynchium hians	On-Adjacent	-0.181	0.042	-0.279	0.082	-4.29	0.000	Significant
Vegetation cover	On-Off	0.449	0.057	0.316	0.581	7.90	0.000	Significant
Vegetation cover	On-Adjacent	-0.325	0.041	-0.420	-0.230	-8.00	0.000	Significant
Cover of bare ground	On-Off	-1.217	0.155	-1.580	-0.855	-7.86	0.000	Significant
Cover of bare ground	On-Adjacent	1.001	0.111	0.741	1.260	9.03	0.000	Significant
Graminoid cover	On-Off	0.672	0.089	0.464	0.879	7.58	0.000	Significant
Graminoid cover	On-Adjacent	-0.512	0.063	-0.660	-0.363	-8.07	0.000	Significant
Herb cover	On-Off	0.228	0.066	0.073	0.383	3.44	0.002	Significant
Herb cover	On-Adjacent	-0.142	0.047	-0.253	-0.031	-3.00	0.008	Significant
Moss cover	On-Off	-347.900	33.400	-425.900	-269.800	-10.43	0.000	Significant

Response	Sample Area	Difference of means	SE of difference	Simultaneous 95% CI		T-value	Adjusted P-value	Statistically Significant
Moss cover	On-Adjacent	320.600	23.900	264.700	376.400	13.43	0.000	Significant
Annual cover	On-Off	-2.947	0.777	-4.764	-1.129	-3.79	0.000	Significant
Annual cover	On-Adjacent	-2.877	0.556	-4.177	-1.577	-5.18	0.000	Significant
Perennial cover	On-Off	-54.400	5.900	-68.200	-40.600	-9.23	0.000	Significant
Perennial cover	On-Adjacent	-38.440	4.220	-48.310	-28.570	-9.11	0.000	Significant

Appendix Table 36 - Results of General Linear Model, with age class (factor) and distance from pipe (covariate) for fixed dune species.

Response	Factor	DF	F-Value	P-Value	Statistically Significant	Covariate	DF	F-Value	P-Value	Statistically Significant
Agrostis stolonifera	Age Class	3	1.01	0.387	Not significant	Distance from Pipe	1	19.44	0.000	Significant
Ammophila arenaria	Age Class	3	63.49	0.000	Significant	Distance from Pipe	1	28.13	0.000	Significant
Arrhenatherum elatius	Age Class	3	21.56	0.000	Significant	Distance from Pipe	1	12.70	0.000	Significant
Carex arenaria	Age Class	3	43.78	0.000	Significant	Distance from Pipe	1	21.23	0.000	Significant
Dactylis glomerata	Age Class	3	1.23	0.298	Not significant	Distance from Pipe	1	3.16	0.076	Not significant
Elytrigia juncea	Age Class	3	3.02	0.030	Significant	Distance from Pipe	1	21.09	0.000	Significant
Festuca arenaria	Age Class	3	15.01	0.000	Significant	Distance from Pipe	1	17.26	0.000	Significant
Festuca rubra	Age Class	3	105.27	0.000	Significant	Distance from Pipe	1	7.16	0.008	Significant
Holcus lanatus	Age Class	3	8.57	0.000	Significant	Distance from Pipe	1	33.68	0.000	Significant
Leymus arenarius	Age Class	3	11.85	0.000	Significant	Distance from Pipe	1	65.66	0.000	Significant
Poa humilis	Age Class	3	2.78	0.041	Significant	Distance from Pipe	1	4.82	0.029	Significant
Achillea millefolium	Age Class	3	0.95	0.417	Not significant	Distance from Pipe	1	23.29	0.000	Significant
Anthyllis vulneraria	Age Class	3	45.18	0.000	Significant	Distance from Pipe	1	0.23	0.633	Not significant
Cakile maritima	Age Class	3	2.38	0.068	Not significant	Distance from Pipe	1	8.51	0.004	Significant
Cerastium fontanum	Age Class	3	2.95	0.032	Significant	Distance from Pipe	1	3.41	0.066	Not significant
Cirsium arvense	Age Class	3	2.05	0.106	Not significant	Distance from Pipe	1	2.20	0.139	Not significant
Diplotaxis tenuifolia	Age Class	3	26.62	0.000	Significant	Distance from Pipe	1	7.10	0.008	Significant
Equisetum arvense	Age Class	3	2.23	0.084	Not significant	Distance from Pipe	1	23.88	0.000	Significant
Galium verum	Age Class	3	8.25	0.000	Significant	Distance from Pipe	1	2.70	0.100	Not significant
Hieracium sp.	Age Class	3	2.24	0.083	Not significant	Distance from Pipe	1	22.23	0.000	Significant
Hypochaeris radicata	Age Class	3	17.48	0.000	Significant	Distance from Pipe	1	0.77	0.380	Not significant
Leontodon saxatilis	Age Class	3	5.74	0.001	Significant	Distance from Pipe	1	5.13	0.024	Significant
Linaria vulgaris	Age Class	3	4.70	0.003	Significant	Distance from Pipe	1	0.11	0.738	Not significant

Response	Factor	DF	F-Value	P-Value	Statistically Significant	Covariate	DF	F-Value	P-Value	Statistically Significant
Lotus corniculatus	Age Class	3	0.14	0.938	Not significant	Distance from Pipe	1	4.18	0.042	Not significant
Ononis repens	Age Class	3	27.76	0.000	Significant	Distance from Pipe	1	5.35	0.021	Significant
Plantago coronopus	Age Class	3	1.2	0.308	Not significant	Distance from Pipe	1	4.49	0.035	Significant
Plantago lanceolata	Age Class	3	5.01	0.002	Significant	Distance from Pipe	1	36.40	0.000	Significant
Rubus fruticosus agg.	Age Class	3	32.72	0.000	Significant	Distance from Pipe	1	0.02	0.900	Not significant
Senecio jacobaea	Age Class	3	28.93	0.000	Significant	Distance from Pipe	1	18.68	0.000	Significant
Sonchus oleraceus	Age Class	3	5.21	0.001	Significant	Distance from Pipe	1	2.90	0.089	Not significant
Taraxacum sp.	Age Class	3	9.27	0.000	Significant	Distance from Pipe	1	11.63	0.001	Significant
Trifolium pratense	Age Class	3	2.20	0.088	Not significant	Distance from Pipe	1	29.99	0.000	Significant
Brachythecium albicans	Age Class	3	30.52	0.000	Significant	Distance from Pipe	1	10.61	0.001	Significant
Calliergonella cuspidata	Age Class	3	1.01	0.387	Not significant	Distance from Pipe	1	19.44	0.000	Significant
Ceratodon purpureus	Age Class	3	63.49	0.000	Significant	Distance from Pipe	1	28.13	0.000	Significant
Hylocomium splendens	Age Class	3	21.56	0.000	Significant	Distance from Pipe	1	12.70	0.000	Significant
Oxyrrhynchium hians	Age Class	3	43.78	0.000	Significant	Distance from Pipe	1	21.23	0.000	Significant
Vegetation cover	Age Class	3	34.85	0.000	Significant	Distance from Pipe	1	6.72	0.010	Significant
Cover of bare ground	Age Class	3	51.57	0.000	Significant	Distance from Pipe	1	6.57	0.011	Significant
Graminoid cover	Age Class	3	44.69	0.000	Significant	Distance from Pipe	1	0.62	0.432	Not significant
Herb cover	Age Class	3	3.13	0.025	Significant	Distance from Pipe	1	10.22	0.001	Significant
Moss cover	Age Class	3	184.73	0.000	Significant	Distance from Pipe	1	3.06	0.081	Not significant
Annual cover	Age Class	3	13.98	0.000	Significant	Distance from Pipe	1	0.07	0.788	Not significant
Perennial cover	Age Class	3	49.69	0.000	Significant	Distance from Pipe	1	6.49	0.011	Significant

Appendix Table 37 - Tukey Pairwise Comparison for fixed dunes using age class.

Response	Difference of Age Class	Difference of means	SE of difference	Simultaneous 95% CI		T-value	Adjusted P-value	Statistically Significant
Ammophila arenaria	Short-Unaffected	0.56	0.103	0.297	0.823	5.46	0.000	Significant
Ammophila arenaria	Short-Medium	-0.8142	0.061	-0.9708	-0.6576	-13.34	0.000	Significant
Ammophila arenaria	Medium-Unaffected	-0.254	0.11	-0.536	0.028	-2.31	0.095	Not significant
Arrhenatherum elatius	Short-Unaffected	0.6656	0.0916	0.4306	0.9006	4.38	0.000	Significant
Arrhenatherum elatius	Short-Medium	-0.2361	0.0545	-0.376	-0.0963	-4.33	0.000	Significant
Arrhenatherum elatius	Medium-Unaffected	0.4294	0.0981	0.1176	0.6813	4.38	0.000	Significant
Arrhenatherum elatius	Long-Unaffected	0.867	0.213	0.319	1.414	4.06	0.000	Significant

Response	Difference of Age Class	Difference of means	SE of difference	Simultaneous 95% CI		T-value	Adjusted P-value	Statistically Significant
Carex arenaria	Short-Unaffected	0.2284	0.051	0.0975	0.3592	4.48	0.000	Significant
Carex arenaria	Short-Medium	-0.337	0.0303	-0.4149	-0.2591	-11.11	0.000	Significant
Carex arenaria	Medium-Unaffected	-0.1086	0.0546	-0.2488	0.0316	-1.99	0.193	Not significant
Elytrigia juncea	Short-Unaffected	0.0412	0.0613	-0.1161	0.1985	0.67	0.904	Not significant
Elytrigia juncea	Short-Medium	0.093	0.0365	-0.0006	0.1866	2.55	0.053	Not significant
Elytrigia juncea	Medium-Unaffected	0.1342	0.0657	-0.0344	0.3028	2.04	0.172	Not significant
Festuca arenaria	Short-Unaffected	-0.637	0.117	-0.937	-0.336	-5.44	0.000	Significant
Festuca arenaria	Short-Medium	0.324	0.0696	0.1452	0.5027	4.65	0.000	Significant
Festuca arenaria	Medium-Unaffected	-0.313	0.125	-0.635	0.009	-2.49	0.061	Not significant
Festuca rubra	Short-Unaffected	0.7839	0.0864	0.5621	1.0057	9.07	0.000	Significant
Festuca rubra	Short-Medium	-0.7928	0.0514	-0.9248	-0.6608	-15.42	0.000	Significant
Festuca rubra	Medium-Unaffected	-0.0089	0.0926	-0.2466	0.2288	-0.10	1.000	Not significant
Holcus lanatus	Short-Unaffected	0.4416	0.0969	0.1928	0.6903	4.56	0.000	Significant
Holcus lanatus	Short-Medium	-0.122	0.0577	-2700	0.0261	-2.11	0.148	Not significant
Holcus lanatus	Medium-Unaffected	0.32	0.104	0.053	0.586	3.08	0.011	Not significant
Leymus arenarius	Short-Unaffected	-0.2734	0.0544	-0.4131	-0.1337	-5.02	0.000	Significant
Leymus arenarius	Short-Medium	0.0621	0.0324	-0.021	0.1453	1.92	0.220	Not significant
Leymus arenarius	Medium-Unaffected	-0.2113	0.0583	-0.361	-0.0616	-3.62	0.002	Significant
Leymus arenarius	Long-Unaffected	-0.598	0.127	-0.924	-0.273	-4.72	0.000	Significant
Poa humilis	Short-Unaffected	-0.112	0.0651	-0.279	0.055	-1.72	0.312	Not significant
Poa humilis	Medium-Unaffected	-0.1047	0.0697	-0.2837	0.0743	-1.50	0.436	Not significant
Anthyllis vulneraria	Short-Unaffected	-0.662	0.113	-0.951	-0.372	-5.87	0.000	Significant
Anthyllis vulneraria	Short-Medium	0.7062	0.0671	0.5339	0.8785	10.52	0.000	Significant
Anthyllis vulneraria	Medium-Unaffected	0.044	0.121	-0.266	0.355	0.37	0.983	Not significant
Cerastium fontanum	Short-Unaffected	0.044	0.0402	-0.0591	0.1471	1.10	0.692	Not significant
Cerastium fontanum	Short-Medium	-0.0282	0.0239	-0.0896	0.0311	-1.18	0.638	Not significant
Cerastium fontanum	Medium-Unaffected	0.0157	0.043	-0.0947	0.1262	0.37	0.983	Not significant
Diplotaxis tenuifolia	Short-Unaffected	-0.436	0.0728	-0.6229	0.2491	-5.99	0.000	Significant
Diplotaxis tenuifolia	Short-Medium	0.3204	0.0433	0.2092	0.4316	7.40	0.000	Significant
Diplotaxis tenuifolia	Medium-Unaffected	-0.1156	0.078	-0.3159	0.0846	-1.48	0.448	Not significant
Galium verum	Short-Unaffected	0.0708	0.0416	-0.036	0.1776	1.70	0.323	Not significant

Response	Difference of Age Class	Difference of means	SE of difference	Simultaneous 95% CI		T-value	Adjusted P-value	Statistically Significant
Galium verum	Short-Medium	-0.119	0.0248	-0.1835	-0.0564	-4.84	0.000	Significant
Galium verum	Medium-Unaffected	-0.0491	0.0446	-0.1636	0.0653	-1.10	0.689	Not significant
Hypochaeris radicata	Short-Unaffected	0.1341	0.0593	-0.0181	0.2862	2.26	0.107	Not significant
Hypochaeris radicata	Short-Medium	-0.2194	0.0353	-0.3099	-0.1288	-6.22	0.000	Significant
Hypochaeris radicata	Medium-Unaffected	-0.0853	0.0635	-0.2484	0.0778	-1.34	0.536	Not significant
Leontodon saxatilis	Short-Unaffected	-0.1002	0.0707	-0.2817	0.0813	-1.42	0.488	Not significant
Leontodon saxatilis	Short-Medium	0.1638	0.0421	0.0558	0.2718	3.89	0.001	Significant
Leontodon saxatilis	Medium-Unaffected	0.0635	0.0758	-0.131	0.258	0.84	0.836	Not significant
Ononis repens	Short-Unaffected	0.3805	0.0916	0.1454	0.6156	4.15	0.000	Significant
Ononis repens	Short-Medium	-0.4508	0.0545	-0.5907	-0.3109	-8.27	0.000	Significant
Ononis repens	Medium-Unaffected	-0.0703	0.0982	-0.3223	0.1816	-0.72	0.891	Not significant
Plantago lanceolata	Short-Unaffected	-0.2004	0.0581	-0.3495	-0.0512	-3.45	0.003	Significant
Plantago lanceolata	Short-Medium	-0.0063	0.0346	-0.095	0.0825	-0.18	0.998	Not significant
Plantago lanceolata	Medium-Unaffected	-0.2066	0.0623	-0.3665	-0.0468	-3.32	0.005	Significant
Rubus fruticosus agg.	Short-Unaffected	0.3052	0.0419	0.1977	0.4127	7.29	0.000	Significant
Rubus fruticosus agg.	Short-Medium	-0.1955	0.0249	-0.2595	-0.1316	-7.85	0.000	Significant
Rubus fruticosus agg.	Medium-Unaffected	0.1097	0.049	-0.0055	0.2249	2.44	0.069	Not significant
Senecio jacobaea	Short-Unaffected	0.1254	0.032	0.0433	0.2075	3.82	0.001	Significant
Senecio jacobaea	Short-Medium	-0.1714	0.019	-0.2203	-0.1225	-9.00	0.000	Significant
Senecio jacobaea	Medium-Unaffected	-0.046	0.0343	-0.134	0.042	-1.34	0.537	Not significant
Taraxacum sp.	Short-Unaffected	0.134	0.0348	0.0446	0.223	3.85	0.001	Significant
Taraxacum sp.	Short-Medium	-0.0788	0.0207	-0.1309	-0.0246	-3.75	0.001	Significant
Taraxacum sp.	Medium-Unaffected	0.0562	0.0373	-0.0348	0.152	1.51	0.433	Not significant
Brachythecium albicans	Short-Unaffected	0.2453	0.0413	0.1392	0.3514	5.94	0.000	Significant
Brachythecium albicans	Short-Medium	-0.2034	0.0246	-0.2665	-0.1402	-8.27	0.000	Significant
Brachythecium albicans	Medium-Unaffected	0.042	0.0443	-0.0717	0.1557	0.95	0.779	Not significant
Ceratodon purpureus	Short-Unaffected	0.56	0.103	0.297	0.823	5.46	0.000	Significant
Ceratodon purpureus	Short-Medium	-0.8142	0.061	-0.9708	0.028	-2.31	0.095	Not significant
Ceratodon purpureus	Medium-Unaffected	-0.254	0.11	-0.536	0.028	-2.31	0.095	Not significant
Hylocomium splendens	Short-Unaffected	0.6656	0.0916	0.4306	0.9006	7.27	0.000	Significant
Hylocomium splendens	Short-Medium	-0.2361	0.0545	-0.376	-0.0963	-4.33	0.000	Significant

Response	Difference of Age Class	Difference of means	SE of difference	Simultaneous 95% CI		T-value	Adjusted P-value	Statistically Significant
Hylocomium splendens	Medium-Unaffected	0.4294	0.0981	0.1776	0.68113	4.38	0.000	Significant
Hylocomium splendens	Long-Unaffected	0.867	0.213	0.319	1.414	4.06	0.000	Significant
Oxyrrhynchium hians	Short-Unaffected	0.2284	0.051	0.0975	0.3592	4.48	0.000	Significant
Oxyrrhynchium hians	Short-Medium	-0.337	0.0303	-0.4149	-0.2591	-11.11	0.000	Significant
Oxyrrhynchium hians	Medium-Unaffected	-0.1086	0.0546	-0.2488	0.0316	-1.99	0.193	Not significant
Vegetation cover	Short-Unaffected	0.3681	0.0535	0.2309	0.5053	6.89	0.000	Significant
Vegetation cover	Short-Medium	-0.2702	0.0318	-0.3519	-0.1886	-8.50	0.000	Significant
Vegetation cover	Medium-Unaffected	0.0978	0.0573	-0.0492	0.2449	1.71	0.320	Not significant
Cover of bare ground	Short-Unaffected	-0.976	0.142	-1.34	-0.613	-6.89	0.000	Significant
Cover of bare ground	Short-Medium	0.9235	0.0843	0.7072	1.1398	10.96	0.000	Significant
Cover of bare ground	Medium-Unaffected	-0.053	0.152	-0.442	0.337	-0.35	0.986	Not significant
Graminoid cover	Short-Unaffected	0.5645	0.0813	0.3559	0.7731	6.94	0.000	Significant
Graminoid cover	Short-Medium	-0.4875	0.0484	-0.6117	-0.3634	-10.08	0.000	Significant
Graminoid cover	Medium-Unaffected	0.077	0.0871	-0.1466	0.3006	0.88	0.813	Not significant
Herb cover	Short-Unaffected	0.1722	0.0633	0.0096	0.3348	2.72	0.033	Significant
Herb cover	Short-Medium	-0.0564	0.0377	-0.1532	0.0404	-1.50	0.440	Not significant
Herb cover	Medium-Unaffected	0.1158	0.0679	-0.0585	0.29	1.71	0.321	Not significant
Moss cover	Short-Unaffected	-290.9	26.1	-358	-223.8	-11.13	0.000	Significant
Moss cover	Short-Medium	346.3	15.6	306.4	386.2	22.26	0.000	Significant
Moss cover	Medium-Unaffected	55.4	28	-16.5	127.3	1.98	0.196	Not significant
Annual cover	Short-Medium	2.108	0.731	0.233	3.984	2.89	0.020	Significant
Annual cover	Medium-Unaffected	0.43	0.783	-1.58	2.439	0.55	0.947	Not significant
Perennial cover	Short-Medium	45.2	5.49	31.1	59.3	8.23	0.000	Significant
Perennial cover	Medium-Unaffected	11.61	5.89	-3.5	26.72	1.97	0.198	Not significant

Dune Grassland

Appendix Table 38 - Results of General Linear Model, with sample area (factor) and distance from pipe (covariate) for dune grassland species.

Response	Factor	DF	F-Value	P-Value	Statistically Significant	Covariate	DF	F-Value	P-Value	Statistically Significant
Agrostis stolonifera	Area	2	8.07	0.000	Significant	Distance from Pipe	1	0.26	0.608	Not significant
Ammophila arenaria	Area	2	4.37	0.014	Significant	Distance from Pipe	1	0.04	0.847	Not significant
Anisantha sterilis	Area	2	8.21	0.000	Significant	Distance from Pipe	1	2.23	0.137	Not significant
Arrhenatherum elatius	Area	2	4.48	0.013	Significant	Distance from Pipe	1	2.50	0.116	Not significant
Briza media	Area	2	3.24	0.041	Significant	Distance from Pipe	1	0.03	0.870	Not significant
Bromus hordeaceus	Area	2	16.11	0.000	Significant	Distance from Pipe	1	13.34	0.000	Significant
Carex arenaria	Area	2	0.46	0.632	Not significant	Distance from Pipe	1	3.36	0.069	Not significant
Carex distans	Area	2	3.05	0.050	Significant	Distance from Pipe	1	5.06	0.026	Significant
Carex disticha	Area	2	0.13	0.880	Not significant	Distance from Pipe	1	0.70	0.403	Not significant
Carex flacca	Area	2	1.19	0.306	Not significant	Distance from Pipe	1	1.07	0.302	Not significant
Carex hirta	Area	2	1.98	0.141	Not significant	Distance from Pipe	1	0.43	0.513	Not significant
Dactylis glomerata	Area	2	0.07	0.932	Not significant	Distance from Pipe	1	6.97	0.009	Significant
Elytrigia atherica	Area	2	0.11	0.894	Not significant	Distance from Pipe	1	0.63	0.430	Not significant
Elytrigia juncea	Area	2	5.76	0.004	Significant	Distance from Pipe	1	0.65	0.423	Not significant
Festuca arenaria	Area	2	0.03	0.967	Not significant	Distance from Pipe	1	0.01	0.929	Not significant
Festuca rubra	Area	2	14.98	0.000	Significant	Distance from Pipe	1	8.79	0.003	Significant
Holcus lanatus	Area	2	3.23	0.042	Significant	Distance from Pipe	1	0.32	0.574	Not significant
Juncus bufonius	Area	2	0.04	0.959	Not significant	Distance from Pipe	1	0.21	0.648	Not significant
Juncus gerardii	Area	2	0.13	0.877	Not significant	Distance from Pipe	1	0.72	0.398	Not significant
Leymus arenarius	Area	2	3.96	0.021	Significant	Distance from Pipe	1	2.01	0.158	Not significant
Lolium perenne	Area	2	0.19	0.830	Not significant	Distance from Pipe	1	0.01	0.919	Not significant
Luzula campestris	Area	2	3.50	0.032	Significant	Distance from Pipe	1	11.17	0.001	Significant
Phleum arenarium	Area	2	0.08	0.923	Not significant	Distance from Pipe	1	0.42	0.516	Not significant
Phragmites australis	Area	2	0.29	0.750	Not significant	Distance from Pipe	1	0.21	0.651	Not significant

Response	Factor	DF	F-Value	P-Value	Statistically Significant	Covariate	DF	F-Value	P-Value	Statistically Significant
Poa humilis	Area	2	7.68	0.001	Significant	Distance from Pipe	1	5.50	0.020	Significant
Poa pratensis	Area	2	1.03	0.359	Not significant	Distance from Pipe	1	0.16	0.692	Not significant
Vulpia bromoides	Area	2	0.03	0.970	Not significant	Distance from Pipe	1	0.16	0.691	Not significant
Achillea millefolium	Area	2	2.04	0.133	Not significant	Distance from Pipe	1	0.85	0.359	Not significant
Achillea ptarmica	Area	2	0.23	0.795	Not significant	Distance from Pipe	1	0.41	0.523	Not significant
Anacamptis pyramidalis	Area	2	0.38	0.686	Not significant	Distance from Pipe	1	1.18	0.278	Not significant
Angelica sylvestris	Area	2	1.05	0.351	Not significant	Distance from Pipe	1	24.23	0.000	Significant
Anthyllis vulneraria	Area	2	0.61	0.543	Not significant	Distance from Pipe	1	4.90	0.028	Significant
Arenaria serpyllifolia	Area	2	0.23	0.798	Not significant	Distance from Pipe	1	0.98	0.323	Not significant
Artemisia vulgaris	Area	2	0.04	0.961	Not significant	Distance from Pipe	1	0.22	0.642	Not significant
Aster x veriscolor	Area	2	0.03	0.972	Not significant	Distance from Pipe	1	0.14	0.708	Not significant
Astragalus danicus	Area	2	0.13	0.882	Not significant	Distance from Pipe	1	0.70	0.403	Not significant
Blackstonia perfoliata	Area	2	1.75	0.176	Not significant	Distance from Pipe	1	0.40	0.526	Not significant
Calystegia sepium	Area	2	0.10	0.907	Not significant	Distance from Pipe	1	0.04	0.848	Not significant
Cardamine pratensis	Area	2	1.25	0.288	Not significant	Distance from Pipe	1	1.69	0.195	Not significant
Carlina vulgaris	Area	2	0.47	0.626	Not significant	Distance from Pipe	1	5.45	0.021	Not significant
Centaurea nigra	Area	2	3.78	0.025	Significant	Distance from Pipe	1	10.97	0.001	Significant
Centaurium erythraea	Area	2	0.85	0.430	Not significant	Distance from Pipe	1	3.35	0.069	Not significant
Cerastium fontanum	Area	2	3.18	0.044	Significant	Distance from Pipe	1	0.89	0.347	Not significant
Cirsium arvense	Area	2	0.07	0.930	Not significant	Distance from Pipe	1	0.03	0.862	Not significant
Cirsium vulgare	Area	2	3.46	0.034	Significant	Distance from Pipe	1	2.92	0.089	Not significant
Clematis vitalba	Area	2	6.73	0.002	Significant	Distance from Pipe	1	2.70	0.102	Not significant
Convolvulus arvensis	Area	2	0.67	0.511	Not significant	Distance from Pipe	1	0.72	0.396	Not significant
Crepis capillaris	Area	2	0.03	0.966	Not significant	Distance from Pipe	1	0.19	0.663	Not significant
Dactylorhiza purpurella	Area	2	0.59	0.554	Not significant	Distance from Pipe	1	2.65	0.105	Not significant
Daucus carota	Area	2	0.41	0.662	Not significant	Distance from Pipe	1	1.73	0.190	Not significant
Diplotaxis tenuifolia	Area	2	0.28	0.757	Not significant	Distance from Pipe	1	0.59	0.443	Not significant
Equisetum arvense	Area	2	3.09	0.048	Significant	Distance from Pipe	1	0.01	0.914	Not significant

Response	Factor	DF	F-Value	P-Value	Statistically Significant	Covariate	DF	F-Value	P-Value	Statistically Significant
Erigeron acris	Area	2	6.15	0.003	Significant	Distance from Pipe	1	0.04	0.843	Not significant
Erodium cicutarium	Area	2	1.26	0.285	Not significant	Distance from Pipe	1	0.53	0.467	Not significant
Eupatorium cannabinum	Area	2	0.84	0.433	Not significant	Distance from Pipe	1	14.55	0.000	Significant
Euphorbia portlandica	Area	2	4.53	0.012	Significant	Distance from Pipe	1	14.29	0.000	Significant
Euphrasia sp.	Area	2	0.12	0.884	Not significant	Distance from Pipe	1	0.46	0.501	Not significant
Galium verum	Area	2	1.71	0.184	Not significant	Distance from Pipe	1	1.51	0.221	Not significant
Glechoma hederacea	Area	2	29.42	0.000	Significant	Distance from Pipe	1	1.67	0.198	Not significant
Geranium dissectum	Area	2	3.80	0.024	Significant	Distance from Pipe	1	0.65	0.420	Not significant
Geranium molle	Area	2	3.36	0.037	Significant	Distance from Pipe	1	0.11	0.741	Not significant
Heracleum sphondylium	Area	2	0.94	0.393	Not significant	Distance from Pipe	1	0.02	0.876	Not significant
Hieracium sp.	Area	2	3.23	0.042	Not significant	Distance from Pipe	1	0.10	0.756	Not significant
Hippophae rhamnoides	Area	2	0.43	0.651	Not significant	Distance from Pipe	1	0.41	0.523	Not significant
Hypochaeris radicata	Area	2	0.93	0.395	Not significant	Distance from Pipe	1	0.84	0.361	Not significant
Lactuca virosa	Area	2	0.16	0.855	Not significant	Distance from Pipe	1	0.03	0.862	Not significant
Lathyrus pratensis	Area	2	0.85	0.429	Not significant	Distance from Pipe	1	0.93	0.335	Not significant
Leontodon saxatilis	Area	2	0.16	0.854	Not significant	Distance from Pipe	1	1.21	0.272	Not significant
Linaria vulgaris	Area	2	3.86	0.023	Significant	Distance from Pipe	1	0.93	0.336	Not significant
Linum catharticum	Area	2	0.32	0.728	Not significant	Distance from Pipe	1	0.32	0.570	Not significant
Lotus corniculatus	Area	2	0.12	0.890	Not significant	Distance from Pipe	1	0.43	0.514	Not significant
Medicago lupulina	Area	2	1.72	0.183	Not significant	Distance from Pipe	1	3.27	0.072	Not significant
Melilotus albus	Area	2	0.02	0.977	Not significant	Distance from Pipe	1	0.08	0.775	Not significant
Mentha aquatica	Area	2	0.07	0.930	Not significant	Distance from Pipe	1	0.40	0.526	Not significant
Odontites vernus	Area	2	0.04	0.960	Not significant	Distance from Pipe	1	0.19	0.661	Not significant
Oenothera glazioviana	Area	2	5.17	0.007	Significant	Distance from Pipe	1	0.48	0.488	Not significant
Ophrys apifera	Area	2	0.89	0.412	Not significant	Distance from Pipe	1	0.51	0.476	Not significant
Pilosella officinarum	Area	2	4.00	0.020	Significant	Distance from Pipe	1	1.74	0.189	Not significant
Plantago coronopus	Area	2	0.38	0.687	Not significant	Distance from Pipe	1	0.33	0.567	Not significant
Plantago lanceolata	Area	2	0.46	0.632	Not significant	Distance from Pipe	1	0.08	0.774	Not significant

Response	Factor	DF	F-Value	P-Value	Statistically Significant	Covariate	DF	F-Value	P-Value	Statistically Significant
Plantago major	Area	2	0.41	0.663	Not significant	Distance from Pipe	1	0.26	0.609	Not significant
Plantago maritima	Area	2	0.58	0.560	Not significant	Distance from Pipe	1	0.38	0.539	Not significant
Polypodium vulgare	Area	2	0.06	0.943	Not significant	Distance from Pipe	1	0.00	0.959	Not significant
Potentilla anserina	Area	2	1.57	0.212	Not significant	Distance from Pipe	1	0.50	0.605	Not significant
Potentilla erecta	Area	2	0.12	0.889	Not significant	Distance from Pipe	1	0.66	0.418	Not significant
Potentilla reptans	Area	2	0.20	0.818	Not significant	Distance from Pipe	1	0.87	0.352	Not significant
Pulicaria dysenterica	Area	2	1.73	0.180	Not significant	Distance from Pipe	1	9.46	0.002	Significant
Ranunculus acris	Area	2	0.64	0.529	Not significant	Distance from Pipe	1	1.31	0.254	Not significant
Ranunculus repens	Area	2	2.34	0.099	Not significant	Distance from Pipe	1	0.34	0.559	Not significant
Reseda lutea	Area	2	0.03	0.970	Not significant	Distance from Pipe	1	0.01	0.907	Not significant
Reseda luteola	Area	2	0.07	0.936	Not significant	Distance from Pipe	1	0.36	0.551	Not significant
Rhinanthus minor	Area	2	0.20	0.823	Not significant	Distance from Pipe	1	0.89	0.348	Not significant
Rosa sp.	Area	2	2.38	0.096	Not significant	Distance from Pipe	1	2.45	0.119	Not significant
Rubus caesius	Area	2	0.31	0.734	Not significant	Distance from Pipe	1	1.09	0.299	Not significant
Rubus fruticosus agg.	Area	2	0.80	0.453	Not significant	Distance from Pipe	1	0.30	0.586	Not significant
Rumex acetosa	Area	2	0.63	0.531	Not significant	Distance from Pipe	1	2.70	0.102	Not significant
Rumex acetosella	Area	2	0.09	0.910	Not significant	Distance from Pipe	1	0.24	0.622	Not significant
Rumex crispus	Area	2	0.59	0.558	Not significant	Distance from Pipe	1	2.14	0.145	Not significant
Scorzoneroides autumnalis	Area	2	0.26	0.774	Not significant	Distance from Pipe	1	0.39	0.534	Not significant
Senecio erucifolius	Area	2	0.44	0.647	Not significant	Distance from Pipe	1	0.61	0.437	Not significant
Senecio jacobaea	Area	2	1.13	0.324	Not significant	Distance from Pipe	1	0.44	0.509	Not significant
Senecio squalidus	Area	2	0.83	0.437	Not significant	Distance from Pipe	1	0.08	0.777	Not significant
Silene dioica	Area	2	2.75	0.067	Not significant	Distance from Pipe	1	0.17	0.684	Not significant
Silene gallica	Area	2	0.93	0.397	Not significant	Distance from Pipe	1	1.71	0.193	Not significant
Silene latifolia	Area	2	4.32	0.015	Significant	Distance from Pipe	1	1.48	0.226	Not significant
Sonchus arvensis	Area	2	0.44	0.643	Not significant	Distance from Pipe	1	1.10	0.295	Not significant
Sonchus oleraceus	Area	2	1.59	0.206	Not significant	Distance from Pipe	1	2.51	0.115	Not significant
Stellaria graminea	Area	2	2.19	0.115	Not significant	Distance from Pipe	1	4.16	0.043	Significant

Response	Factor	DF	F-Value	P-Value	Statistically Significant	Covariate	DF	F-Value	P-Value	Statistically Significant
Taraxacum sp.	Area	2	0.13	0.877	Not significant	Distance from Pipe	1	2.70	0.102	Not significant
Thalictrum minus	Area	2	1.94	0.147	Not significant	Distance from Pipe	1	1.98	0.162	Not significant
Torilis nodosa	Area	2	0.15	0.861	Not significant	Distance from Pipe	1	0.26	0.611	Not significant
Tragopogon pratensis	Area	2	0.35	0.706	Not significant	Distance from Pipe	1	0.31	0.576	Not significant
Trifolium arvense	Area	2	11.21	0.000	Significant	Distance from Pipe	1	1.20	0.275	Not significant
Trifolium campestre	Area	2	0.65	0.523	Not significant	Distance from Pipe	1	0.24	0.623	Not significant
Trifolium dubium	Area	2	0.45	0.639	Not significant	Distance from Pipe	1	0.02	0.897	Not significant
Trifolium pratense	Area	2	3.30	0.039	Significant	Distance from Pipe	1	5.72	0.018	Significant
Trifolium repens	Area	2	0.32	0.726	Not significant	Distance from Pipe	1	0.92	0.340	Not significant
Tussilago farfara	Area	2	0.04	0.962	Not significant	Distance from Pipe	1	0.08	0.773	Not significant
Urtica dioica	Area	2	2.74	0.067	Not significant	Distance from Pipe	1	8.73	0.004	Significant
Vicia cracca	Area	2	0.52	0.595	Not significant	Distance from Pipe	1	0.03	0.873	Not significant
Vicia hirsuta	Area	2	16.14	0.000	Significant	Distance from Pipe	1	4.81	0.030	Significant
Vicia sativa	Area	2	3.17	0.044	Significant	Distance from Pipe	1	0.63	0.427	Not significant
Barbula convoluta	Area	2	0.06	0.941	Not significant	Distance from Pipe	1	0.32	0.573	Not significant
Brachythecium albicans	Area	2	0.35	0.707	Not significant	Distance from Pipe	1	1.43	0.233	Not significant
Brachythecium rutabulum	Area	2	0.22	0.807	Not significant	Distance from Pipe	1	0.15	0.702	Not significant
Bryum sp.	Area	2	0.30	0.742	Not significant	Distance from Pipe	1	2.32	0.130	Not significant
Bryum pseudotriquetrum	Area	2	1.03	0.361	Not significant	Distance from Pipe	1	1.65	0.201	Not significant
Calliergonella cuspidata	Area	2	8.07	0.000	Significant	Distance from Pipe	1	0.26	6.080	Not significant
Ceratodon purpureus	Area	2	4.37	0.014	Significant	Distance from Pipe	1	0.04	0.847	Not significant
Didymodon fallax	Area	2	8.21	0.000	Significant	Distance from Pipe	1	2.23	0.137	Not significant
Hylocomium splendens	Area	2	4.48	0.013	Significant	Distance from Pipe	1	2.50	0.116	Not significant
Hypnum lacunosum	Area	2	3.24	0.041	Significant	Distance from Pipe	1	0.03	0.870	Not significant
Kindbergia praelonga	Area	2	16.11	0.000	Significant	Distance from Pipe	1	13.34	0.000	Significant
Oxyrrhynchium hians	Area	2	0.46	0.632	Not significant	Distance from Pipe	1	3.36	0.069	Not significant
Pellia endiviifolia	Area	2	3.05	0.050	Significant	Distance from Pipe	1	5.06	0.026	Significant
Peltigera sp.	Area	2	0.13	0.880	Not significant	Distance from Pipe	1	0.70	0.403	Not significant

Response	Factor	DF	F-Value	P-Value	Statistically Significant	Covariate	DF	F-Value	P-Value	Statistically Significant
Pseudoscleropodium purum	Area	2	1.19	0.306	Not significant	Distance from Pipe	1	1.07	0.302	Not significant
Rhynochostegium megapolitanum	Area	2	1.98	0.141	Not significant	Distance from Pipe	1	0.43	0.513	Not significant
Vegetation cover	Area	2	1.61	0.203	Not significant	Distance from Pipe	1	0.04	0.845	Not significant
Cover of bare ground	Area	2	0.38	0.685	Not significant	Distance from Pipe	1	0.34	0.563	Not significant
Graminoid cover	Area	2	0.64	0.527	Not significant	Distance from Pipe	1	0.00	0.955	Not significant
Herb cover	Area	2	0.16	0.852	Not significant	Distance from Pipe	1	0.26	0.613	Not significant
Moss cover	Area	2	8.23	0.000	Significant	Distance from Pipe	1	7.95	0.005	Significant
Annual cover	Area	2	2.03	0.135	Not significant	Distance from Pipe	1	1.39	0.240	Not significant
Perennial cover	Area	2	0.70	0.493	Not significant	Distance from Pipe	1	0.17	0.683	Not significant

Appendix Table 39 - Tukey Pairwise Comparison for dune grassland species using sample area.

Response	Sample Area	Difference of means	SE of difference	Simultaneous 95% CI		T-value	Adjusted P-value	Statistically Significant
Ammophila arenaria	On-Off	-0.659	0.224	-1.188	-0.130	-2.94	0.010	Significant
Ammophila arenaria	On-Adjacent	-0.179	0.122	-0.468	0.109	-1.47	0.309	Not significant
Bromus hordeaceus	On-Off	0.126	0.040	0.032	0.220	3.17	0.005	Significant
Bromus hordeaceus	On-Adjacent	-0.043	0.022	-0.094	0.008	-1.98	0.121	Not significant
Carex distans	On-Off	0.122	0.054	-0.006	0.250	2.25	0.065	Not significant
Carex distans	On-Adjacent	0.063	0.030	-0.007	0.132	2.13	0.087	Not significant
Festuca rubra	On-Off	0.641	0.322	-0.119	1.401	1.99	0.118	Not significant
Festuca rubra	On-Adjacent	-0.052	0.175	-0.937	-0.109	-2.98	0.009	Significant
Luzula campestris	On-Off	0.117	0.044	0.012	0.221	2.64	0.024	Significant
Luzula campestris	On-Adjacent	0.035	0.024	-0.022	0.092	1.44	0.323	Not significant
Poa humilis	On-Off	0.156	0.142	-0.178	0.491	1.11	0.512	Not significant
Poa humilis	On-Adjacent	-0.186	0.077	-0.368	-0.004	-2.41	0.045	Significant
Centaurea nigra	On-Off	0.227	0.083	0.031	0.424	2.74	0.019	Significant
Centaurea nigra	On-Adjacent	0.083	0.045	-0.024	0.190	1.83	0.164	Not significant
Clematis vitalba	On-Off	-0.042	0.012	-0.070	-0.013	-3.47	0.002	Significant
Clematis vitalba	On-Adjacent	-0.007	0.007	-0.022	0.008	-1.06	0.540	Not significant
Euphorbia portlandica	On-Off	0.136	0.050	0.017	0.255	2.71	0.020	Significant

Response	Sample Area	Difference of means	SE of difference	Simultaneous 95% CI		T-value	Adjusted P-value	Statistically Significant
Euphorbia portlandica	On-Adjacent	0.014	0.027	-0.051	0.079	0.52	0.864	Not significant
Glechoma hederacea	On-Off	-0.429	0.064	-0.581	-0.278	-6.68	0.000	Significant
Glechoma hederacea	On-Adjacent	-0.029	0.035	-0.112	0.054	-0.83	0.683	Not significant
Trifolium pratense	On-Off	0.022	0.258	-0.586	0.630	0.09	0.996	Not significant
Trifolium pratense	On-Adjacent	0.300	0.140	-0.032	0.631	2.14	0.086	Not significant
Vicia hirsuta	On-Off	-0.386	0.068	-0.546	-0.225	-5.66	0.000	Significant
Vicia hirsuta	On-Adjacent	-0.137	0.037	-0.224	-0.049	-3.68	0.001	Significant
Kindbergia praelonga	On-Off	0.126	0.040	0.032	0.220	3.17	0.005	Significant
Kindbergia praelonga	On-Adjacent	-0.043	0.022	-0.094	0.008	-1.98	0.121	Not significant
Pellia endiviifolia	On-Off	0.122	0.054	-0.006	0.250	2.25	0.065	Not significant
Pellia endiviifolia	On-Adjacent	0.063	0.030	-0.007	0.132	2.13	0.087	Not significant
Moss cover	On-Off	129.0	126.0	-168.0	425.0	1.03	0.562	Not significant
Moss cover	On-Adjacent	259.1	68.4	97.5	420.7	3.79	0.001	Significant

Appendix Table 40 - Results of General Linear Model, with Age Class (Factor) and Distance from Pipe (Covariate) for dune grassland species.

Response	Factor	DF	F-Value	P-Value	Statistically Significant	Covariate	DF	F-Value	P-Value	Statistically Significant
Agrostis stolonifera	Age Class	2	16.40	0.000	Significant	Distance from Pipe	1	0.99	0.321	Not significant
Ammophila arenaria	Age Class	2	8.65	0.000	Significant	Distance from Pipe	1	0.34	0.561	Not significant
Arrhenatherum elatius	Age Class	2	1.04	0.357	Not significant	Distance from Pipe	1	0.04	0.843	Not significant
Dactylis glomerata	Age Class	2	15.15	0.000	Significant	Distance from Pipe	1	0.32	0.571	Not significant
Elytrigia repens	Age Class	2	7.53	0.001	Significant	Distance from Pipe	1	0.24	0.624	Not significant
Festuca rubra	Age Class	2	18.48	0.000	Significant	Distance from Pipe	1	15.98	0.000	Significant
Holcus lanatus	Age Class	2	7.51	0.001	Significant	Distance from Pipe	1	0.00	0.965	Not significant
Poa humilis	Age Class	2	6.67	0.002	Significant	Distance from Pipe	1	13.01	0.000	Significant
Achillea millefolium	Age Class	2	0.73	0.485	Not significant	Distance from Pipe	1	0.00	0.974	Not significant
Anthyllis vulneraria	Age Class	2	9.39	0.000	Significant	Distance from Pipe	1	1.95	0.165	Not significant
Cerastium fontanum	Age Class	2	0.32	0.733	Not significant	Distance from Pipe	1	0.15	0.695	Not significant
Cirsium arvense	Age Class	2	0.09	0.917	Not significant	Distance from Pipe	1	0.06	0.803	Not significant
Equisetum arvense	Age Class	2	5.32	0.006	Significant	Distance from Pipe	1	4.52	0.035	Significant

Response	Factor	DF	F-Value	P-Value	Statistically Significant	Covariate	DF	F-Value	P-Value	Statistically Significant
Eupatorium cannabinum	Age Class	2	0.70	0.499	Not significant	Distance from Pipe	1	8.54	0.004	Significant
Galium verum	Age Class	2	24.42	0.000	Significant	Distance from Pipe	1	1.30	0.255	Not significant
Heracleum sphondylium	Age Class	2	0.53	0.589	Not significant	Distance from Pipe	1	2.51	0.115	Not significant
Lotus corniculatus	Age Class	2	9.58	0.000	Significant	Distance from Pipe	1	1.10	0.295	Not significant
Ononis repens	Age Class	2	2.32	0.101	Not significant	Distance from Pipe	1	4.83	0.029	Significant
Plantago lanceolata	Age Class	2	0.59	0.557	Not significant	Distance from Pipe	1	0.14	0.713	Not significant
Potentilla reptans	Age Class	2	6.04	0.003	Significant	Distance from Pipe	1	0.61	0.435	Not significant
Rhinanthus minor	Age Class	2	1.41	0.246	Not significant	Distance from Pipe	1	2.87	0.092	Not significant
Taraxacum sp.	Age Class	2	0.82	0.442	Not significant	Distance from Pipe	1	4.79	0.030	Significant
Trifolium pratense	Age Class	2	14.34	0.000	Significant	Distance from Pipe	1	5.23	0.023	Significant
Trifolium repens	Age Class	2	2.12	0.123	Not significant	Distance from Pipe	1	0.03	0.867	Not significant
Bryum pseudotriquetrum	Age Class	2	28.80	0.000	Significant	Distance from Pipe	1	4.00	0.047	Significant
Calliergonella cuspidata	Age Class	2	16.40	0.000	Significant	Distance from Pipe	1	0.99	0.321	Not significant
Ceratodon purpureus	Age Class	2	8.65	0.000	Significant	Distance from Pipe	1	0.34	0.561	Not significant
Hylocomium splendens	Age Class	2	1.04	0.357	Not significant	Distance from Pipe	1	0.04	0.843	Not significant
Oxyrrhynchium hians	Age Class	2	19.78	0.000	Significant	Distance from Pipe	1	0.01	0.910	Not significant
Rhynochostegium megapolitanum	Age Class	2	6.99	0.001	Significant	Distance from Pipe	1	0.93	0.335	Not significant
Vegetation cover	Age Class	2	1.57	0.211	Not significant	Distance from Pipe	1	0.52	0.472	Not significant
Cover of bare ground	Age Class	2	5.90	0.003	Significant	Distance from Pipe	1	0.25	0.619	Not significant
Graminoid cover	Age Class	2	0.17	0.842	Not significant	Distance from Pipe	1	1.11	0.295	Not significant
Herb cover	Age Class	2	0.36	0.698	Not significant	Distance from Pipe	1	0.05	0.830	Not significant
Moss cover	Age Class	2	90.03	0.000	Significant	Distance from Pipe	1	5.13	0.025	Significant
Annual cover	Age Class	3	2.24	0.109	Not significant	Distance from Pipe	1	1.16	0.282	Not significant
Perennial cover	Age Class	3	2.69	0.070	Not significant	Distance from Pipe	1	0.07	0.793	Not significant

Appendix Table 41 - Tukey Pairwise Comparison for dune grassland species using age class.

Response	Age-class	Difference of means	SE of difference	Simultaneous 95% CI		T-value	Adjusted P-value	Statistically Significant
Agrostis stolonifera	Short-Unaffected	-0.248	0.26	-0.863	0.366	-0.95	0.607	Not significant
Agrostis stolonifera	Short-Medium	0.58	0.106	0.33	0.829	5.48	0.000	Significant

Response	Age-class	Difference of means	SE of difference	Simultaneous 95% CI		T-value	Adjusted P-value	Statistically Significant
Agrostis stolonifera	Medium-Unaffected	0.331	0.233	-0.22	0.882	1.42	0.333	Not significant
Ammophila arenaria	Short-Unaffected	0.752	0.199	0.283	1.221	3.79	0.001	Significant
Ammophila arenaria	Short-Medium	-0.2603	0.0807	-0.4508	-0.0697	-3.23	0.004	Significant
Ammophila arenaria	Medium-Unaffected	0.492	0.178	0.071	0.913	2.76	0.017	Significant
Festuca rubra	Short-Unaffected	-0.703	0.287	-1.381	-0.025	-2.45	0.040	Significant
Festuca rubra	Short-Medium	-0.454	0.117	-0.729	-0.179	-0.39	0.000	Significant
Festuca rubra	Medium-Unaffected	-1.157	0.257	-1.765	-0.549	-4.50	0.000	Significant
Poa humilis	Short-Unaffected	-0.242	0.129	-0.547	0.063	-1.87	0.149	Not significant
Poa humilis	Short-Medium	-0.1035	0.0524	-0.2274	0.0204	-1.97	0.122	Not significant
Poa humilis	Medium-Unaffected	-0.345	0.116	-0.619	-0.07	-2.99	0.009	Significant
Equisetum arvense	Short-Unaffected	-0.71	0.239	-1.274	-0.145	-2.97	0.010	Significant
Equisetum arvense	Short-Medium	0.2461	0.0971	0.0167	0.4755	2.53	0.032	Significant
Equisetum arvense	Medium-Unaffected	-0.463	0.214	-0.97	0.043	-2.16	0.081	Not significant
Lotus corniculatus	Short-Unaffected	-0.501	0.212	-1.02	0.001	-2.36	0.051	Not significant
Lotus corniculatus	Short-Medium	0.3754	0.0862	0.1717	0.5791	4.35	0.000	Significant
Lotus corniculatus	Medium-Unaffected	-0.125	0.19	-0.575	0.324	-0.66	0.788	Not significant
Trifolium pratense	Short-Unaffected	-0.205	0.22	-0.726	0.315	-0.93	0.621	Not significant
Trifolium pratense	Short-Medium	0.4601	0.0896	0.2486	0.6716	5.14	0.000	Significant
Trifolium pratense	Medium-Unaffected	0.255	0.198	-0.212	0.721	1.29	0.404	Not significant
Bryum pseudotriquetrum	Short-Unaffected	0.262	0.139	-0.068	0.591	1.88	0.149	Not significant
Bryum pseudotriquetrum	Short-Medium	-0.4202	0.0566	-0.5539	-0.2864	-7.42	0.000	Significant
Bryum pseudotriquetrum	Medium-Unaffected	-0.159	0.125	-0.454	0.137	-1.27	0.415	Not significant
Calliergonella cuspidata	Short-Unaffected	-0.248	0.26	-0.863	0.366	-0.95	0.607	Not significant
Calliergonella cuspidata	Short-Medium	0.58	0.106	0.33	0.829	5.48	0.000	Significant
Calliergonella cuspidata	Medium-Unaffected	0.331	0.233	-0.22	0.882	1.42	0.333	Not significant
Ceratodon purpureus	Short-Unaffected	0.752	0.199	0.283	1.221	3.79	0.001	Significant
Ceratodon purpureus	Short-Medium	-0.2603	0.0807	-0.4508	-0.0697	-3.23	0.004	Significant
Ceratodon purpureus	Medium-Unaffected	0.492	0.178	0.071	0.913	2.76	0.017	Significant
Rhynochostegium megapolitanum	Short-Unaffected	0.1665	0.094	-0.0556	0.3886	1.77	0.183	Not significant
Rhynochostegium megapolitanum	Short-Medium	-0.1427	0.0382	-0.233	-0.0525	-3.70	0.001	Significant
Rhynochostegium megapolitanum	Medium-Unaffected	0.0238	0.0843	-0.1753	0.228	0.28	0.957	Not significant

Response	Age-class	Difference of means	SE of difference	Simultaneous 95% CI		T-value	Adjusted P-value	Statistically Significant
Moss cover	Short-Unaffected	-344.4	83.5	-541.5	-147.3	-4.13	0.000	Significant
Moss cover	Short-Medium	449.9	33.9	369.8	529.9	13.27	0.000	Significant
Moss cover	Medium-Unaffected	105.5	74.8	-71.2	282.2	1.41	0.338	Not significant

Dune Slacks

Appendix Table 42 - Results of General Linear Model, with sample area (factor) and distance from pipe (covariate) for dune slack species.

Response	Factor	DF	F-Value	P-Value	Statistically Significant	Covariate	DF	F-Value	P-Value	Statistically Significant
Agrostis stolonifera	Area	2	8.07	0.000	Significant	Distance from Pipe	1	0.26	0.608	Not significant
Ammophila arenaria	Area	2	4.37	0.014	Significant	Distance from Pipe	1	0.04	0.847	Not significant
Anisantha sterilis	Area	2	8.21	0.000	Significant	Distance from Pipe	1	2.23	0.137	Not significant
Agrostis capillaris	Area	2	0.29	0.751	Not significant	Distance from Pipe	1	0.32	0.572	Not significant
Agrostis stolonifera	Area	2	1.28	0.290	Not significant	Distance from Pipe	1	0.10	0.751	Not significant
Aira praecox	Area	2	1.28	0.289	Not significant	Distance from Pipe	1	3.92	0.054	Not significant
Ammophila arenaria	Area	2	0.06	0.940	Not significant	Distance from Pipe	1	1.32	0.940	Not significant
Anthoxanthum odoratum	Area	2	4.07	0.024	Significant	Distance from Pipe	1	10.70	0.002	Significant
Arrhenatherum elatius	Area	2	0.26	0.773	Not significant	Distance from Pipe	1	0.11	0.747	Not significant
Bolboschoenus maritimus	Area	2	13.63	0.000	Significant	Distance from Pipe	1	0.40	0.532	Not significant
Bromus hordeaceus	Area	2	0.07	0.936	Not significant	Distance from Pipe	1	1.50	0.228	Not significant
Carex arenaria	Area	2	3.44	0.042	Significant	Distance from Pipe	1	0.36	0.553	Not significant
Carex distans	Area	2	0.25	0.783	Not significant	Distance from Pipe	1	4.34	0.044	Significant
Carex flacca	Area	2	3.09	0.056	Not significant	Distance from Pipe	1	1.36	0.250	Not significant
Carex hirta	Area	2	2.08	0.138	Not significant	Distance from Pipe	1	4.62	0.038	Significant
Carex nigra	Area	2	5.35	0.009	Significant	Distance from Pipe	1	10.40	0.002	Significant
Catapodium rigidum	Area	2	0.03	0.968	Not significant	Distance from Pipe	1	0.75	0.392	Not significant
Cynosurus cristatus	Area	2	0.64	0.531	Not significant	Distance from Pipe	1	1.42	0.240	Not significant
Dactylis glomerata	Area	2	1.73	0.191	Not significant	Distance from Pipe	1	0.85	0.361	Not significant

Response	Factor	DF	F-Value	P-Value	Statistically Significant	Covariate	DF	F-Value	P-Value	Statistically Significant
Danthonia decumbens	Area	2	1.28	0.289	Not significant	Distance from Pipe	1	3.92	0.054	Not significant
Eleocharis uniglumis	Area	2	9.05	0.001	Significant	Distance from Pipe	1	0.26	0.614	Not significant
Eleocharis quinqueflora	Area	2	23.64	0.000	Significant	Distance from Pipe	1	0.07	0.793	Not significant
Festuca rubra	Area	2	2.52	0.093	Not significant	Distance from Pipe	1	9.04	0.004	Significant
Holcus lanatus	Area	2	8.40	0.001	Significant	Distance from Pipe	1	0.62	0.434	Not significant
Juncus articulatus	Area	2	2.02	0.145	Not significant	Distance from Pipe	1	3.04	0.089	Not significant
Juncus gerardii	Area	2	2.26	0.117	Not significant	Distance from Pipe	1	0.63	0.430	Not significant
Juncus inflexus	Area	2	0.26	0.773	Not significant	Distance from Pipe	1	0.22	0.640	Not significant
Luzula campestris	Area	2	3.50	0.040	Significant	Distance from Pipe	1	7.12	0.011	Significant
Poa humilis	Area	2	0.66	0.522	Not significant	Distance from Pipe	1	2.26	0.141	Not significant
Schedonorus arundinaceus	Area	2	0.09	0.913	Not significant	Distance from Pipe	1	2.07	0.157	Not significant
Schoenoplectus tabernaemontani	Area	2	3.77	0.032	Significant	Distance from Pipe	1	0.53	0.472	Not significant
Achillea millefolium	Area	2	1.24	0.301	Not significant	Distance from Pipe	1	1.87	0.179	Not significant
Angelica sylvestris	Area	2	0.04	0.962	Not significant	Distance from Pipe	1	0.90	0.349	Not significant
Anthyllis vulneraria	Area	2	0.22	0.806	Not significant	Distance from Pipe	1	2.08	0.157	Not significant
Arenaria serpyllifolia	Area	2	0.06	0.946	Not significant	Distance from Pipe	1	1.02	0.317	Not significant
Artemisia vulgaris	Area	2	0.04	0.958	Not significant	Distance from Pipe	1	0.98	0.327	Not significant
Blackstonia perfoliata	Area	2	3.11	0.055	Not significant	Distance from Pipe	1	4.73	0.035	Significant
Cardamine pratensis	Area	2	5.14	0.010	Significant	Distance from Pipe	1	0.01	0.930	Not significant
Carlina vulgaris	Area	2	0.22	0.804	Not significant	Distance from Pipe	1	5.09	0.029	Not significant
Centaurium erythraea	Area	2	5.02	0.011	Significant	Distance from Pipe	1	10.73	0.002	Significant
Centaurium littorale	Area	2	1.09	0.345	Not significant	Distance from Pipe	1	1.04	0.313	Not significant
Cerastium fontanum	Area	2	1.72	0.192	Not significant	Distance from Pipe	1	0.32	0.576	Not significant
Cirsium arvense	Area	2	0.15	0.860	Not significant	Distance from Pipe	1	2.79	0.102	Not significant
Cirsium vulgare	Area	2	0.04	0.966	Not significant	Distance from Pipe	1	0.24	0.627	Not significant
Convolvulus arvensis	Area	2	0.10	0.902	Not significant	Distance from Pipe	1	2.33	0.134	Not significant
Crepis capillaris	Area	2	0.03	0.972	Not significant	Distance from Pipe	1	0.43	0.518	Not significant
Dactylorhiza purpurella	Area	2	5.51	0.008	Significant	Distance from Pipe	1	6.51	0.015	Significant

Response	Factor	DF	F-Value	P-Value	Statistically Significant	Covariate	DF	F-Value	P-Value	Statistically Significant
Daucus carota	Area	2	0.04	0.958	Not significant	Distance from Pipe	1	0.98	0.327	Not significant
Diplotaxis tenuifolia	Area	2	0.07	0.932	Not significant	Distance from Pipe	1	1.63	0.208	Not significant
Equisetum arvense	Area	2	1.38	0.264	Not significant	Distance from Pipe	1	0.01	0.918	Not significant
Erigeron acris	Area	2	1.33	0.275	Not significant	Distance from Pipe	1	2.15	0.150	Not significant
Eupatorium cannabinum	Area	2	2.55	0.091	Not significant	Distance from Pipe	1	0.19	0.660	Not significant
Euphrasia sp.	Area	2	8.10	0.001	Significant	Distance from Pipe	1	10.72	0.002	Significant
Glaux maritima	Area	2	8.77	0.001	Significant	Distance from Pipe	1	0.14	0.712	Not significant
Hieracium sp.	Area	2	0.22	0.800	Not significant	Distance from Pipe	1	5.23	0.027	Significant
Hippophae rhamnoides	Area	2	0.04	0.962	Not significant	Distance from Pipe	1	0.90	0.349	Not significant
Hydrocotyle vulgaris	Area	2	0.00	0.998	Not significant	Distance from Pipe	1	0.91	0.345	Not significant
Hypochaeris radicata	Area	2	1.91	0.160	Not significant	Distance from Pipe	1	0.17	0.682	Not significant
Leontodon saxatilis	Area	2	5.71	0.007	Significant	Distance from Pipe	1	20.71	0.000	Significant
Linaria vulgaris	Area	2	0.06	0.943	Not significant	Distance from Pipe	1	1.03	0.316	Not significant
Linum catharticum	Area	2	3.13	0.054	Not significant	Distance from Pipe	1	0.40	0.528	Not significant
Lotus corniculatus	Area	2	12.91	0.000	Significant	Distance from Pipe	1	3.10	0.086	Not significant
Medicago lupulina	Area	2	0.03	0.969	Not significant	Distance from Pipe	1	0.29	0.592	Not significant
Melilotus officinalis	Area	2	3.07	0.057	Not significant	Distance from Pipe	1	1.26	0.267	Not significant
Mentha aquatica	Area	2	0.28	0.761	Not significant	Distance from Pipe	1	1.41	0.243	Not significant
Oenanthe lachenalii	Area	2	2.35	0.108	Not significant	Distance from Pipe	1	2.26	0.141	Not significant
Ononis repens	Area	2	1.20	0.310	Not significant	Distance from Pipe	1	27.28	0.000	Significant
Pilosella officinarum	Area	2	0.49	0.614	Not significant	Distance from Pipe	1	0.99	0.325	Not significant
Plantago lanceolata	Area	2	4.14	0.023	Significant	Distance from Pipe	1	0.05	0.819	Not significant
Plantago maritima	Area	2	1.90	0.163	Not significant	Distance from Pipe	1	3.17	0.082	Not significant
Polypodium vulgare	Area	2	2.03	0.144	Not significant	Distance from Pipe	1	4.41	0.042	Significant
Potentilla anserina	Area	2	1.54	0.227	Not significant	Distance from Pipe	1	0.00	0.981	Not significant
Potentilla reptans	Area	2	5.74	0.006	Significant	Distance from Pipe	1	5.31	0.026	Significant
Prunella vulgaris	Area	2	7.32	0.002	Significant	Distance from Pipe	1	17.87	0.000	Significant
Pulicaria dysenterica	Area	2	9.50	0.000	Significant	Distance from Pipe	1	0.49	0.489	Not significant

Response	Factor	DF	F-Value	P-Value	Statistically Significant	Covariate	DF	F-Value	P-Value	Statistically Significant
Ranunculus acris	Area	2	0.35	0.707	Not significant	Distance from Pipe	1	0.00	0.999	Not significant
Ranunculus flammula	Area	2	0.23	0.799	Not significant	Distance from Pipe	1	0.21	0.647	Not significant
Ranunculus repens	Area	2	4.63	0.015	Significant	Distance from Pipe	1	0.24	0.626	Not significant
Rhinanthus minor	Area	2	3.49	0.040	Significant	Distance from Pipe	1	11.65	0.001	Significant
Rosa sp.	Area	2	2.58	0.088	Not significant	Distance from Pipe	1	0.41	0.525	Not significant
Rubus caesius	Area	2	5.93	0.005	Significant	Distance from Pipe	1	11.14	0.002	Significant
Rubus fruticosus agg.	Area	2	0.12	0.883	Not significant	Distance from Pipe	1	2.90	0.096	Not significant
Rumex acetosa	Area	2	0.35	0.704	Not significant	Distance from Pipe	1	0.10	0.748	Not significant
Rumex crispus	Area	2	0.03	0.972	Not significant	Distance from Pipe	1	0.43	0.518	Not significant
Sagina nodosa	Area	2	10.38	0.000	Significant	Distance from Pipe	1	26.47	0.000	Significant
Salix cinerea	Area	2	4.19	0.022	Significant	Distance from Pipe	1	7.65	0.008	Significant
Salix repens	Area	2	3.53	0.038	Significant	Distance from Pipe	1	9.83	0.003	Significant
Scorzoneroides autumnalis	Area	2	4.61	0.016	Significant	Distance from Pipe	1	0.99	0.326	Not significant
Senecio erucifolius	Area	2	0.33	0.720	Not significant	Distance from Pipe	1	1.25	0.270	Not significant
Senecio jacobaea	Area	2	1.29	0.286	Not significant	Distance from Pipe	1	0.01	0.933	Not significant
Senecio squalidus	Area	2	0.04	0.966	Not significant	Distance from Pipe	1	0.24	0.627	Not significant
Sonchus oleraceus	Area	2	1.51	0.233	Not significant	Distance from Pipe	1	0.01	0.921	Not significant
Taraxacum sp.	Area	2	1.03	0.367	Not significant	Distance from Pipe	1	0.47	0.499	Not significant
Trifolium dubium	Area	2	0.09	0.918	Not significant	Distance from Pipe	1	1.36	0.251	Not significant
Trifolium micranthum	Area	2	1.79	0.181	Not significant	Distance from Pipe	1	4.54	0.039	Significant
Trifolium pratense	Area	2	3.79	0.031	Significant	Distance from Pipe	1	6.87	0.012	Significant
Trifolium repens	Area	2	3.60	0.036	Significant	Distance from Pipe	1	0.96	0.332	Not significant
Tussilago farfara	Area	2	0.24	0.788	Not significant	Distance from Pipe	1	5.55	0.023	Significant
Typha latifolia	Area	2	0.36	0.697	Not significant	Distance from Pipe	1	0.32	0.576	Not significant
Vicia sativa	Area	2	1.00	0.377	Not significant	Distance from Pipe	1	0.14	0.707	Not significant
Brachythecium albicans	Area	2	2.30	0.113	Not significant	Distance from Pipe	1	2.55	0.118	Not significant
Brachythecium rutabulum	Area	2	0.15	0.865	Not significant	Distance from Pipe	1	3.35	0.074	Not significant
Bryum pseudotriquetrum	Area	2	0.29	0.751	Not significant	Distance from Pipe	1	0.32	0.572	Not significant

Response	Factor	DF	F-Value	P-Value	Statistically Significant	Covariate	DF	F-Value	P-Value	Statistically Significant
Calliergonella cuspidata	Area	2	1.28	0.290	Not significant	Distance from Pipe	1	0.10	0.751	Not significant
Camphyliadelphus chrysophyllus	Area	2	1.28	0.289	Not significant	Distance from Pipe	1	3.92	0.054	Not significant
Ceratodon purpureus	Area	2	1.32	0.257	Not significant	Distance from Pipe	1	0.06	0.940	Not significant
Drepanocladus polygamus	Area	2	4.07	0.024	Significant	Distance from Pipe	1	10.70	0.002	Significant
Hylocomium splendens	Area	2	0.26	0.773	Not significant	Distance from Pipe	1	0.11	0.747	Not significant
Hypnum cupressiforme	Area	2	13.63	0.000	Significant	Distance from Pipe	1	0.40	0.532	Not significant
Kindbergia praelonga	Area	2	0.07	0.936	Not significant	Distance from Pipe	1	1.50	0.228	Not significant
Rhytidiadelphus squarrosus	Area	2	5.35	0.009	Significant	Distance from Pipe	1	10.40	0.002	Significant
Syntrichia intermedia	Area	2	0.03	0.968	Not significant	Distance from Pipe	1	0.75	0.392	Not significant
Syntrichia ruralis	Area	2	0.64	0.531	Not significant	Distance from Pipe	1	1.42	0.240	Not significant
Vegetation cover	Area	2	0.42	0.658	Not significant	Distance from Pipe	1	0.00	0.991	Not significant
Cover of bare ground	Area	2	11.50	0.000	Significant	Distance from Pipe	1	17.85	0.000	Significant
Graminoid cover	Area	2	3.53	0.038	Significant	Distance from Pipe	1	0.38	0.541	Not significant
Herb cover	Area	2	8.42	0.001	Significant	Distance from Pipe	1	0.48	0.493	Not significant
Moss cover	Area	2	15.05	0.000	Significant	Distance from Pipe	1	35.15	0.000	Significant
Annual cover	Area	2	1.21	0.309	Not significant	Distance from Pipe	1	0.11	0.737	Not significant
Perennial cover	Area	2	0.78	0.467	Not significant	Distance from Pipe	1	0.00	0.964	Not significant

Appendix Table 43 - Tukey Pairwise Comparison for dune slack species using sample area.

Response	Sample Area	Difference of means	SE of difference	Simultaneous 95% CI		T-value	Adjusted P-value	Statistically Significant
Anthoxanthum odoratum	On-Off	0.156	0.061	0.009	0.304	2.57	0.004	Significant
Anthoxanthum odoratum	On-Adjacent	0.093	0.049	0.026	0.211	1.90	0.151	Not significant
Bolboschoenus maritimus	On-Off	-0.911	0.183	-1.357	-0.466	-4.98	0.000	Significant
Bolboschoenus maritimus	On-Adjacent	0.015	0.147	-0.342	0.372	0.10	0.994	Not significant
Carex nigra	On-Off	-0.322	0.100	-0.566	-0.079	-3.22	0.007	Significant
Carex nigra	On-Adjacent	-0.028	0.080	-0.022	0.167	-0.04	0.934	Not significant
Eleocharis quinqueflora	On-Off	-0.703	0.108	-0.966	-0.439	-6.48	0.000	Significant
Eleocharis quinqueflora	On-Adjacent	0.034	0.087	-0.178	0.245	0.39	0.921	Not significant

Response	Sample Area	Difference of means	SE of difference	Simultaneous 95% CI		T-value	Adjusted P-value	Statistically Significant
Holcus lanatus	On-Off	0.450	0.181	0.010	0.890	2.49	0.044	Significant
Holcus lanatus	On-Adjacent	0.555	0.145	0.202	0.908	3.82	0.001	Significant
Luzula campestris	On-Off	0.139	0.060	-0.006	0.284	2.33	0.062	Not significant
Luzula campestris	On-Adjacent	0.088	0.048	-0.028	0.204	1.85	0.167	Not significant
Centaurium erythraea	On-Off	0.170	0.061	0.023	0.318	2.81	0.020	Significant
Centaurium erythraea	On-Adjacent	0.107	0.486	-0.012	0.225	2.19	0.084	Not significant
Dactylorhiza purpurella	On-Off	-0.379	0.114	-0.657	-0.100	-3.31	0.005	Significant
Dactylorhiza purpurella	On-Adjacent	-0.063	0.092	-0.285	0.161	-0.68	0.775	Not significant
Euphrasia sp.	On-Off	0.567	0.190	0.104	1.030	2.98	0.013	Significant
Euphrasia sp.	On-Adjacent	0.523	0.152	0.152	0.894	3.43	0.004	Significant
Glaux maritima	On-Off	-0.483	0.115	-0.764	-0.202	-4.18	0.000	Significant
Glaux maritima	On-Adjacent	-0.088	0.093	-0.313	0.137	-0.95	0.610	Not significant
Leontodon saxatilis	On-Off	0.210	0.111	-0.062	0.481	1.88	0.158	Not significant
Leontodon saxatilis	On-Adjacent	0.288	0.089	0.071	0.505	3.22	0.007	Significant
Lotus corniculatus	On-Off	0.918	0.235	0.349	1.487	3.93	0.001	Significant
Lotus corniculatus	On-Adjacent	0.786	0.187	0.331	1.242	4.20	0.000	Significant
Ononis repens	On-Off	-0.220	0.242	-0.807	0.368	-0.91	0.637	Not significant
Ononis repens	On-Adjacent	0.184	0.194	-0.287	0.655	0.95	0.611	Not significant
Potentilla reptans	On-Off	0.531	0.189	0.073	0.990	2.82	0.020	Significant
Potentilla reptans	On-Adjacent	0.392	0.151	0.024	0.759	2.59	0.034	Significant
Prunella vulgaris	On-Off	0.608	0.177	0.177	1.040	3.43	0.004	Significant
Prunella vulgaris	On-Adjacent	0.368	0.142	0.022	0.714	2.59	0.035	Significant
Pulicaria dysenterica	On-Off	-0.397	0.100	-0.641	-0.153	-3.96	0.001	Significant
Pulicaria dysenterica	On-Adjacent	0.052	0.080	-0.014	0.247	0.64	0.797	Not significant
Rhinanthus minor	On-Off	-0.536	0.221	-1.073	0.001	-2.43	0.051	Not significant
Rhinanthus minor	On-Adjacent	0.057	0.221	-1.073	0.001	0.32	0.944	Not significant
Rubus caesius	On-Off	0.309	0.102	0.060	0.558	3.02	0.012	Significant
Rubus caesius	On-Adjacent	0.200	0.082	0.000	0.399	2.44	0.050	Significant
Sagina nodosa	On-Off	0.247	0.060	0.101	0.394	4.10	0.001	Significant
Sagina nodosa	On-Adjacent	0.148	0.048	0.030	0.266	3.06	0.011	Significant
Salix cinerea	On-Off	0.453	0.179	0.018	0.888	2.53	0.040	Significant

Response	Sample Area	Difference of means	SE of difference	Simultaneous 95% CI		T-value	Adjusted P-value	Statistically Significant
Salix cinerea	On-Adjacent	0.295	0.143	-0.054	0.643	2.05	0.112	Not significant
Salix repens	On-Off	0.383	0.159	-0.004	0.769	2.41	0.053	Significant
Salix repens	On-Adjacent	0.223	0.159	-0.087	0.263	-0.92	0.631	Not significant
Scorzoneroides autumnalis	On-Off	-0.412	0.138	-0.747	-0.077	-2.99	0.013	Significant
Scorzoneroides autumnalis	On-Adjacent	-0.146	0.110	-0.414	0.123	-1.32	0.392	Not significant
Trifolium pratense	On-Off	-0.384	0.165	-0.786	0.017	-2.33	0.063	Not significant
Trifolium pratense	On-Adjacent	0.101	0.132	-0.221	0.422	0.76	0.729	Not significant
Drepanocladus polygamus	On-Off	0.156	0.061	0.009	0.340	2.57	0.036	Significant
Drepanocladus polygamus	On-Adjacent	0.093	0.049	-0.026	0.211	1.90	0.151	Not significant
Hypnum cupressiforme	On-Off	-0.911	0.180	-1.357	-0.466	-4.98	0.000	Significant
Hypnum cupressiforme	On-Adjacent	0.015	0.147	-0.342	0.372	0.10	0.994	Significant
Rhytidiadelphus squarrosus	On-Off	-0.322	0.100	-0.566	-0.079	-3.22	0.007	Significant
Rhytidiadelphus squarrosus	On-Adjacent	-0.028	0.080	-0.223	0.167	-0.35	0.934	Not significant
Cover of bare ground	On-Off	-1.567	0.395	-2.527	-0.608	-3.97	0.001	Significant
Cover of bare ground	On-Adjacent	0.464	0.316	-0.306	1.233	1.47	0.318	Not significant
Herb cover	On-Off	0.123	0.149	-0.024	0.486	0.83	0.690	Not significant
Herb cover	On-Adjacent	0.489	0.120	0.198	0.780	4.09	0.001	Significant
Moss cover	On-Off	-131.6	24.3	-190.6	-72.6	-5.43	0.000	Significant
Moss cover	On-Adjacent	-14.2	19.4	-61.5	33.1	-0.73	0.746	Not significant

Appendix Table 44 - Results of General Linear Model, with age class (factor) and distance from pipe (covariate) for dune grassland species.

Response	Factor	DF	F-Value	P-Value	Statistically Significant	Covariate	DF	F-Value	P-Value	Statistically Significant
Agrostis stolonifera	Age Class	2	0.08	0.92	Not significant	Distance from Pipe	1	0.01	0.920	Not significant
Bolboschoenus maritimus	Age Class	2	17.14	0.000	Significant	Distance from Pipe	1	2.54	0.118	Not significant
Carex arenaria	Age Class	2	1.15	0.328	Not significant	Distance from Pipe	1	0.05	0.833	Not significant
Carex distans	Age Class	2	6.07	0.005	Significant	Distance from Pipe	1	0.55	0.463	Not significant
Carex flacca	Age Class	2	1.62	0.210	Not significant	Distance from Pipe	1	0.09	0.762	Not significant
Dactylis glomerata	Age Class	2	0.21	0.808	Not significant	Distance from Pipe	1	1.98	0.167	Not significant
Eleocharis uniglumis	Age Class	2	3.14	0.054	Not significant	Distance from Pipe	1	7.04	0.011	Significant
Eleocharis quinqueflora	Age Class	2	24.10	0.000	Significant	Distance from Pipe	1	0.00	0.995	Not significant

Response	Factor	DF	F-Value	P-Value	Statistically Significant	Covariate	DF	F-Value	P-Value	Statistically Significant
Festuca rubra	Age Class	2	0.05	0.953	Not significant	Distance from Pipe	1	9.65	0.003	Significant
Holcus lanatus	Age Class	2	0.81	0.452	Not significant	Distance from Pipe	1	0.13	0.722	Not significant
Juncus gerardii	Age Class	2	1.67	0.200	Not significant	Distance from Pipe	1	3.13	0.084	Not significant
Dactylorhiza purpurella	Age Class	2	8.72	0.001	Significant	Distance from Pipe	1	1.50	0.227	Not significant
Equisetum arvense	Age Class	2	2.36	0.107	Not significant	Distance from Pipe	1	1.05	0.311	Not significant
Euphrasia sp.	Age Class	2	6.38	0.004	Significant	Distance from Pipe	1	0.44	0.511	Not significant
Glaux maritima	Age Class	2	12.67	0.000	Significant	Distance from Pipe	1	1.20	0.280	Not significant
Hydrocotyle vulgaris	Age Class	2	0.02	0.982	Not significant	Distance from Pipe	1	0.96	0.334	Not significant
Hypochaeris radicata	Age Class	2	0.13	0.882	Not significant	Distance from Pipe	1	0.90	0.347	Not significant
Leontodon saxatilis	Age Class	2	4.91	0.012	Significant	Distance from Pipe	1	3.64	0.063	Not significant
Linum catharticum	Age Class	2	1.16	0.322	Not significant	Distance from Pipe	1	0.14	0.711	Not significant
Lotus corniculatus	Age Class	2	4.79	0.013	Significant	Distance from Pipe	1	0.20	0.645	Not significant
Ononis repens	Age Class	2	3.61	0.036	Significant	Distance from Pipe	1	18.70	0.000	Significant
Plantago lanceolata	Age Class	2	0.09	0.911	Not significant	Distance from Pipe	1	0.55	0.463	Not significant
Potentilla anserina	Age Class	2	0.89	0.417	Not significant	Distance from Pipe	1	1.08	0.304	Not significant
Potentilla reptans	Age Class	2	9.52	0.000	Significant	Distance from Pipe	1	0.04	0.851	Not significant
Prunella vulgaris	Age Class	2	9.59	0.000	Significant	Distance from Pipe	1	3.36	0.074	Not significant
Pulicaria dysenterica	Age Class	2	9.49	0.000	Significant	Distance from Pipe	1	0.29	0.591	Not significant
Rhinanthus minor	Age Class	2	14.90	0.000	Significant	Distance from Pipe	1	3.72	0.061	Not significant
Salix cinerea	Age Class	2	4.14	0.023	Significant	Distance from Pipe	1	1.11	0.298	Not significant
Scorzoneroides autumnalis	Age Class	2	5.34	0.009	Significant	Distance from Pipe	1	0.06	0.813	Not significant
Senecio erucifolius	Age Class	2	5.93	0.005	Significant	Distance from Pipe	1	0.10	0.754	Not significant
Sonchus oleraceus	Age Class	2	0.55	0.583	Not significant	Distance from Pipe	1	0.31	0.583	Not significant
Taraxacum sp.	Age Class	2	1.26	0.295	Not significant	Distance from Pipe	1	0.00	0.947	Not significant
Trifolium pratense	Age Class	2	5.16	0.010	Significant	Distance from Pipe	1	3.77	0.059	Not significant
Trifolium repens	Age Class	2	3.79	0.031	Significant	Distance from Pipe	1	0.49	0.488	Not significant
Bryum pseudotriquetrum	Age Class	2	0.44	0.649	Not significant	Distance from Pipe	1	1.34	0.253	Not significant
Calliergonella cuspidata	Age Class	2	0.08	0.920	Not significant	Distance from Pipe	1	0.01	0.920	Not significant
Hypnum cupressiforme	Age Class	2	17.14	0.000	Significant	Distance from Pipe	1	2.54	0.118	Not significant
Oxyrrhynchium hians	Age Class	2	1.15	0.328	Not significant	Distance from Pipe	1	0.05	0.833	Not significant
Pellia endiviifolia	Age Class	2	6.07	0.005	Significant	Distance from Pipe	1	0.55	0.463	Not significant

Response	Factor	DF	F-Value	P-Value	Statistically Significant	Covariate	DF	F-Value	P-Value	Statistically Significant
Pseudoscleropodium purum	Age Class	2	1.62	0.210	Not significant	Distance from Pipe	1	0.09	0.762	Not significant
Vegetation cover	Age Class	2	5.45	0.008	Significant	Distance from Pipe	1	2.65	0.111	Not significant
Cover of bare ground	Age Class	2	17.55	0.000	Significant	Distance from Pipe	1	10.64	0.002	Significant
Graminoid cover	Age Class	2	0.40	0.674	Not significant	Distance from Pipe	1	0.32	0.576	Not significant
Herb cover	Age Class	2	0.07	0.935	Not significant	Distance from Pipe	1	0.11	0.747	Not significant
Moss cover	Age Class	2	52.11	0.000	Significant	Distance from Pipe	1	20.64	0.000	Significant
Annual cover	Age Class	2	0.09	0.919	Not significant	Distance from Pipe	1	0.09	0.766	Not significant
Perennial cover	Age Class	2	3.22	0.050	Significant	Distance from Pipe	1	0.86	0.360	Not significant

Appendix Table 45 - Tukey Pairwise Comparison for dune slack species using age class.

Response	Age-class	Difference of means	SE of difference	Simultaneous 95% CI		T-value	Adjusted P-value	Statistically Significant
Bolboschoenus maritimus	Short-Unaffected	1.091	0.187	0.635	1.547	5.82	0.000	Significant
Bolboschoenus maritimus	Short-Medium	-0.231	0.112	-0.504	0.042	-2.06	0.112	Not significant
Bolboschoenus maritimus	Medium-Unaffected	0.86	0.169	0.448	1.272	5.08	0.000	Significant
Eleocharis uniglumis	Short-Unaffected	-0.389	0.323	-1.174	0.397	-1.20	0.458	Not significant
Eleocharis uniglumis	Short-Medium	0.484	0.193	0.014	0.955	2.50	0.042	Significant
Eleocharis uniglumis	Medium-Unaffected	0.095	0.292	-0.615	0.806	0.33	0.943	Not significant
Eleocharis quinqueflora	Short-Unaffected	0.674	0.116	0.392	0.957	5.81	0.000	Significant
Eleocharis quinqueflora	Short-Medium	0.0529	0.0695	-0.1162	0.2219	0.76	0.729	Not significant
Eleocharis quinqueflora	Medium-Unaffected	0.727	0.105	0.472	0.983	6.93	0.000	Significant
Dactylorhiza purpurella	Short-Unaffected	0.233	0.116	-0.05	0.515	2.01	0.124	Not significant
Dactylorhiza purpurella	Short-Medium	0.1641	0.0695	-0.0049	0.3332	2.36	0.059	Not significant
Dactylorhiza purpurella	Medium-Unaffected	0.397	0.105	0.142	0.652	3.78	0.001	Significant
Euphrasia sp.	Short-Unaffected	-0.104	0.211	-0.618	0.41	-0.49	0.875	Not significant
Euphrasia sp.	Short-Medium	-0.371	0.126	-0.678	-0.063	-2.93	0.015	Significant
Euphrasia sp.	Medium-Unaffected	-0.475	0.191	-0.939	-0.011	-2.49	0.044	Significant
Glaux maritima	Short-Unaffected	0.317	0.117	0.034	0.601	2.72	0.025	Significant
Glaux maritima	Short-Medium	0.1781	0.0699	0.0082	0.3481	2.55	0.038	Significant
Glaux maritima	Medium-Unaffected	0.496	0.105	0.239	0.752	4.70	0.000	Significant
Leontodon saxatilis	Short-Unaffected	0.055	0.122	-0.242	0.351	0.45	0.895	Not significant

Response	Age-class	Difference of means	SE of difference	Simultaneous 95% CI		T-value	Adjusted P-value	Statistically Significant
Leontodon saxatilis	Short-Medium	-2165	0.0729	-0.3939	-0.0391	-2.97	0.014	Significant
Leontodon saxatilis	Medium-Unaffected	-0.162	0.11	-0.43	0.106	-1.47	0.316	Not significant
Ononis repens	Short-Unaffected	0.022	0.247	-0.578	0.621	0.09	0.996	Not significant
Ononis repens	Short-Medium	0.348	0.148	-0.011	0.707	2.36	0.059	Not significant
Ononis repens	Medium-Unaffected	0.369	0.223	-0.173	0.912	1.66	0.234	Not significant
Potentilla reptans	Short-Unaffected	-0.078	0.19	-0.539	0.384	-0.41	0.912	Not significant
Potentilla reptans	Short-Medium	0.419	0.114	-0.695	-0.143	-3.69	0.002	Significant
Potentilla reptans	Medium-Unaffected	-0.497	0.171	-0.914	-0.08	-2.90	0.016	Significant
Prunella vulgaris	Short-Unaffected	-0.209	0.184	-0.656	0.237	-1.14	0.495	Not significant
Prunella vulgaris	Short-Medium	-0.358	0.11	-0.625	-0.091	-3.26	0.006	Significant
Prunella vulgaris	Medium-Unaffected	-0.567	0.166	-0.971	-0.164	-3.42	0.004	Significant
Pulicaria dysenterica	Short-Unaffected	0.384	0.108	0.122	0.647	3.56	0.003	Significant
Pulicaria dysenterica	Short-Medium	0.0406	0.0646	-0.1165	0.1977	0.63	0.806	Not significant
Pulicaria dysenterica	Medium-Unaffected	0.4248	0.0975	0.1876	0.662	4.36	0.000	Not significant
Rhinanthus minor	Short-Unaffected	0.164	0.196	-0.312	0.639	0.84	0.683	Not significant
Rhinanthus minor	Short-Medium	0.519	0.117	0.234	0.804	4.43	0.000	Significant
Rhinanthus minor	Medium-Unaffected	0.683	0.177	0.253	1.113	3.86	0.001	Significant
Hypnum cupressiforme	Short-Unaffected	1.091	0.187	0.635	1.547	5.82	0.000	Significant
Hypnum cupressiforme	Short-Medium	-0.231	0.112	-0.504	0.042	-2.06	0.112	Not significant
Hypnum cupressiforme	Medium-Unaffected	0.86	0.169	0.448	1.272	5.08	0.000	Significant
Pellia endiviifolia	Short-Unaffected	-0.286	0.3	-1.016	0.443	-0.95	0.610	Not significant
Pellia endiviifolia	Short-Medium	0.614	0.18	0.178	1.051	3.42	0.004	Significant
Pellia endiviifolia	Medium-Unaffected	0.328	0.271	-0.331	0.988	1.21	0.454	Not significant
Vegetation cover	Short-Unaffected	-0.0571	0.0261	-1206	0.0064	-2.19	0.085	Not significant
Vegetation cover	Short-Medium	0.0499	0.156	0.0119	0.0879	3.19	0.007	Significant
Vegetation cover	Medium-Unaffected	-0.0072	0.0236	-0.0646	0.0502	-0.31	0.950	Not significant
Cover of bare ground	Short-Unaffected	1.164	0.389	0.217	2.111	2.99	0.013	Significant
Cover of bare ground	Short-Medium	0.749	0.233	0.182	1.316	3.21	0.007	Significant
Cover of bare ground	Medium-Unaffected	1.913	0.352	1.057	2.769	5.43	0.000	Significant
Moss cover	Short-Unaffected	71.9	18.3	27.5	116.4	3.94	0.001	Significant
Moss cover	Short-Medium	72.4	10.9	45.8	99	6.62	0.000	Significant

Response	Age-class	Difference of means	SE of difference	Simultaneous 95% CI		T-value	Adjusted P-value	Statistically Significant
Moss cover	Medium-Unaffected	144.3	16.5	104.2	184.5	8.74	0.000	Significant
Perennial cover	Short-Unaffected	-15.64	7.5	-33.89	2.61	-2.08	0.106	Not significant

Appendix 5 Construction and Reinstatement

Appendix Table 46 - Species and propagation information based on Brook et al. (1999)

Species	Life Cycle	Propagation method[5]	Notes on propagation - Seeds	Notes on propagation - Vegetative	Cover established in < 2 years
Salicornia spp.	Annuals	Seeds or **Vegetative propagules**	Seeds can be collected from drift material, but this is a more labour-intensive method, seeds are then broadcast over a site. Seed material collected can be immediately broadcast on a site (where it will germinate the following spring) or refrigerated over winter before being sown the following year after winter storms have past.	The best means of propagation is by cutting existing material from a donor site at 40-60 mm above the ground surface using a hand-cutter before collecting up the cut pieces and spreading it over bare areas. The material should be hand-tilled into the substrate where it will readily root.	Yes
Spartina anglica	Perennial	Seeds or **vegetative propagules**	Seeds can be harvested in late summer / autumn. The seeds then need to be stored in saltwater under refrigerated conditions for 60-90 days to break dormancy. However, many seeds are not viable and germination tests are advisable.	*Spartina anglica* is stoloniferous and therefore lends itself to vegetative propagation. Clumps of material from the donor marsh is sub-divided into smaller transplants. Plants should be spaced on 0.25 m to 1 m centres depending on conditions and project goals.	Yes
Suaeda maritima	Annual	Seeds	Seed harvesting of *Suaeda maritima* should occur in early autumn with a fine net. Seeds should be dry stored in refrigerated conditions before being sown the following spring; alternatively, seeds can be broadcast immediately among a nurse crop.	Not suitable	Yes
Atriplex portulacoides	Perennial	**Seeds** or vegetative propagules	*Atriplex portulacoides* produces prolific seeds, which can be gathered (by sweeping with a net) in autumn and broadcast immediately onto a restoration site or holding them in	Not suitable	Yes

[5] best method in bold

Species	Life Cycle	Propagation method[5]	Notes on propagation - Seeds	Notes on propagation - Vegetative	Cover established in < 2 years
			refrigerated conditions over winter for broadcast the following spring. It is likely that strandline/ drift material will also contain *Atriplex portulacoides* seeds.		
Puccinellia maritima	Perennial	Seeds or **vegetative propagules**	Seed harvesting in autumn is probably only worthwhile where sufficient plant material is available. It is likely that strandline/ drift material will also contain *Puccinellia maritima* seeds.	*Puccinellia maritima* produces over-ground stolons from which new plants can develop. This is often the best method of propagation either gathering rooted stolons or lifting clumps and sub-dividing it.	Yes
Agrostis stolonifera	Perennial	Seeds	*Agrostis stolonifera* produces abundant seeds, which should be collected in autumn, stored dry, and sown the following spring.	Not suitable.	Yes
Aster tripolium	Biennial	Seeds	*Aster tripolium* can be grown from seeds harvested in autumn (by sweeping or by collecting seed heads). Seeds should be stored dry over winter, then sowed the following spring. If the sown area is protected from winter storms seeds can be sown in autumn.	Not suitable.	No
Atriplex prostrata	Annual	Seeds	*Atriplex prostrata* can be propagated by the collection of seed heads, sweeping or vacuuming in autumn. Seeds should be stored dry and then broadcast onto the receptor site the following spring.	Not suitable.	No
Spergularia spp.	Perennial	Seeds	*Spergularia* spp. can be propagated by the collection of seed heads or sweeping in autumn. Seeds should be stored dry and then broadcast onto the receptor site the following spring.	Not suitable.	No
Armeria maritima	Perennial	Seeds	*Armeria maritima* can be propagated by the collection of seed heads, sweeping or vacuuming in autumn. Seeds should be stored dry and then broadcast onto the	Not suitable.	No

Species	Life Cycle	Propagation method[5]	Notes on propagation - Seeds	Notes on propagation - Vegetative	Cover established in < 2 years
			receptor site the following spring.		
Cochlearia spp.	Perennial/ annual / biennial	Seeds	*Cochlearia* spp. should be propagated by the collection of seed pods, sweeping or vacuuming once the seed matures after flowering. Seeds should be stored dry over winter and then broadcast onto the receptor site the following spring. It is likely that strandline/ drift material will also contain *Cochlearia* spp. seeds.	Not suitable.	Yes
Festuca rubra	Perennial	Seeds	Seeds can be collected in autumn for propagation the following spring.	Not suitable.	Yes
Limonium vulgare	Perennial	Seeds	*Limonium vulgare* rarely flowers until their third year and seed viability is relatively low. Seeds are the best means of propagation and should be harvested by sweeping a fine net in autumn through donor material. The seeds should be sown immediately on the receptor site or stored dry in a refrigerator until spring.	Not suitable.	No
Plantago maritima	Perennial	Seeds	Seeds should be collected in autumn by sweeping, vacuuming or collection of whole seed head. Seeds should be stored dry in a cool moist area until planting in spring. They can be sown directly at the receptor site in autumn if protected from winter storms.	Not suitable.	No
Artemisia maritima	Shrubby Perennial	Seeds or vegetative propagules	*Artemisia maritima* produce numerous flower heads and seeds can be propagated by surface sowing from late winter to early summer in a greenhouse, making sure that the compost does not dry out. When large enough to handle, the seedlings should be planted into individual pots and grow them on in	Cuttings of half-ripe wood can be taken in July/August and kept overwinter in a cold frame.	No

Species	Life Cycle	Propagation method[5]	Notes on propagation - Seeds	Notes on propagation - Vegetative	Cover established in < 2 years
			the greenhouse for their first winter. Plant out in late spring or early summer.		
Triglochin maritimum	Perennial	**Seeds** or vegetative propagules	The best method for propagation is seed collection in autumn after flowering.	*Triglochin maritimum* can be harvested by collecting rhizomes, however it is a slow growing species, and this method will produce limited donor material.	No
Bolboschoenus maritimus	Perennial	**Seeds** or Vegetative propagules	The best method of propagation of this species is seed collection of heads in autumn. Seeds should be stored under cool, wet conditions to scarify seed coats, then broadcast on new site in spring.	*Bolboschoenus maritimus* is a rhizomatous species and plants can be dug from around parent plants, however this is labour intensive.	
Carex spp.	Perennial	**Seeds** or Vegetative propagules	Seeds should be collected in late summer / early autumn (plants can drop their seeds earlier than other species). Seeds should be stored under cool, moist conditions over winter then broadcast on new site in spring.	Some species of *Carex* are rhizomatous and therefore material can be dug from around parent plants, however this is labour intensive.	
Elytrigia atherica and *Elytrigia repens*	Perennial	**Seeds** or Vegetative propagules	Seeds can be collected in autumn, dried stored over winter then broadcast on new site in spring. *Elytrigia atherica* seeds may also be found in drift / strandline litter.	*Elytrigia* are rhizomatous and therefore material can be dug from around parent plants, however this is labour intensive.	
Juncus gerardii and *Juncus maritimus*	Perennial	**Seeds** or Vegetative propagules	The best method of propagation of this species is seed collection of heads in autumn by sweeping or vacuuming. Seeds should be stored under cool, wet conditions using fresh water to scarify seed coats, then broadcast on new site in spring.	Both *Juncus gerardii* and *Juncus maritimus* are rhizomatous and therefore material can be dug from around parent plants, however this is labour intensive.	
Phragmites australis	Perennial	**Seeds** or Vegetative propagules	The best method of propagation of this species is seed collection of heads in autumn. Seeds should be stored under cool, moist conditions, then broadcast on new site in spring.	*Phragmites australis* can be harvest by lifting rhizomes and burial in wet sediment.	
Typha angustifolia	Perennial	**Seeds**	The best method of propagation of these	*Typha* are rhizomatous and therefore material	

Species	Life Cycle	Propagation method[5]	Notes on propagation - Seeds	Notes on propagation - Vegetative	Cover established in < 2 years
and *Typha latifolia*			species is seed head harvest in autumn. The seeds should be stored under cool, moist conditions in plastic bags over winter. The seed can then be shredded to release the seeds in spring.	can be dug from around parent plants, however this is labour intensive.	

Appendix 6 Monitoring

Appendix Table 47 – A review of typical survey methods used in vegetation monitoring.

Method	Description	Pros	Cons
Extended Phase 1 habitat survey supported by aerial photography JNCC (2010)	Large-scale vegetation mapping designed to quickly classify vegetation to broad habitat types. The use of target-notes allows for greater detail.	▪ Rapid assessment potentially used to initially scope proposed pipeline/ cable route. ▪ Aids planning a monitoring programming identifying features of interest.	▪ Insufficient detail to determine baseline or post-construction recovery. *E.g.* saltmarsh coded by 3 colour-codes (based on vegetation densities) and sand dunes by 5 divided by main vegetation type.
National Vegetation Classification with quadrat sampling and supported by aerial photography Hill (2015), Rodwell (2006), Rodwell (2000), Rodwell et al. (2000), Thomson (2004)	Widely accepted (in the UK) classification method designed to assign vegetation to community types. Surveyor can assign vegetation types by eye or use quadrats to increase repeatability. Use of software such as MATCH or TableFit allows a measure of fit.	▪ Good for baseline surveys to determine what vegetation types were present prior to construction. ▪ Can aid alignment of working width. ▪ Aids planning subsequent monitoring programming. ▪ Allows interpretation of changes in vegetation and confirmation of features and attributes when monitoring is required. ▪ Other attributes *i.e.* bare ground, vegetation height can also be recorded.	▪ Requires skilled surveyors and can be time-consuming depending on the number of quadrats and extent of survey. ▪ Boundaries between communities can be difficult to assign especially where vegetation forms mosaics and transitions. ▪ Early post-construction recovery will not be easily assigned to defined vegetation types.
Common Standards Monitoring (CSM) JNCC (2004a), JNCC (2004b), JNCC (2004c)	Classification method used to determine condition of notified features within designated sites (*i.e.* SAC and SSSI) by statutory authorities. Uses specified attributes for each habitat type and a structured walk with stops (minimum recommended is 10). It should be noted that the CSM was not developed for use on non-statutory sites, or as part of a monitoring programme of the wider countryside.	▪ Standard measurable attributes focusing on extent, physical structure, vegetation structure, vegetation composition and negative indicators. ▪ Percentage cover or presence/ absence of species recorded but designed to be a rapid assessment. ▪ The use of the structured walk with stops is efficient, designed to give the assessor an overview of the site.	▪ Depending on the number of stops used and size of site, potentially insufficient level of detail recorded to monitor change following impact. ▪ Coastal habitats are intrinsically dynamic (even where heavily modified), and sites may demonstrate many successional stages. Care is therefore needed in determining whether a change in extent of one vegetation type to another is part of normal succession (or due to external factors), otherwise a incorrect verdict of unfavourable

Method	Description	Pros	Cons
		▪ Designed so that non-specialists (with general habitat knowledge) can undertake assessment.	condition may be attributed.
Permanent belt transects Hill et al. (2005)	Belt transects are useful for monitoring vegetation changes along environmental gradients or across vegetation boundaries *e.g.* monitoring between On, Adjacent and Off the working width. The length of the transect should be sufficient to cover all three sample zones.	▪ Permanent belt transects allow detailed information on vegetation change over time to be recorded. ▪ By using fixed quadrats along the transect sampling variation is reduced, therefore reducing the number of quadrats required to detect change. ▪ Other attributes *i.e.* bare ground, vegetation height can also be recorded.	▪ Requires skilled surveyors. ▪ Accurately re-locating permanent transects can be time-consuming and difficult especially in featureless terrains *e.g.* saltmarsh, even when GPS are used. ▪ Quadrat sampling with measures of abundance is subjective (but can be used with presence/ absence). ▪ Repeated sampling in the same area can in itself cause vegetation change, especially in saltmarsh.
Stratified random quadrats Hill et al. (2005)	The use of stratified random quadrats (where the study area is divided into strata and then random samples are taken in each stratum) is suitable for both saltmarsh and sand dunes as these habitat types have a strong zonation effect.	▪ Ensures that all main vegetation types (strata) are sampled. ▪ Data is more homogenous within strata (reduced variability). ▪ More efficient in terms of time, as quadrats do not need to be re-located during each repeated visit.	▪ Planning of survey using strata ahead of sampling can be more difficult (although up-to-date aerial photos can help). ▪ Strata may change over time
GPS-guided Unmanned Aerial Vehicles (UAV) Klemas (2015)	The use of UAV's to capture high resolution aerial photos (and potentially other data *i.e.* multispectral imaging) over time is valuable to document vegetation change/ recovery.	▪ Up-to-date aerial images can be obtained for actual working width. ▪ Pre-programmed flights allow repeated images over time. ▪ Flights can be timed during low tides. ▪ Extent of bare ground/ vegetation damage can be easily identified.	▪ Although the cost of UAV is reduced (compared to manned flyovers), costs are still significant, and the use of UAVs should be costed into monitoring scheme from start. ▪ Ground-truthing will be still be needed.
LiDAR - Remote sensing Blott and Pye (2004), Collins et al. (2005), Millard et al. (2013)	Digital image classification allows particular vegetation types to be identified based on the amount of radiation reflected at different spectral wavelengths. It can also be used to achieve fine-scaled Digital Elevation Models (DEMs_(to +/-0.15m),	▪ Allows spatial-temporal change analysis, as can be repeated over time. ▪ Once calibrated the use of remote sensing can minimise field effort. ▪ Remote sensing can be used to classify large	▪ Frequency of data collection cannot be controlled by end-user (compared to UAV). ▪ Difference in accuracies may occur if LiDAR collected in summer or winter. ▪ Field survey is still required to ground-truth and

Method	Description	Pros	Cons
	allowing accurate site topography. In the UK, the Environment Agency provides high resolution LIDAR[6] data (through the Open Government Licence) free of charge.	areas of habitats *i.e.* saltmarsh. ▪ Technique good for distinguishing between vegetated and non-vegetated surfaces, and between distinctive plant communities. ▪ The DEM could be used to identify low-lying areas on the saltmarsh where compaction has occurred, and also provide dune heights for reinstatement.	calibrate digital image classification. ▪ Need capability and access to specific software for data analysis and interpretation.
Fixed-point photography Hill et al. (2005)	Provides a relatively simple method of recording visual changes in the broad vegetation type change over time. Fixed-point photography can be used to record landscape-scale or quadrat-scale change.	▪ Efficient, requires limited photographic equipment. ▪ Useful for convincing people that a change has actually occurred especially over long timescales.	▪ Standard methods are needed to ensure repeatability *i.e.* a record of location, direction, timing and camera configuration. ▪ In mobile habitats *e.g.* dunes, it can be difficult to establish fixed points for monitoring.

Appendix Table 48 - Proposed survey strategy.

Survey period	Survey method
Baseline survey at planning stage	▪ A NVC survey with quadrat sampling to determine community types. The use of recent aerial photos will help distinguish the main vegetation types. The level of survey detail will depend on the survey extent but typically 1:5000 scale is appropriate to monitor extents of habitats on most designated sites (Hill et al., 2005). The resulting NVC survey will be sufficient for most planning submissions; will aid route alignment selections; and will allow the development of a suitable pre-construction survey method *i.e.* developing a stratified sampling scheme with vegetation zones.
Pre-construction survey (Option 1)	▪ Using the NVC survey a stratified quadrat sampling approach based on vegetation zones can be developed. Random quadrats are taken from each vegetation zone (stratum), so that the sample is representative of the average conditions in that zone, providing the sample is large enough. The location of the quadrats is pre-determined using a random point generator in GIS. The points can be loaded onto a hand-help GPS device and surveyors navigate between points. Quadrats 1m×1m subdivided into 25 cells *i.e.* using a 5×5 grid allow species presence to be recorded along with an indication of abundance (*i.e.* a count out of 25). This approach is more reliable in terms of repeatability than recording percentage cover. All species should be recorded. Other attributes based on those set out in the Common Standards Monitoring guidelines should also be recorded *i.e.* presence of negative indicators, average vegetation height, cover of bare ground. In addition, a record of the level of vegetation and sediment disturbance should be recorded. A photograph of each quadrat provides useful evidence of recovery. This approach may work best where there are discrete patches of each community type *e.g.* sand dunes. ▪ A survey form should be developed so that data collection is standardised.

[6] Light Detection and Ranging (LIDAR) is an airborne mapping technique, which uses a laser to measure the distance between the aircraft and the ground. Up to 100,000 measurements per second are made of the ground, allowing highly detailed terrain models to be generated at spatial resolutions of between 25cm and 2 metres.

	▪ In addition, the use of a UAV *i.e.* drone flying over the survey extent will provide up-to-date aerial imagery giving an indication as to the vegetation condition prior to construction, amount of naturally occurring bare sand or mud, and determine the location and arrangement of creeks, pools and pans. ▪ Fixed-point photograph taken from good vantage points is a key tool for documenting landscape level changes over time. A full record of each photographs position and camera setup is necessary.
Pre-construction survey (Option 2)	▪ Using the NVC survey, a stratified survey approach using belt-transects is designed so that permanent transect running perpendicular to the working width are repeated within each of the main sample zones. The belt-transects need to be sufficiently long to extend across the entire working width and also record in the surrounding unaffected vegetation. The start and end point as well as the direction of transect alignment needs to be clearly documented, so that each transect can be set up in subsequent years. Saltmarsh habitats in particular are quite featureless, and those features such as creeks can move in location over time (especially following construction which may result in creek patterns changing), therefore a suitable strategy for relocating the transects is required. The use of a hand-held GPS is likely to result in inaccuracies relocating the point, however the use of marker posts will need agreement with statutory authorities and are often removed. Species presence can be recorded using subdivided 1m×1m quadrats with 25 cells. All species should be recorded. Quadrats should be laid along the transect so that impacted quadrats are separated from unaffected quadrats. Additional attributes should be recorded, and a photograph taken of the quadrat. The number of transects will depend on length of disturbed habitat and complexity of vegetation, but this approach may work well for saltmarsh habitats which forms discrete vegetation bands out from the shore. ▪ A standard survey form should be used. ▪ The use of the UAV and fixed-point photography should also be taken as specified previously.
Post-construction survey	▪ The post-construction survey should replicate the pre-construction methods. ▪ For the random stratified quadrat sampling approach, the previously surveyed quadrats do not need to be relocated but new quadrats determined (using GIS). This approach should speed up the field survey time compared to the setup of transects. ▪ Only where there is a compelling reason should the methods be changed. In such a situation agreement should be made with the statutory bodies overseeing the project. ▪ The UVA survey should be repeated at specified intervals after construction. *E.g.* a drone survey completed immediately after construction will evaluate the actual damage, providing the maximum extent of damage from which post-construction recovery can be measured. Further drone surveys after 1 year, 5 years and 10 years would be informative, and would show the direction and rate of recovery.