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Pembrey Burrows – a geomorphological appraisal and options for dune rejuvenation

Kenneth Pye and Simon J Blott

NRW Evidence Report No. 42

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**Pembrey Burrows –
a geomorphological appraisal and
options for dune rejuvenation**

Kenneth Pye and Simon J. Blott

External Investigation Report No. EX1502

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Kenneth Pye and Simon J. Blott

External Investigation Report No. EX1502

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1. Crynodeb Gweithredol

Mae'r adroddiad hwn yn cyflwyno asesiad geomorffolegol o Dwyni Pen-bre, a'i fwriad yw bod yn sail ar gyfer gwneud penderfyniadau rheoli yn y dyfodol. Mae'r adroddiad yn seiliedig ar adolygiad o ddata amgylcheddol perthnasol, deunyddiau darllen wedi'u cyhoeddi a heb eu cyhoeddi, dehongliad LiDAR a lluniau o'r awyr, ymweliadau â'r safle a thrafodaethau â staff Cyfoeth Naturiol Cymru a swyddogion eraill perthnasol.

Mae Twyni Pen-bre yn enghraifft dda o system bardwyni, sydd wedi esblygu mewn sawl cam yn ystod y cyfnod Fflandriaidd Hwyr (Ôl-rewlifol). Mae prif ran y system dwyni yn llai na 500 o flynyddoedd oed, ac mae'r tafodau bar mwyaf dan gapan o dwyni, sydd ar bob pen i'r system, wedi datblygu'n bennaf yn ystod y 130 mlynedd diwethaf. Ar ddiwedd y bedwaredd ganrif ar bymtheg ac ar ddechrau'r ugeinfed ganrif, roedd gorchudd clytiog o laswelltir twyni a phocedi o brysgwydd a lleiniau o dywod noeth a thwyni symudol ar y rhan fwyaf o ardal y twyni. Roedd nifer o lynnoedd bas arwyddocaol a darnau corsio yn y pantiau rhwng y twyni. Rhoddwyd mesurau ar waith ar raddfa fawr yn y 1890au cynnar, i reoli tywod a oedd yn chwythu a thwyni a oedd yn mudo. Erbyn canol yr ugeinfed ganrif, roedd y Comisiwn Coedwigaeth wedi plannu coed conwydd yn y rhan fwyaf o ddwy ran o dair gogleddol y system dwyni. Gwelwyd rhywfaint o sefydlogi yn yr ardaloedd heb eu plannu yng ngogledd a de'r system, gyda glaswelltir a rhywogaethau prysgwydd, helyg y môr (*Hippophae rhamnoides*) yn bennaf, ac roedd ardaloedd o dywod noeth a thwyni symudol, gyda llystyfiant rhannol wedi'u cyfyngu bron i gyd i ardaloedd o gasgliad tywod gweithredol, yn bennaf ym mhen gogleddol a de ddwyreiniol y system. Ar ôl dadansoddi lluniau o'r awyr o 2010, gwelwyd bod tywod noeth yn gorchuddio llai na 2% o'r ardal lle'r oedd tywod chwythedig. Mae llynnoedd bas a llaciau gwlyb wedi gordyfu ac maent yn llawn deunydd organig, sydd wedi arwain at nifer o rywogaethau allweddol fel Gefell-lys y Figen, a gofnodwyd yma ddiwethaf yn 1989, a'r Petalys, yn colli cynefin.

Mae ymdrechion wedi cael eu gwneud i roi sylw i'r problemau sy'n gysylltiedig â cholli cynefinoedd ers y 1980au o leiaf, ac yn enwedig yn y degawd diwethaf, yn unol â Chynllun Gweithredu Bioamrywiaeth Lleol Sir Gaerfyrddin. Mae llawer o helyg y môr wedi cael eu tynnu, ac mae tir pori wedi cael ei ailgyflwyno mewn rhai mannau, ac mae nifer o lynnoedd / pyllau bas wedi cael eu creu. Argymhellir y dylid dal ati gyda'r gweithgareddau hyn, ac y dylid eu hymestyn. Hefyd, argymhellir y dylid cymryd mesurau ychwanegol. Dylai'r rhain gynnwys: (a) torri planhigfeydd coniferaidd sydd o ansawdd gwael ar unwaith ym Mharc Gwledig Pen-bre ac yng Nghoedwig Pen-bre; (b) torri a chlirio rhagor o glystyrau aeddfed yng Nghoedwig Pen-bre yn y tymor canolig, a dim ailblannu, a sicrhau bod aildyfiant conwydd a phrysgwydd yn cael ei reoli ar ôl hynny; (c) dylid dechrau cynnal treialon mewn mannau penodol yn y tymor byr i weld pa mor effeithiol yw'r gwaith torri coed, symud bonion, tynnu tywyrch, ac addasu topograffeg arwynebau o ran adfer symudedd tywod ar y twyni ger y blaen ac mewn mannau lle ceir twyni uwch ymhellach ar y mewndir. Dylid llunio cynlluniau dylunio ar gyfer y treialon ar ôl ymgynghori pellach.

2. Executive Summary

This report provides a geomorphological assessment of Pembrey Burrows and is intended to inform future management decision making. The report is based on a review of relevant environmental data, published and unpublished literature, air photograph and LiDAR interpretation, site visits and discussions with NRW and other relevant personnel.

Pembrey Burrows is a fine example of a barrier dune system which has evolved in several stages during the Late Flandrian (Post-glacial) period. The main part of the dune system is less than 500 years old, and major dune-capped barrier spits at either end of the system have developed largely within the past 130 years. In the late 19th and early 20th century most of the dune area had a patchy cover of dune grassland with pockets of scrub and patches of bare sand and mobile dunes. Several significant shallow lakes and marshy areas existed within inter-dune depressions. Measures to control blowing sand and dune migration were started on a significant scale in the early 1890s and by the mid 20th century most of the northern two thirds of the dune system had been planted with conifers by the Forestry Commission. Unplanted areas at the northern and southern ends of the system experienced stabilization by grassland and scrub species, notably sea buckthorn (*Hippophae rhamnoides*), and areas of bare sand and mobile, partially vegetated dunes became limited almost entirely to areas of active sand accretion, mainly at the northern and southeastern ends of the system. Analysis of 2010 aerial photographs indicated that bare sand covered less than 2% of the blow sand area. Shallow lakes and wet slacks have become overgrown and in-filled by organic matter accumulation, resulting in loss of habitat for key species such as Fen Orchid, which was last recorded here in 1989, and Petalwort.

Attempts have been made to address the problems associated with loss of habitat since at least the 1980s, and especially in the past decade in accordance with the Carmarthenshire Local Biodiversity Action Plan. Significant areas of sea buckthorn have been removed, grazing has been re-introduced in some areas, and several new ponds / scrapes have been created. It is recommended that these activities should be continued and extended, but also that additional measures are taken. These should include: (a) immediate felling of poor-quality coniferous plantations within Pembrey Country Park and Pembrey Forest; (b) more widespread clear-felling of mature timber stands within Pembrey Forest in the medium term, with no replanting and follow-up management to control regrowth of conifers and scrub; (c) trials should be started at selected locations in the short term to explore the effectiveness of tree-felling, stump removal, turf stripping, and surface topography modification in restoring sand mobility in both the near-frontal dunes and on areas of higher dunes further inland. Design plans for the trials should be drawn up following further consultation.

3. Report scope and purpose

This report has been prepared on behalf of Natural Resources Wales (NRW) with the purpose of providing a geomorphological assessment of the Pembrey Burrows dune system which will inform future management policy of the site, including options for dune rejuvenation. The report is the latest in a series which describe the geomorphological characteristics of major sand dune systems in Wales (Pye & Blott, 2011a,b, 2012, 2014a).

The report is based on:

- a review of relevant environmental data, published and unpublished literature
- analysis of aerial photographs and LiDAR imagery
- analysis of historical maps and charts
- analysis of strategic coastal monitoring data
- site visits and discussions with representatives of NRW, Carmarthenshire County Council and Defence Training Estates in January and February 2014
- laboratory analysis of sand samples collected during site visits

4. Location and conservation importance of Pembrey Burrows

Pembrey Burrows forms one of a number of dune systems which fringe the eastern part of Carmarthen Bay (Figure 1). It represents a double barrier spit system which is connected to the mainland shore by a relatively narrow sandy ridge. Behind the barrier are extensive tidal flats and marshes, now partly embanked and reclaimed. At its widest point the central part of dune system is more than 2 km wide.

The central part of the dune system lies within Pembrey Forest and Pembrey Country Park, but the northern end (Tywyn Burrows) forms part of the Pembrey Sands Air Weapons Range and the southern end is designated as the Pembrey Burrows and Saltings Local Nature Reserve (Figure 2).

The main part of the high dune system is relatively young, having formed since the Middle Ages. In the past 120 years, dune-capped spit systems have developed at the northern and southern ends of the system, near Tywyn Point and 'the Nose', respectively (Figure 2). A separate belt of dunes extends westwards from Burry Port towards Ashburnham and is now separated from the sea by a seawall, Burry Saltings and younger dune ridges further seaward.

The First Edition Ordnance Survey (OS) One-Inch map, first published in 1830, referred to the entire dune system as Pen-bre Burrows. However, the First edition Six-Inch maps of the area published in 1891, based on surveys between 1878 and 1881, described the main sand dune area as Towyn Burrows and used the name Pembrey Burrows only for the smaller area of dunes to the south and southwest of Pembrey village. In this report the name Pembrey Burrows is applied to the entire dune system between Tywyn Point in the north and Burry Port in the south.

The dunes at the northern and southern ends of the Pembrey dune system are included within the Carmarthen Bay Dunes Special Area of Conservation (SAC) (Figure 3a). They also lie within the Pembrey Coast Site of Special Scientific Interest (SSSI) which also includes the frontal dunes along the entire Pembrey coast (Figure 3b). The older and younger dunes west of Burry Port also lie within the Burry Inlet Special Protection Area (SPA) (Figure 3c), and the younger dunes also lie within the Pembrey Burrows and Saltings Local Nature Reserve (LNR) (Figure 3d). The central part of Pembrey Burrows, within Pembrey Forest and Pembrey Country Park, is not included within the designated areas of biological conservation interest. However, the entire dune complex, and the adjoining Cefn Sidan and Gwendraeth estuary intertidal areas, form important constituents of the Carmarthen Bay Geological Conservation Review (GCR) site, which is classified as a Coastal Assemblage (May, 2003).

The Twywn Gwendraeth - Cefn Sidan Sands SSSI was first notified in 1953 and extended in 1979. The dunes south of Twyn Point were classified as being of Grade 2 conservation importance in the Nature Conservation Review, being the only part of the Pembrey Burrows dune system which has not been planted with conifers (Ratcliffe, 1977). The SSSI was re-notified under the Wildlife and Countryside Act 1981 and the name changed to Pembrey Coast SSSI in 1983. There were further boundary changes in 1988/9 and 2002, and the SSSI now covers an area of approximately 4120 ha. The Pembrey Coast SSSI is cited as being of special interest for its intertidal, saltmarsh and sand dune habitats including vegetation transitions, wet woodland, neutral grassland, and open channel habitats (CCW, 2002). The vegetation of the dunes and transitional habitats was mapped by Dargie (1989).

Annex I habitats that are a primary reason for the selection of the Carmarthen Bay Dunes SAC site are:

2110 Embryonic shifting dunes – with well-developed transitions to marram
Ammophila arenaria dunes

2120 Shifting dunes along the shoreline with *Ammophila arenaria* (“white dunes”)

2130 Fixed dunes with herbaceous vegetation (“grey dunes”)

2170 Dunes with *Salix repens* ssp. *argentea* (*Salicion arenariae*)

2190 Humid dune slacks

All are found within the Pembrey dune system.

Annex II species that are a primary reason for selection of the SAC site include:

1014 Narrow-mouthed whorl snail *Vertigo angustior*

1395 Petalwort *Petalophyllum ralfsii*

1903 Fen Orchid *Liparis loeselii*

The narrow-mouthed whorl snail is most abundant at Whiteford Burrows but is also found at Pembrey. Petalwort and Fen Orchid are now either very rare or extinct at Pembrey, with Fen Orchid last recorded in 1989.

The area south of Tywyn Point hosts a number of nationally rare or scarce invertebrates, including the weevil *Datonychus arquatus* and the ground beetle *Panagaeus cruxmajor*, last recorded in 1998. The margins of seasonally wet slack areas and the sand dune to saltmarsh transition areas are especially important in terms of specialist habitats.

The management vision for the Carmarthen Bay Dunes SAC, set out in the 2008 Core Management Strategy (CCW 2008), included the following objectives:

- continuation of the natural coastal and dune forming processes that determine the dynamics and proportions of habitats around Carmarthen Bay
- to maintain existing habitats where possible by management of factors within human control
- to maintain or increase the range of communities with the sand dune areas, with a high proportion of sparsely vegetated and open dune slacks or wet hollows
- to maintain the range or nationally rare and scarce plants and their ability to reproduce and sustain themselves through factors within human control
- the site will be managed to promote the natural diversity of the sand dunes through measures including scrub control and management of other vegetation

5. Geomorphological character and landscape evolution

5.1. Dunefield morphology and evolution

The Pembrey dune system forms the seaward end of an area of windblown sand which has a general 'hammer-head' plan shape. The high dunes partially overlie

intertidal sands and older windblown sands with lower relief. Stabilized dunes also occur around the base of the higher ground between Burry Port and Kidwelly. It is likely that these shore dunes formed after the maximum of the post-glacial marine transgression, around 4000 to 5000 years ago. Subsequent coastal sediment accumulation has led to westward progradation of the shoreline and the formation of the Pembrey barrier feature.

LiDAR data (Figure 4) show an E-W ridge of slightly higher ground extending westwards from the foot Pen-bre Mountain. This probably represents a sandy spit system which developed in the later Holocene before the main high dune ridges at Pembrey were formed. These consist of a series of ridges, sub-parallel to the modern shoreline, which become younger towards the sea. They represent phases of vertical dune growth and slight eastwards dune migration since the Middle Ages. Over the past 500 years the shoreline at Pembrey has shown an overall trend to move seawards. The age of the oldest blown sand deposits in the eastern part of the system has not been determined, but the main body of the sand dune system is only a few hundred years old. Shell-middens found in the dunes date to no earlier than the Medieval period (James, 1991).

Several distinct morphological units have been mapped based on interpretation of the LiDAR data and aerial photographs (Figures 4 & 5). A descriptive key to the geomorphological units and other features of interest is provided in Table 1. The main stages in the geomorphological evolution of the area are shown schematically in Figure 6.

The back-barrier areas behind the main dune ridges originally consisted of sandy tidal flats, mudflats and saltmarshes on the flanks of the Gwendraeth estuary. These have been partially embanked and reclaimed over the last 300 years, and part of this area is now occupied by Pembrey Airport and a motor racing circuit.

5.2. Aeolian processes and dune morphology

Long-term meteorological data are available for RAF Pembrey Sands near the northern end of the dune system. The average daily monthly maximum ranges from 7.9°C in January to 19.9°C in August. Average daily monthly minimum temperatures range from 3.4°C in January to 12.8°C in August (Table 2). Average monthly rainfall exceeds 100 mm between September and January and is at a minimum in June (84.2 mm). Monthly average hourly wind speed shows only a small variation but is highest between October and February (12.2 to 13.2 knots). Rainfall is relatively frequent in all months and tends to suppress aeolian sand movement.

The prevailing wind direction at Pembrey Sands is southwesterly (Figure 7). Mean hourly wind speed for the periods 1993-2014 was 11.8 knots, and wind speeds in excess of the threshold for aeolian sand entrainment (12 knots) were recorded for 44.5% of the time (Table 3). The aeolian Drift Potential (DP), calculated using a

modified version of the method proposed by Fryberger & Dean (1979), is 1562 Vector Units (VU). The Resultant Drift Direction (RDD) for winds > 12 knots is N53.2°E (towards the northeast), and the Resultant Drift Potential (RDP) is 1189.1 VU. The RDP/DP ratio, which provides an indicator of the unidirectionality of the effective sand transporting winds, is 0.76 (a value of 1 indicates perfect unidirectionality).

Although southwesterly and westerly winds are the most important for sand transport, northeasterly winds blowing across the Tywi and Gwendraeth estuaries are a significant secondary component and are responsible for forming low dune-capped ridges facing the Gwendraeth to the east of Tywyn Point. Near Burry Port, southeasterly winds blowing across the Burry Inlet are also a significant secondary component of the wind regime.

5.3. Coastal processes and beach morphology

The Pembrey area experiences a large mean spring tidal range (7.5 m, Table 4) and can be classified as *macrotidal* (spring tidal range > 4 m) according to the scheme proposed by Davies (1964) or *hypertidal* (spring tidal range > 6m) according to the scheme suggested by Archer (2013). A wide sandy foreshore is exposed at low tide, creating a large potential source area for windblown sand. However, much of the mid and lower beach has a very low angle and remains wet for much of the tidal cycle. Deflation of sand by the wind occurs mainly on the higher, drier parts of the beach, especially the backshore above the level of mean high water (MHW).

The northeastern shores of Carmarthen Bay are exposed to a large wave fetch. High energy swell waves from the Atlantic break some distance offshore, creating spilling breakers which dissipate much of their energy across Cefn Sidan before they reach the dune toe. These waves are generally responsible for landward movement of sand towards the upper beach. Beach profiles recorded since 1998 as part of the Swansea and Carmarthen Bay Coastal Engineering Groups strategic beach monitoring programme are presented in Appendix 1. The locations of the profile lines are shown on Figure 2. The open coast beach profiles (P48 to P54) are slightly concave-upwards, characteristic of an energy-dissipative regime, while those at either end of the system are convex in their lower sections and concave only in their upper sections, reflecting the influence of tidal current transport processes and reduced swell-wave influence on the margins of approach channels to the Burry Inlet and the Three Rivers (Taf, Tywi, Gwendraeth) estuary.

Changes in the morphology of the beach near Tywyn Point and at the southeastern end of Pembrey dunes have been monitored in more detail since 1998 by way of RTK GPS surveys which allow 3-D digital elevation models (DEMs) to be created (see Appendix 2). At Tywyn Point there has been frontal dune erosion of up to 170 m between 1998 and 2013 (Figure A2.1 in Appendix 2). There has been no net change near the control tower where rock armour has anchored the shoreline, but

immediately to the south there has been up to 40 m of dune erosion since 1998. The southeastern end of the Pembrey dune system, immediately to the east of the County Park beach access, has prograded by up to 200 m since 1998, leading to the formation of embryo dunes and new foredune ridges. Further east the beach has narrowed since 1998 due to onshore movement of the low water channel, resulting in breaching of the frontal dune ridge since 2010. Sediment accumulation is continuing at the very eastern end of the system, with development of embryo dunes near the entrance to Pembrey Saltings (Figure A2.2 in Appendix 2).

During periods of high tides and strong onshore winds, steeper, shorter period waves are created and are responsible for offshore movement of sand and upper beach lowering. Periods with several successive storms, such as that experienced during the 2013-14 winter, can lower the upper beach level by a metre or more, and storm waves may break directly against the dune front. During the winter of 2013-14 much of the Pembrey dune frontage experienced erosion of 5 to 15 m, leading to dune cliffing (see photographs in Appendix 3).

Most wave crests approach the central part of the Pembrey coast orthogonally, but there is refraction around Tywyn Point and the 'Nose' at southern end of Pembrey Burrows. Net rates of littoral drift are low in the central part of the system but increase towards the northern and southern ends. In the absence of sand supply from offshore, the central part of the Burrows shoreline would experience slow net erosion due to slow net longshore drift to the north and south and aeolian transport of sand from the beach into the frontal dunes. However, for most of the past 400 years the rate of onshore sand transport has been sufficient to allow progradation of the central part of the shoreline as well as alongshore extension and seaward growth of the spit systems at Tywyn Point and The Nose. In the past 120 years the supply of sand from offshore appears to have reduced although not ceased, and there has been only limited seaward movement of the dune toe along the central part of the shoreline since 1906. A point of no net change occurs approximately 2 km north of the Pembrey Country Park beach access point (Figures 8 & 9). At the northern and southern ends of the system episodes of frontal dune progradation and erosion have occurred over this time period due to movements of the low water channels and consequence changes in wave height at the shoreline (Figure 10).

5.4. Changes in bare sand area

In the late 19th and early 20th centuries the Pembrey dune system appears, on the basis of early maps and documentary accounts, to have had a relatively high proportion of bare, mobile sand, in common with other Welsh sand dunes systems (Blott & Pye, 2012; Pye *et al.*, 2014), although quantification is not possible. Attempts to stabilize the sand by erection of brushwood fences, planting of marram and creation of conifer plantations have been made at least since the 1890s (see below), and by the mid 1940s most of the area had already been stabilized by vegetation

(Figure 11). Quantitative analysis of the 1946 RAF aerial photography has indicated that bare sand comprised only 5.1% of the total sand dune area at that time (Table 5), and was mostly located on the higher dune ridges in the central part of the system. In 2010 the percentage bare sand had declined further to only 1.8% (Table 5; Figure 12).

5.5. Human intervention and management

Following the Norman Conquest a manor was established at Pembrey, initially owned by the le Boteler (Butler family). The original caput of the manor of Pembrey may have been a mound located about 1.5 km north of Burry port, but the village of Pembrey contains a number of buildings which originate from Norman times, including St Illtyd's Church. At some stage in the Middle Ages, the manor was relocated to Court Farm, Pembrey, which was built mainly in 1560 but contained the remains of an earlier medieval structure. Ownership of the estate passed from the Butler family through marriage to the Vaughan family and then, from 1677 onwards, to the Ashburnham family who owned the estate until it was sold in 1922. Throughout this time the more inland parts of the Pembrey estate were farmed but the coastal strip remained as common land until the mid-19th century. The tithe map of 1841 shows most of the Pembrey dune area (the 'Great Outlet') as common land with only one farm (Towyn Canol) located on the eastern margin of the dunes. This farm is also shown on the OS Six Inch First Edition map Sheet LVII NW, surveyed in 1879. Virtually no information is available concerning the usage of the dunes in this period but, like many other Welsh dune systems, they are likely to have been grazed and parts managed as a warren.

In the early 18th century the first coal mines were opened north of Burry Port, and many more were developed in the 18th and early 19th centuries. A network of canals, tramlines and a turnpike were built from the mid 18th century onwards to facilitate transport of coal from the mines, initially to Kidwelly and a wharf on the Gwendraeth estuary (Morris, 1970). In 1819 a harbour (later known as Pembrey Old Harbour) was opened at Pembrey, on land acquired from the Ashburnham Estate, by George Bowser and Thomas Gaunt (Nicholson, 1991). The harbour was relatively small but had a scouring reservoir with sluice gates at its head to maintain water depth. The western pier and breakwater of the harbour extended approximately 800 yards across the beach from the spring tide high mark. Railroads connected the harbour with collieries and iron works further inland (see Dessiou's *Plan of Pembrey Harbour*, reproduced in Craig *et al.*, 2002, p486). However, it proved difficult to maintain adequate water depth to allow vessels larger than 100 tons laden weight to enter and leave the harbour.

In 1825 an Act of Parliament was obtained by a rival company to begin work on a new harbour (Pembrey New Harbour, later called Burry Port) at Tywyn Bach, approximately 1.5 km east of Pembrey Old Harbour. The new harbour opened in

1836 and a second dock basin, located further inland, was completed by 1860 (see Fitzmaurice's *Plan of Burry Port Harbour, 1840*, reproduced in Craig *et al.*, 2002, p488). The Kidwelly and Llanelly Canal was extended to the Harbour and tramways constructed to link local collieries. The GWR railway line between Llanelly and Kidwelly was completed in 1852 and the Burry Port and Gwendraeth railway built between 1859 and 1891 to connect Burry Port Harbour with the inland collieries. Rapid industrialization of the surrounding area occurred in the 19th century and trade through Burry Port Harbour reached a peak in the late 19th century.

Pembrey Old Harbour was declared unused in 1878 but it was dredged and briefly reopened between 1887 and the early 1900s in order to serve the Nobel dynamite works in the southern part of the Pembrey dune system, to which it was connected by a tramway. Both the tramway and the harbour appear to have fallen into dis-use before the First World War. Since that time the inner reservoir basin of Pembrey Old Harbour has been infilled with sediment and the harbour itself now contains an extensive area of saltmarsh.

Burry Port Harbour also declined significantly after WWI as an increasing number of collieries closed (Craig *et al.*, 2002). Commercial shipping ceased in 1943 and most of the port infrastructure was removed in the early 1980s. Today the harbour is used by leisure craft but sedimentation within the harbor itself and in the entrance channel remains a problem. Frequent maintenance dredging is required, most recently in May 2014. Present licensing requires that the dredged sediments are put back into the estuary as close to the harbour as possible, with the result that much finds its way back into the harbour.

Between about 1887 and 1891 an extensive area of land on the Ashburnham Estate was planted with marram and conifers (mainly Corsican pine *Pinus nigra var. maritima*) to control sand drifting onto cultivated land. Two main areas were planted with conifers. The first, covering about 30 ha, was planted in 1891 in the centre of Pembrey Burrows, and the second planted in 1892 at Lifeboat Plantation, near what is now Ashburnham Golf Course. The areas to be planted were first defined by construction of brushwood fencing and seeds of Corsican pine were then sown in beds about 12 ft (3.5 m) wide. Brushwood was spread on the sand surface to prevent it, and the seeds, being blown away. A third small plantation (Cliffe Plantation) was established on the Ashburnham Estate using soil mixed with sand and planting of young pine trees. Planting of marram to control sand blow elsewhere in the Burry Port and Pembrey area continued until the First World War (Case, 1914).

The Ashburnham Golf Club was established on the dunes south of Pembrey village in 1894 and the first course was completed in 1896. Substantial modifications to the course layout were undertaken in 1910, but there has been relatively little change to

the course since that time. The land was initially leased from the Ashburnham Estate but subsequently bought when the Estate was sold in 1922.

The land later to be occupied by Pembrey Forest was acquired by the Forestry Commission in 1928 and planting began in 1929 (Spence, 2013). Prior to tree planting, the sand was stabilized using brushwood fencing and marram. A nursery was established at Pembrey in 1930 and supplied young trees for use on site and at other locations until the early 1970s. The Pembrey dunes were mostly planted Corsican pine with some Sitka spruce (*Picea stichensis*) and Norway spruce (*Picea abies*). Sea buckthorn was also planted in some places to stabilize the sand. Figure 13 shows the distribution of trees which were planted in the Forest before 1960 and Figure 14 shows the locations identified in the Forest Design Plan where felling is planned before and after 2020. Figure 15 shows the present mix of habitat types within Pembrey Forest.

A munitions factory was established on a 63 ha site within the dunes at Pembrey by the Explosives Company of Stowmarket (later the New Explosives Company Ltd) and then sold to the Nobel's Explosives Company in 1885. A tramway was built to link the works with Pembrey Old Harbour, and the harbour was dredged between 1887 and 1901 to improve vessel access (Craig *et al.*, 2002). In 1914 Nobel Explosives built a new TNT manufacturing facility on the site, which was taken over in 1917 by the Ministry of Munitions and it became a National Explosives Factory, covering an area of about 310 ha. At the end of WWI the factory was closed. The administration buildings were used as a convalescent home and rehabilitation centre for the children of unemployed miners, but many other buildings were demolished. Unsuccessful attempts were made to sell the site in the 1920s and much of it became derelict. In 1938/9 the site was re-occupied and rebuilt as Pembrey Royal Ordnance Factory (ROF). The site was bombed by the Luftwaffe on a number of occasions, including in July 1940 when several workers were killed, but production continued. At its peak in 1942 more than 3000 people were employed at the 200 ha site. Production declined at the end of WWII and the main function of the factory changed to decommissioning of unwanted ordnance brought from other locations, with the recovered metal being sold for scrap. By 1964 the number of employees had fallen to about 400; the site was finally closed in 1965.

In the late 1960s the Ministry of Defence (MOD) proposed the transfer of weapons development and testing facilities from Shoeburyness, Essex, to Pembrey but the proposal was eventually dropped following strong public opposition (Ladd, 1992). The site was largely stripped and fell derelict before being bought in the mid 1970s by Carmarthenshire County Council. The land was restored with support from Llanelli Borough Council and opened as Pembrey Country Park on 1st August 1980. Most of the ROF buildings and infrastructure were demolished although some remain. Visitor facilities now include a caravan park, dry ski slope, toboggan run, café, equestrian

centre, 9 hole pitch and put course, miniature railway, adventure playground, beach kiosk and visitor centre.

Construction of an airfield and gunnery school (RAF Station Pembrey) began in 1937 and the facility opened in March 1939. Operations were wound down after WWII and the airfield was finally closed in 1957. One runway was re-opened as Pembrey Airport in August 1997, but most of the site now forms the Welsh Motor Sport Centre. The airport is still used to support the nearby RAF Pembrey Sands Air Weapons Range, opened in 1966. The main control tower, including the weather station, is located at the southwest corner of the Range, adjacent to the beach. The main aerial target area is located behind the main dune ridges in the middle part of the range (see photographs in Appendix 3). A 7000 foot long Tactical Landing Zone is located on the adjacent beach and used by C-130 Hercules crews to practice natural surface landings and take-offs. Conservation management of the Range is managed by Defence Training Estates (DTE).

During WWII a series of gun emplacements was constructed across parts of the Burrows as elements of the 'Command Line' between Llanelli and Kidwelly designed to halt a possible German invasion. Several observation posts were also established in the frontal dunes south of Tywyn Point as part of the defences for the airfield and military training camps. Several of these still survive, together with a number of WWII bunkers and tunnels further back within the dune system, although little trace remains of the former parade ground and above-ground buildings. At the present time these have no formal heritage conservation status. The distribution of known sites of archaeological interest within the area is shown in Figure 15 and a list of the sites within Pembrey Forest provided in Table 6.

The morphology of parts of the dune system has been substantially modified over the years by excavations for buildings and infrastructure, creation of drains and water storage features. Significant areas were flattened for roads and buildings during construction and operation of the munitions factories and the WWII military training facilities. Further modifications were made in preparation for planting by the Forestry Commission from the 1930s onwards. More recently, the 'Scrape' pond within Pembrey Forest at SN373039 was excavated in the 1970s - now invaded by *Phragmites* and normally dries up in the summer. Another pond was excavated in the adjoining area in the late 1980s, and a scrape was created next to the RAF Target near Tywyn Point (SN 364051) prior to the mid 1980s. A pond was excavated in the early 1990s within Pembrey Forest at SN 392015 and has since been invaded by reed beds and scrub. In the mid 1990s other ponds were created within the Forest at SN 397007 and close close to the dry ski-slope at SN409000. When buckthorn was cleared from parts of the Pembrey site in 1998 two ponds were created at SS 413996 and SS 425994. The ponds and marginal wetland areas are important from a biodiversity point of view, and two additional areas within the Air Weapons Range

have recently been identified as suitable areas for further wet slack / pond creation for rare bryophytes (Bosanquet, 2013).

Large parts of the Pembrey system were grazed before the two World Wars but grazing effectively ceased after 1939. Grazing was reintroduced for conservation purposes to the southern part of the Pembrey Burrows dunes in 2006/07 when 77 ha were fenced off. Since then additional areas have been fenced and are now being grazed following sea buckthorn clearance.

The Pembrey dune system has not been greatly affected by coastal defence works except near the Air Weapons Range control tower, south of Tywyn Point, and in the Burry Port - Pembrey Old Harbour area. In the 1980s rock armour was placed along the dune toe and on the upper beach opposite the access ramp to provide erosion protection near the Air Weapons Range control tower. Between 1998 and 2006 additional rock structures were built and these have fixed the local shoreline position, although erosion has continued to the north and south (Figures 17 - 21). To the south of the Air Weapons Range, on the central Pembrey frontage, there has been relatively minor net change in the shoreline position since 1879 and this, combined with an absence of infrastructure, has resulted in no requirement for protective structures (Figures 22 - 25).

At the southern end of the Pembrey coast, Williams (1907) reported a fall in beach levels and significant frontal dune erosion to the west and east of Pembrey Old Harbour, and between the east pier of Pembrey Harbour and the west pier of Bury Port Harbour (Figures 26 - 29) He also refers to the fact that some years previously erosion was threatened one mile to the west of Pembrey Harbour but was arrested by erecting hedges of dead wood to trap windblown sand and a plantation of Corsican pine (Lifeboat Plantation) was also effective in preventing sand drift further inland. A diagonal groyne was erected on the beach to divert a stream flowing parallel to the dune front, but was reportedly not very successful. Extensive marram planting was also undertaken. Around this time, a timber revetment was built along this part of the shore to protect the dunes; this was later reinforced with rock armour to protect a route which is now followed by the Wales Coast Path.

In 1879 the outer dune-capped spit and back-barrier saltings did not exist, and the shoreline west of Pembrey Old Harbour was exposed to the direct action of waves (Figure 29). However, eastward growth of The Nose between 1879 and 1946, and more markedly after 1946 (Figures 27 & 28), isolated the old shoreline from the sea and allowed the development of Pembrey Saltings.

5.6. Sand size and composition

Sediment samples have been collected from the Pembrey dune system as part of a number of previous geomorphological investigations. Saye (2003) collected a suite of 15 sand samples in 1999 from the frontal dunes and analysed them by laser

diffraction to determine the particle size and by X-ray fluorescence spectrometry (XRF) to determine the major and trace element composition. The present authors collected samples from a number of boreholes within the Country Park in 2008 and 2010 and analyzed them for moisture content and particle size (by sieving). As part of the present study, a number of additional sediment samples were collected and analysed to determine their particle size characteristics. The sediment sampling locations are shown in Figure 30. These samples were dry-sieved at 'quarter phi' intervals using a mechanical shaker and the raw data processed using the GRADISTAT software package (Blott & Pye, 2001). The particle size results obtained from all of these investigations are summarised in Table 6. The great majority of the dune samples can be classified as unimodal, very well sorted fine sands with a median (D50) size generally in the range 130 to 200 microns. This reflects the fine sandy nature of the beach and shallow subtidal sediments in northern Carmarthen Bay. Owing to the relatively fine grain size, the fluid threshold wind velocity for aeolian sand transport at Pembrey is relatively low (0.2 to 0.25 m/s, equivalent to a wind a mean wind speed of 5.6 - 6.75 m/s measured at a standard height of 10m.

Elemental analysis of the samples taken from the frontal dunes by Saye (2003), and reported by Pye *et al.* (2007), showed that the sands have an average calcium oxide (CaO) content of 3.5 to 6.0% (Table 7), which is approximately equivalent to 5 – 10% calcium carbonate (CaCO₃). Most of the carbonate material represents broken shell fragments although some detrital limestone grains are also present. The elemental composition is dominated by silica (81 – 86%), reflecting the fact that quartz is the main mineral present, with traces of feldspar, calcite and heavy minerals.

5.7. Hydrology of the dune system

No dip well data were available for analysis in this study. However, it is evident from the morphology of the system that the groundwater table lies relatively close to the surface in many of the inter-dune depressions and seasonal winter flooding can be extensive (as in the winter of 2013-14). Several significant lakes and pools within the system are shown on historical maps, and wet vegetated depressions can be identified on the aerial photographs and LiDAR DEM. Concerns were expressed between the 1970s and 1990s about an evident fall in water table levels which may have been exacerbated by growth of the tree plantations and creation of drainage ditches, although climatic factors probably also played a role. These concerns led to the creation of a number of artificial ponds and wet slack areas within the dunes (see above).

While the lower lying areas of the dune system have a relatively high water table and some are subject to winter flooding, the higher dunes areas are well drained.

Analysis of sand samples taken from three auger holes dug in the near-frontal dunes south of the Pembrey Country Park Visitor Centre in August 2008 showed that the moisture content above the water table ranges between 5 and 8%, but may locally reach 11-12% in fine-grained sand layers. The residual moisture content held by the

sample after removal from the ground of samples taken below the water table was found to range from 16 to 27% (Figure 31).

5.8. Effects of changes in sea level and climate

Sea level in this part of South Wales has not varied by more than 1 m since c. 6000 yrs BP. There is some morphological evidence that there may have been a slight regression (relative sea level fall) following the maximum of the postglacial transgression, which would have favoured the development of coastal barriers on emergent tidal flats. More recent changes in mean sea level are not well documented, but tide-gauge records from southwest England and South Wales provide limited evidence of renewed transgression over the past century (average rate of 1.8 mm/yr at Newlyn since 1915, and 5.0 mm/yr at Fishguard since 1975; Figure 32).

Firm evidence of recent climate change is also elusive, and there is a difficulty in separating the effects of normal decadal-scale variability from longer-term trends. Figure 33 shows the temporal record of mean wind speed and direction recorded at Pembrey Sands since the early 1990s. A slight increase in wind speed is evident, but there is no significant trend in direction. This pattern is reflected in the calculated values for aeolian sand drift potential (DP) and resultant drift potential (RDP) (Figure 34). Owing to the lack of data for earlier years, it is impossible to say if this apparent increase in sand transport potential is significant. However, by comparison with other stations in the UK and overseas, Pembrey presently experiences a moderate to high wind energy environment; lack of wind is not a major limiting factor on dune mobility in this area.

UKCP09 projections for this part of the South Wales coast suggest that mean sea level will rise by between 17.1 and 77.4 mm by 2100, with a central estimate for the medium emissions scenario of 40.8 mm. Increases in high tide levels would be significantly greater than this due to the large tidal range, and the potential consequences of such changes, should they occur, would be significant for the Pembrey dune system. Increased water depths offshore would raise the wave base and reduce the onshore movement of sand from Carmarthen Bay and would lead to an increase in wave heights. Erosion of the frontal dunes would be inevitable, with shoreline recession along the central part of the Pembrey frontage of up to 200m possible. However, alongshore transfer of sand would result in greater intertidal accretion within sheltered locations such as the Gwendraeth estuary, Pembrey Saltings and the Burry Inlet. Some formation of new embryo dunes and foredune ridges would also be likely in these areas. On the exposed central part of the frontage, a change from shoreline stability / accretion to progressive erosion would be likely to lead to blowouts and transgressive dunes, thereby increasing the extent of bare sand, mobile dunes and pioneer dune slack habitat.

At the present time, there is great uncertainty regarding possible future changes in temperature, precipitation, mean wind speeds and storminess. Current climate models cannot accurately forecast such changes which are intimately linked to the position and stability of the mid-latitude jet stream across the British Isles.

6. Requirements and options for dune rejuvenation

Given the uncertainties regarding the extent and timing of possible future changes in climate and sea level, such changes cannot be relied upon to provide a solution to the problem of over-stabilization and loss of biodiversity within the Pembrey dune system. Any effects of climate and sea level change are likely to be relatively small in the short term (next 20 years), by which time, if no further management measures were implemented, much of the dune system could be over-run by scrub and juvenile woodland.

Sea buckthorn was planted in parts of the dune system by the Forestry Commission in the 1930s to stabilize the sand. It has established itself very successfully and dense stands of buckthorn are now found in several places. Both male and female plants produce suckers which encourage rapid spread into surrounding areas. It is a nitrogen fixer and favours the long-term change of habitat towards scrub / emergent woodland. The problem posed by sea buckthorn in areas outside its native range on the East Coast of England has been recognized for some time. Local clearances of buckthorn have been undertaken at Pembrey at least since the mid 1990s. An area of more than 20 ha was cleared between 2011 and 2014 within the Pembrey Country Park area as part of the Carmarthenshire Local Biodiversity Action Plan, with Welsh Government providing a grant of £50,000 for clearance from 2013 to 2015. The procedure used within the Country Park and Pembrey Forest areas has been to use a modified digging machine with a specially fabricated rake to allow removal of the entire plant, including roots (Parry, 2012). The uprooted buckthorn has either been removed by a tractor fitted with a grab and placed into skips, or burnt on site. Grazing has been re-introduced within fenced enclosures in some of the cleared areas. Similar clearance of approximately 3 ha of predominantly sea buckthorn scrub has been carried out by Carillion Enterprise Ltd, on behalf of Defence Training Estates, within the Air Weapons Range since 2007 (see photographs in Appendix 3).

Although control of sea buckthorn and restoration of dune grassland habitats should remain key management objectives, they alone will not be sufficient to rejuvenate and enhance the biodiversity of the Pembrey dune system. This will require a range of measures, including removal of a significant area of forest plantation, turf stripping in some areas to create areas of bare sand and mobile, partially vegetated dune, and the enhancement of existing 'blow through' depressions in the frontal dunes to allow

greater sand flux into the dune areas behind the beach. The following specific actions are recommended (see also Figure 35):

- continuation of scrub clearance programmes to create and maintain a 100 - 200 m wide scrub-free zone landward of the dune edge;
- removal of poor-quality stands of conifers at the northern end of Pembrey Country Park and within the southern, more seaward part of Pembrey Forest;
- felling of other coupes within Pembrey Forest which are approaching maturity; only limited replanting should be undertaken and measures taken to control natural regeneration of pines or other scrub;
- a trial site should be established on part of one of the higher inland dunes ridges to assess the feasibility of maintaining partially bare / mobile sand habitat in these locations;
- one or more further trial sites should be established closer to the beach to assess the feasibility of maintaining partially bare / mobile sand habitats in areas where wind exposure is higher and input of new sand from the beach can be engineered by creating or enhancing 'notches' in the frontal dunes. These could be points where paths created by visitors have already led to destruction of vegetation and allowed limited sand-blow – e.g. the beach access point at SN 37640251 and other points closer to the car parks in the middle – southern part of Pembrey Country Park;
- excavation of surface sand to create / recreate additional wet slack habitat in suitable locations – e.g. inter-dune depressions where shallow lakes / wet slacks once existed.

7. Conclusions

Pembrey Burrows provides a good example of a coastal barrier dune system which has evolved in several distinct stages during the Late Flandrian period. The available evidence suggests that main part of the dune system is less than 500 years old, and major dune-capped barrier spits at either end of the system have developed largely within the past 130 years.

In the late 19th and early 20th century most of the dune area had a patchy cover of dune grassland with pockets of scrub and large patches of bare sand and mobile dunes. Several significant shallow lakes and marshy areas existed within inter-dune depressions. Measures to control blowing sand and dune migration were started on a www.naturalresourceswales.gov.uk

significant scale in the early 1890s and by the mid 20th century most of the northern two thirds of the dune system had been planted with conifers by the Forestry Commission. Unplanted areas at the northern and southern ends of the system experienced stabilization by grassland and scrub species, notably sea buckthorn, and areas of bare sand and mobile, partially vegetated dunes became limited almost entirely to areas of active sand accretion, mainly at the northern and southeastern ends of the system. Analysis of 2010 aerial photographs indicated that bare sand covered less than 2% of the blow sand area. Shallow lakes and wet slacks have become overgrown and in-filled by organic matter accumulation, resulting in loss of habitat for key species such as Petalwort and Fen Orchid.

Attempts have been made to address the problems associated with loss of habitat have been made since at least the 1980s, and especially in the past decade in accordance with the Carmarthenshire Local Biodiversity Action Plan for Sand Dunes. Significant areas of sea buckthorn have been removed, grazing re-introduced in some areas, and several new ponds / scrapes created.

It is recommended that these activities be continued and extended but also that additional measures are taken. These should include: (a) immediate felling of areas of poor-quality coniferous plantation within Pembrey Country Park and Pembrey Forest; (b) more widespread clear-felling of mature timber stands in the medium term; (c) trials should be started in the short term to explore the effectiveness of tree-felling, stump removal, turf stripping, and surface topography modification in restoring sand mobility in both the near-frontal dunes and on areas of higher dune further inland. Design plans for the trials should be drawn up following further consultation.

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9. References

Archer, A. W. (2013) World's highest tides: Hypertidal coastal systems in North America, South America and Europe. *Sedimentary Geology* 284-285, 1-25.

Blott, S.J. & Pye, K. (2001) Gradistat: a grain size distribution and statistics package for the analysis of unconsolidated sediments. *Earth Surface Processes and Landforms* 26, 1237-1248.

- Bosanquet, S.D.S. (2013) *Dune Slack Bryophytes at Pembrey / Tywyn Burrows*. Unpublished Report, Natural Resources Wales, 24pp.
- Case, G.O. (1914) *Coast Sand Dunes, Sand Spits and Sand Wastes*. St. Bride's Press, London, 162pp.
- CCW (2002) *Arfordir Pen-bre / Pembrey Coast Site of Special Scientific Interest Citation*. Countryside Council for Wales, 4pp.
- CCW (2008) *Core Management Plan Including Conservation Objectives for Carmarthen Bay Dunes / Twyni Bae Caerfyrddin SAC (Special Area of Conservation)*. Countryside Council for Wales, 43pp.
- Craig, R.S., Protheroe Jones, R. & Symons, M.V. (2002) *The Industrial and Maritime History of Llanelli and Burry Port 1750-2000*. Carmarthenshire County Council, Carmarthen, 672pp.
- Dargie, T.C.D. (1989) *Pembrey Coast 1989. National Sand Dune Vegetation Survey. Site Report No. 52*. Contract Surveys No.102, Nature Conservancy Council, Peterborough.
- Davies, J.L. (1964) A morphogenic approach to world shorelines. *Zeitschrift fur Geomorphologie* 8, *Mortensen Sonderheft*, 127-142.
- Folk, R.L. & Ward, W.C. (1957) Brazos River bar: a study in grain size parameters. *Journal of Sedimentary Petrology* 27, 3-26.
- Fryberger, S.G. & Dean, G. (1979) Dune forms and wind regime. In McKee, E.D. (ed.) *A Study of Global Sand Seas*. United States Geological Survey Professional Paper 1052, 137-169.
- James, T. (1991) Where sea meets land. The changing Carmarthenshire coastline. In: James, H. (ed.) *Sir Gar: Studies in Carmarthenshire History*. Carmarthenshire Antiquarian Society Monograph Series No. 4. Carmarthenshire Antiquarian Society, Carmarthen, 143-166.
- Ladd, J.R. (1992) *S.O.S. The Save Our Sands Crusade*. Llanelli Borough Council, Llanelli, 101pp.
- May, V.J. (2003) Carmarthen Bay, Carmarthenshire (SN 220 070 – SN 421 868). In: May, V.J. & Hansom, J.D. (eds.) *Coastal Geomorphology of Great Britain*. Geological Review Series No. 28, Joint Nature Conservation Committee, Peterborough, 583- 593

- Morris, M.A. (1970) The canals of the Gwendraeth Valley. Part I. *The Carmarthen Antiquary* vi, 53-58.
- Nicholson, J. (1991) The two harbours of Burry Port. In: James, H. (ed.) *Sir Gar: Studies in Carmarthenshire History*. Carmarthenshire Antiquarian Society Monograph Series No. 4. Carmarthenshire Antiquarian society, Carmarthen, 121-142.
- Parry W. Ll. (2012) *Sea Buckthorn Clearance from Sand Dunes at Pembrey Country Park 2011/12*. Unpublished report dated 31st January 2012, available at <http://www.ukbars.defra.gov.uk/action/show/2244>
- Pye, K. & Blott, S.J. (2011a) *Kenfig Sand Dunes - Potential for Dune Reactivation*. CCW Science Report 971, Countryside Council for Wales, Bangor, 19pp, 2 tables, 31 figures & 2 appendices.
- Pye, K. & Blott, S.J. (2011b) *Merthyr Mawr Warren - Potential for Dune Reactivation*. CCW Science Report 978, Countryside Council for Wales, Bangor, 13pp, 5 tables, 25 figures & 4 appendices
- Pye, K. & Blott, S.J. (2012) *A Geomorphological Survey of Welsh Dune Systems to Determine Best Methods of Dune Rejuvenation*. CCW Science Report 1002, Countryside Council for Wales, Bangor, 409pp.
- Pye, K. & Blott, S.J. (2014a) *Crymlyn Burrows and Baglan Burrows: Geomorphological Assessment*. KPAL Report No. 160894 to Neath-Port Talbot County Borough Council, Kenneth Pye Associates Ltd, Solihull, 74pp.
- Pye, K. & Blott, S.J. (2014b) *Swansea Bay and Carmarthen Bay Coastal Engineering Groups Beach Profile Monitoring Data 1998-2013: Analysis and Interpretation*. KPAL Report 160720. Report to Swansea Bay and Carmarthen Bay Coastal Engineering Groups, January 2014, Kenneth Pye Associates Ltd., Solihull, 71p.
- 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.E. & Blott, S.J. (2007) *Sand Dune Processes and Management for Flood and Coastal Defence. Parts I to V*. R & D Technical Report FD1302/TR, DEFRA, London.
- Ratcliffe, D.A. (1977) *A Nature Conservation Review – The Selection of Biological Sites of National Importance to Nature Conservation. Volume 2. Site Accounts*. Cambridge University Press, Cambridge, 330pp.

Saye, S.E. (2003) *Morphology and Sedimentology of Coastal Sand Dune Systems in England and Wales*. PhD Thesis, Royal Holloway University of London, 548pp + appendices.

Spence B. (2013) *The Forestry Commission in Wales 1919-2013*. Forestry Commission Wales, Aberystwyth, 96pp.

Williams, G.G. (1907) Burry Port (Earl of Ashburnham's Property) In: *First Report of the Royal Commission Appointed to Enquire Into and to Report On Certain Questions Affecting Coast Erosion and the Reclamation of Tidal Lands in the United Kingdom. Volume I (Part I)*, HMSO, London, p341.

Table 1: Geomorphological features and other locations of interest at Pembrey Burrows (see Figures 4 & 5 for locations).

Number	Description
1	old dynamite works
2	old Pembrey Harbour (infilled)
3	Burry Port Outer Harbour
4	Burry Port Inner Harbour
5	concrete promenade
6	Café
7	control tower
8	Pembrey Sands Meteorological Station
9	bombing target area
10	range limit marker
11	rock armour hard point at beach access point
12	former Royal Ordnance Factory 1937-1965
13	dry ski slope
14	car park

Letter	Geomorphological Feature
A	headland-attached sand/shingle spit
B	hummocky dune ridge
C	former tombolo, linking barrier island to coastline
D	sand sheet of various ages, formed downwind of frontal dune ridges
E	large parabolic dune
F	most landward shore-parallel former frontal dune ridge
G	shore-parallel former frontal dune ridge, further seaward and younger than F
H	shore-parallel former frontal dune ridge, further seaward and younger than G
I	shore-parallel former frontal dune ridge, further seaward and younger than H
J	shore-parallel former frontal dune ridge, further seaward and younger than I, dating from c. 1800
K	shore-parallel former frontal dune ridge, dating from c. 1870
L	shore-parallel former frontal dune ridge, dating from c. 1920
M	shore-parallel spit and frontal dune, which accreted northward at Tywyn Point, c. 1945
N	shore-parallel spit and frontal dune, which accreted eastwards at the southern end of the system, c. 1945
O	multiple shore-parallel ridges, dating from 1945-2010
P	ephemeral embryo dunes, subject to periodic erosion and accretion, formed since 2010

Table 2: Monthly average daily maximum and minimum temperature, monthly rainfall, and monthly average wind speed. Parameters recorded at RAF Pembrey Sands (SN 365044) during the period January 1993 to January 2014. Data source: UK Met Office.

	Monthly Average	Monthly Average	Monthly Total	Monthly Average
	Daily Maximum	Daily Minimum	Rainfall	Hourly Wind Speed
	Temperature (°C)	Temperature (°C)	(mm)	(knots)
Jan	7.9	3.4	177.4	13.2
Feb	8.4	3.0	99.0	12.2
Mar	10.3	3.7	85.9	11.4
Apr	12.7	5.1	72.3	10.8
May	15.6	7.7	90.1	11.2
Jun	17.8	10.4	84.2	11.0
Jul	19.7	12.6	96.0	10.9
Aug	19.9	12.8	99.9	10.8
Sep	18.1	10.8	115.3	11.3
Oct	14.9	9.0	138.8	13.2
Nov	11.3	6.0	171.5	12.7
Dec	8.4	3.6	135.7	12.8
Year	13.7	7.3	1389.0	11.8

Table 3: Wind parameters recorded at RAF Pembrey Sands (December 1993 to January 2014). Data source: UK Met Office.

Wind parameters, averaged over the length of record	Pembrey Sands 1993-2014
Mean hourly wind speed (knots)	11.8
% hours 12 knots and above	44.5
Resultant Drift Direction (RDD)	53.2
Resultant Drift Potential (RDP)	1189.1
Drift Potential (DP)	1562.0
RDP/DP	0.76

Table 4: Tidal levels and tidal ranges (m. OD) at the Standard Ports of Milford Haven and Swansea and the Secondary Ports of Ferryside and Burry Port (from 2013 Admiralty Tide Tables), Estimated values for Pembrey Sands are taken from Pye & Blott (2014b).

	HAT	MHWS	MHWN	MSL	MLWN	MLWS	LAT	CD	MSTR	MNTR
Milford Haven	4.19	3.29	1.49	0.14	-1.21	-3.01	-3.71	-3.71	6.3	2.7
Ferryside	5.2	4.2	2	nd	-1.7	-2.4	nd	-2.5	6.6	3.7
Pembrey Sands	4.8	3.9	1.9	0	-1.7	-3.6	-4.4	nd	7.5	3.6
Burry Port	4.8	3.9	1.9	0.05	-1.7	-3.6	nd	-4.7	7.5	3.6
Swansea	5.5	4.5	2.2	0.1	-1.9	-4.1	-5	-5	8.6	4.1

Table 5: Changes in the area of blown sand and bare sand at Pembrey Burrows, based on analysis of aerial photographs flown in 1946 and 2010.

	Blown sand area (ha)			Bare sand area (ha)			Bare sand %		
	Designated	Non	Total	Designated	Non	Total	Designated	Non	Total
	as SAC	SAC		as SAC	SAC		as SAC	SAC	
1946	221.2	1456.0	1677.2	26.2	59.3	85.5	11.8	4.1	5.1
2010	365.0	1506.4	1871.4	24.5	9.1	33.6	6.7	0.6	1.8
<i>Gains/Losses (ha):</i>									
1946-2010	143.8	50.4	194.2	-1.6	-50.2	-51.8			
<i>Gains/Losses (%):</i>									
1946-2010	65.0	3.5	11.6	-6.2	-84.7	-60.7			

Table 6: Archaeological sites within Pembrey Forest.

Grid Ref	Period	Description or Dyfed Archaeological Trust hyperlink
SN380030	Unknown	http://www.cofiadurcahcymru.org.uk/arch/query/page.php?prn=DAT2131
SN390030	Post-Medieval	http://www.cofiadurcahcymru.org.uk/arch/query/page.php?prn=DAT29995
SN390030	Post-Medieval	http://www.cofiadurcahcymru.org.uk/arch/query/page.php?prn=DAT29995
SN390030	Post-Medieval	http://www.cofiadurcahcymru.org.uk/arch/query/page.php?prn=DAT29995
SN374035	Post-Medieval	http://www.cofiadurcahcymru.org.uk/arch/query/page.php?prn=DAT29996
SN374035	Post-Medieval	http://www.cofiadurcahcymru.org.uk/arch/query/page.php?prn=DAT29996
SN380029	Unknown	http://www.cofiadurcahcymru.org.uk/arch/query/page.php?prn=DAT30086
SN387033	Modern	http://www.cofiadurcahcymru.org.uk/arch/query/page.php?prn=DAT31112
SN398028	Modern	http://www.cofiadurcahcymru.org.uk/arch/query/page.php?prn=DAT31129
SN400028	Modern	http://www.cofiadurcahcymru.org.uk/arch/query/page.php?prn=DAT31225
SN401028	Modern	http://www.cofiadurcahcymru.org.uk/arch/query/page.php?prn=DAT31226
SN396011	Modern	http://www.cofiadurcahcymru.org.uk/arch/query/page.php?prn=DAT31229
SN396010	Modern	http://www.cofiadurcahcymru.org.uk/arch/query/page.php?prn=DAT31230
SN384030	Modern	http://www.cofiadurcahcymru.org.uk/arch/query/page.php?prn=DAT31231
SN385031	Modern	http://www.cofiadurcahcymru.org.uk/arch/query/page.php?prn=DAT31232
SN385031	Modern	http://www.cofiadurcahcymru.org.uk/arch/query/page.php?prn=DAT31233
SN387033	Modern	http://www.cofiadurcahcymru.org.uk/arch/query/page.php?prn=DAT31234
SN391030	Modern	http://www.cofiadurcahcymru.org.uk/arch/query/page.php?prn=DAT31335
SN393029	Modern	http://www.cofiadurcahcymru.org.uk/arch/query/page.php?prn=DAT31336
SN396028	Modern	http://www.cofiadurcahcymru.org.uk/arch/query/page.php?prn=DAT31337
SN387042	Modern	http://www.cofiadurcahcymru.org.uk/arch/query/page.php?prn=DAT31353
SN390036	Post-Medieval	http://www.cofiadurcahcymru.org.uk/arch/query/page.php?prn=DAT31356
SN407012	Post-Medieval	http://www.cofiadurcahcymru.org.uk/arch/query/page.php?prn=DAT31362
SN407012	Post-Medieval	http://www.cofiadurcahcymru.org.uk/arch/query/page.php?prn=DAT31362
SN420014	Modern	http://www.cofiadurcahcymru.org.uk/arch/query/page.php?prn=DAT31363
SN420014	Modern	http://www.cofiadurcahcymru.org.uk/arch/query/page.php?prn=DAT31363
SN420014	Modern	http://www.cofiadurcahcymru.org.uk/arch/query/page.php?prn=DAT31364
SN420014	Modern	http://www.cofiadurcahcymru.org.uk/arch/query/page.php?prn=DAT31364
SN397006	Modern	http://www.cofiadurcahcymru.org.uk/arch/query/page.php?prn=DAT31375
SN377026	Modern	http://www.cofiadurcahcymru.org.uk/arch/query/page.php?prn=DAT31376
SN387020	Medieval	http://www.cofiadurcahcymru.org.uk/arch/query/page.php?prn=DAT31396
SN387020	Post-Medieval	http://www.cofiadurcahcymru.org.uk/arch/query/page.php?prn=DAT31396
SN401012	Modern	http://www.cofiadurcahcymru.org.uk/arch/query/page.php?prn=DAT31397
SN403012	Modern	http://www.cofiadurcahcymru.org.uk/arch/query/page.php?prn=DAT31400
SN403012	Unknown	http://www.cofiadurcahcymru.org.uk/arch/query/page.php?prn=DAT31401
SN403012	Modern	http://www.cofiadurcahcymru.org.uk/arch/query/page.php?prn=DAT31402
SN403012	Modern	http://www.cofiadurcahcymru.org.uk/arch/query/page.php?prn=DAT31403
SN403012	Modern	http://www.cofiadurcahcymru.org.uk/arch/query/page.php?prn=DAT31404
SN404021	Post-Medieval	http://www.cofiadurcahcymru.org.uk/arch/query/page.php?prn=DAT31410
SN370035	Modern	http://www.cofiadurcahcymru.org.uk/arch/query/page.php?prn=DAT31414
SN372032	Modern	http://www.cofiadurcahcymru.org.uk/arch/query/page.php?prn=DAT31415
SN398009	Modern	A red brick tunnel running under the forest track
SN400012	Modern	Concrete bunker
SN399013	Modern	Two tunnels in line, 20m from the track
SN396011	Modern	Small red brick building west of track
SN396010	Modern	Small red brick building
SN396011	Modern	Large red brick structure, walls remaining and ground features
SN402014	Modern	Remains of building
SN402014	Modern	Remains of building

Table 7: Particle size analysis of beach and dune sediment samples from Pembrey. Sources: (A) Sampled 28/08/1999, analysed by laser diffraction; (B) Sampled 17-09-2008, analysed by dry sieving; (C) Sampled 18/01/2010, analysed by dry sieving; (D) Sampled 28/02/2014, analysed by dry sieving. Parameters determined using Gradistat software (Pye & Blott, 2001); Phi sorting and sorting description according to the scheme of Folk & Ward, 1957).

Location and sample		Depth	Mean	Mode	D10	D50	D90	Phi	Sorting Description	Source
		(cm)	(µm)	(µm)	(µm)	(µm)	(µm)	Sorting		
Frontal dune	PEMB1	0-5	179	169	125	178	261	0.414	Well Sorted	A
Frontal dune	PEMB2	0-5	174	169	123	174	247	0.389	Well Sorted	A
Frontal dune	PEMB3	0-5	163	154	115	162	235	0.401	Well Sorted	A
Embryo dune	PEMB4a	0-5	159	154	116	159	219	0.356	Well Sorted	A
Frontal dune	PEMB4b	0-5	166	169	119	166	234	0.380	Well Sorted	A
Lower frontal dune	PEMB5a	0-5	168	169	117	167	243	0.408	Well Sorted	A
Upper frontal dune	PEMB5b	0-5	159	154	115	159	222	0.368	Well Sorted	A
Frontal dune	PEMB6	0-5	164	154	115	162	238	0.406	Well Sorted	A
Frontal dune	PEMB7	0-5	164	169	115	164	233	0.404	Well Sorted	A
Embryo dune	PEMB8a	0-5	152	154	113	152	207	0.340	Very Well Sorted	A
Frontal dune	PEMB8b	0-5	156	154	115	156	213	0.347	Very Well Sorted	A
Frontal dune	PEMB9	0-5	184	169	124	181	283	0.462	Well Sorted	A
Frontal dune	PEMB10	0-5	177	169	122	175	262	0.429	Well Sorted	A
Frontal dune	PEMB11	0-5	200	169	126	195	332	0.539	Moderately Well Sorted	A
Frontal dune	PEMB12	0-5	216	224	142	216	326	0.468	Well Sorted	A
Frontal dune	PEMB13	0-5	227	245	151	229	331	0.436	Well Sorted	A
Frontal dune	PEMB14a	0-5	196	204	133	197	282	0.425	Well Sorted	A
Inland dune	PEMB14b	0-5	225	245	143	228	339	0.485	Well Sorted	A
Embryo dune	PEMB15a	0-5	176	169	116	176	261	0.468	Well Sorted	A
Frontal dune	PEMB15b	0-5	192	204	129	193	281	0.437	Well Sorted	A
Frontal dune	PEMB16	0-5	207	224	134	209	309	0.473	Well Sorted	A
Borehole 1	A1-1	0-5	137	138	111	137	171	0.233	Very Well Sorted	B
	A1-2	30	136	138	110	136	171	0.239	Very Well Sorted	B
	A1-3	60	152	138	123	148	200	0.279	Very Well Sorted	B
	A1-4	90	147	138	120	145	183	0.246	Very Well Sorted	B
	A1-5	120	147	138	118	144	186	0.253	Very Well Sorted	B
	A1-6	150	147	138	117	144	185	0.257	Very Well Sorted	B
	A1-7	180	149	138	123	145	191	0.255	Very Well Sorted	B
	A1-8	210	140	138	112	138	176	0.256	Very Well Sorted	B
	A1-9	240	146	138	119	143	179	0.237	Very Well Sorted	B
	A1-10	270	149	138	121	146	193	0.259	Very Well Sorted	B
	A1-11	300	155	138	120	151	209	0.321	Very Well Sorted	B
	A1-12	330	185	196	131	187	270	0.395	Well Sorted	B
	A1-13	360	165	196	126	165	219	0.328	Very Well Sorted	B
	A1-14	390	183	196	130	186	249	0.371	Well Sorted	B
	A1-15	420	166	196	127	168	219	0.319	Very Well Sorted	B
	A1-16	450	160	138	123	159	211	0.325	Very Well Sorted	B
	A1-17	480	162	165	126	161	212	0.321	Very Well Sorted	B
	A1-18	510	162	138	125	160	217	0.335	Very Well Sorted	B
	A1-19	540	174	196	120	173	257	0.427	Well Sorted	B
	A1-20	570	176	196	119	175	266	0.444	Well Sorted	B
	A1-21	600	174	138	123	170	266	0.434	Well Sorted	B
	A1-22	630	159	165	125	158	205	0.293	Very Well Sorted	B
	A1-23	660	151	138	121	149	196	0.264	Very Well Sorted	B
	A1-24	690	153	138	121	152	198	0.273	Very Well Sorted	B
	A1-25	720	168	165	127	168	231	0.334	Very Well Sorted	B

Location and sample		Depth	Mean	Mode	D10	D50	D90	Phi	Sorting Description	Source
		(cm)	(µm)	(µm)	(µm)	(µm)	(µm)	Sorting		
Borehole 2	A2-1	0-5	144	138	115	141	179	0.251	Very Well Sorted	B
	A2-2	30	139	138	112	138	177	0.259	Very Well Sorted	B
	A2-3	60	146	138	117	144	180	0.251	Very Well Sorted	B
	A2-4	90	147	138	120	144	180	0.244	Very Well Sorted	B
	A2-5	120	143	138	115	140	178	0.245	Very Well Sorted	B
	A2-6	150	145	138	117	142	179	0.246	Very Well Sorted	B
	A2-7	180	144	138	115	141	181	0.259	Very Well Sorted	B
	A2-8	210	146	138	116	142	181	0.251	Very Well Sorted	B
	A2-9	240	147	138	118	144	186	0.252	Very Well Sorted	B
	A2-10	270	146	138	117	143	186	0.256	Very Well Sorted	B
	A2-11	300	147	138	118	144	186	0.255	Very Well Sorted	B
	A2-12	330	178	196	128	178	257	0.393	Well Sorted	B
	A2-13	360	170	196	127	169	241	0.368	Well Sorted	B
	A2-14	390	159	165	122	158	207	0.313	Very Well Sorted	B
	A2-15	420	192	196	137	194	264	0.353	Well Sorted	B
	A2-16	450	170	138	125	166	250	0.397	Well Sorted	B
	A2-17	480	183	196	126	181	286	0.474	Well Sorted	B
	A2-18	510	183	196	129	184	270	0.412	Well Sorted	B
	A2-19	540	188	196	127	191	278	0.438	Well Sorted	B
Borehole 3	A3-1	0-5	143	138	114	140	185	0.270	Very Well Sorted	B
	A3-2	30	141	138	113	139	179	0.261	Very Well Sorted	B
	A3-3	60	139	138	111	138	177	0.258	Very Well Sorted	B
	A3-4	90	139	138	112	138	177	0.260	Very Well Sorted	B
	A3-5	120	146	138	116	142	188	0.263	Very Well Sorted	B
	A3-6	150	140	138	111	138	180	0.270	Very Well Sorted	B
	A3-7	180	141	138	112	139	178	0.262	Very Well Sorted	B
	A3-8	210	143	138	114	140	182	0.262	Very Well Sorted	B
	A3-9	240	147	138	116	143	191	0.267	Very Well Sorted	B
	A3-10	270	140	138	112	138	177	0.258	Very Well Sorted	B
	A3-11	300	144	138	115	141	177	0.240	Very Well Sorted	B
	A3-12	330	146	138	117	143	185	0.251	Very Well Sorted	B
	A3-13	360	153	138	122	149	200	0.278	Very Well Sorted	B
	A3-14	390	156	165	127	156	197	0.255	Very Well Sorted	B
	A3-15	420	175	196	128	175	250	0.384	Well Sorted	B
	A3-16	450	149	138	115	146	193	0.271	Very Well Sorted	B
Backshore	CB22	0-5	145	138	116	142	185	0.256	Very Well Sorted	C
Upper foreshore	CB23	0-5	144	138	113	140	193	0.284	Very Well Sorted	C
Lower foreshore	CB24	0-5	163	138	124	154	245	0.390	Well Sorted	C
Dune 500 m inland	CB25	0-5	174	196	126	176	245	0.388	Well Sorted	C
Mid beach	CB26	0-5	170	196	126	170	241	0.380	Well Sorted	C
Upper foreshore	CB27	0-5	250	275	164	256	353	0.447	Well Sorted	C
Upper foreshore	CB28	0-5	208	196	150	205	291	0.380	Well Sorted	C
Frontal dune	CB29	0-5	197	196	138	196	281	0.385	Well Sorted	C
Dune 25 m inland	CB30	0-5	187	196	140	191	240	0.290	Very Well Sorted	C
Frontal dune	PEM50	0-5	144	138	114	142	177	0.246	Very Well Sorted	D
Vegetated dune	PEM51	0-5	166	196	127	169	211	0.309	Very Well Sorted	D
Frontal dune	PEM52	0-5	162	165	125	163	206	0.288	Very Well Sorted	D
Eroded dune	PEM53	0-5	159	165	126	160	201	0.266	Very Well Sorted	D

Table 8: Geochemical analysis of six dune sediment samples from Pembrey by XRF analysis. Data source: Pye *et al.* (2007).

	PEMB 2	PEMB 5A	PEMB 5B	PEMB 11	PEMB 14A	PEMB 14B
SiO ₂	81.77	81.19	81.6	83.01	85.67	83.22
Al ₂ O ₃	2.80	2.84	3.00	2.69	2.29	2.34
Fe ₂ O ₃	1.15	1.10	1.51	0.99	1.33	1.58
MgO	0.43	0.44	0.56	0.36	0.34	0.37
CaO	5.72	6.22	5.52	5.60	3.95	5.25
Na ₂ O	0.43	0.44	0.47	0.41	0.35	0.35
K ₂ O	0.99	1.02	0.92	1.04	0.74	0.77
TiO ₂	0.10	0.11	0.23	0.08	0.14	0.17
P ₂ O ₅	0.05	0.04	0.06	0.04	0.05	0.06
MnO	0.03	0.04	0.04	0.03	0.03	0.04
Co	2	2	2	1	1	2
Cr	9	10	18	6	11	15
Cu	5	4	5	2	3	5
Ni	8	8	10	8	8	9
Sc	2	2	3	1	2	2
V	15	15	21	13	17	21
Y	6	6	9	5	6	8
Zn	26	26	27	23	25	26
Zr	53	81	269	37	198	252
Pb	8.87	10.13	8.86	8.66	9.21	12.06
Ba	167	167	159	172	133	139
Sr	208	224	165	221	129	169
Li	18	17	17	18	14	14
La	6	8	12	5	8	11
Ce	12	14	22	11	16	17
Nd	0	0	12.972	0	0	11.844
Sm	0	0.746	1.787	0.644	0	0.705
Eu	0	0	0.6728	0	0	0.552
Dy	1.3	1.3	1.8	1.1	1.3	1.6
Yb	0.5	0.5	0.7	0	0.5	0.7
Si/Al	29.2	28.6	27.2	30.9	37.4	35.6
Si/Ca	14.3	13.1	14.8	14.8	21.7	15.9
Al/Fe	2.43	2.58	1.99	2.72	1.72	1.48
Al/K	2.83	2.78	3.26	2.59	3.09	3.04
La/Ce	0.50	0.57	0.55	0.45	0.50	0.65
Nd/Sm	0.00	0.00	7.26	0.00	0.00	16.80

Table 9: Sea level rise projections by UKCP09 (5th, 50th and 95th percentile model outputs for three future emission scenarios), relative to the year 2010.

Year	Sea level rise relative to 2100 (cm)								
	Low emission scenario			Medium emission scenario			High emission scenario		
	5%	50%	95%	5%	50%	95%	5%	50%	95%
2030	3.2	6.1	9.0	3.4	7.2	11.0	3.8	8.6	13.4
2060	8.7	16.9	25.0	9.3	20.0	30.8	10.4	23.9	37.5
2100	17.1	34.3	51.3	18.5	40.8	63.3	20.6	49.0	77.4

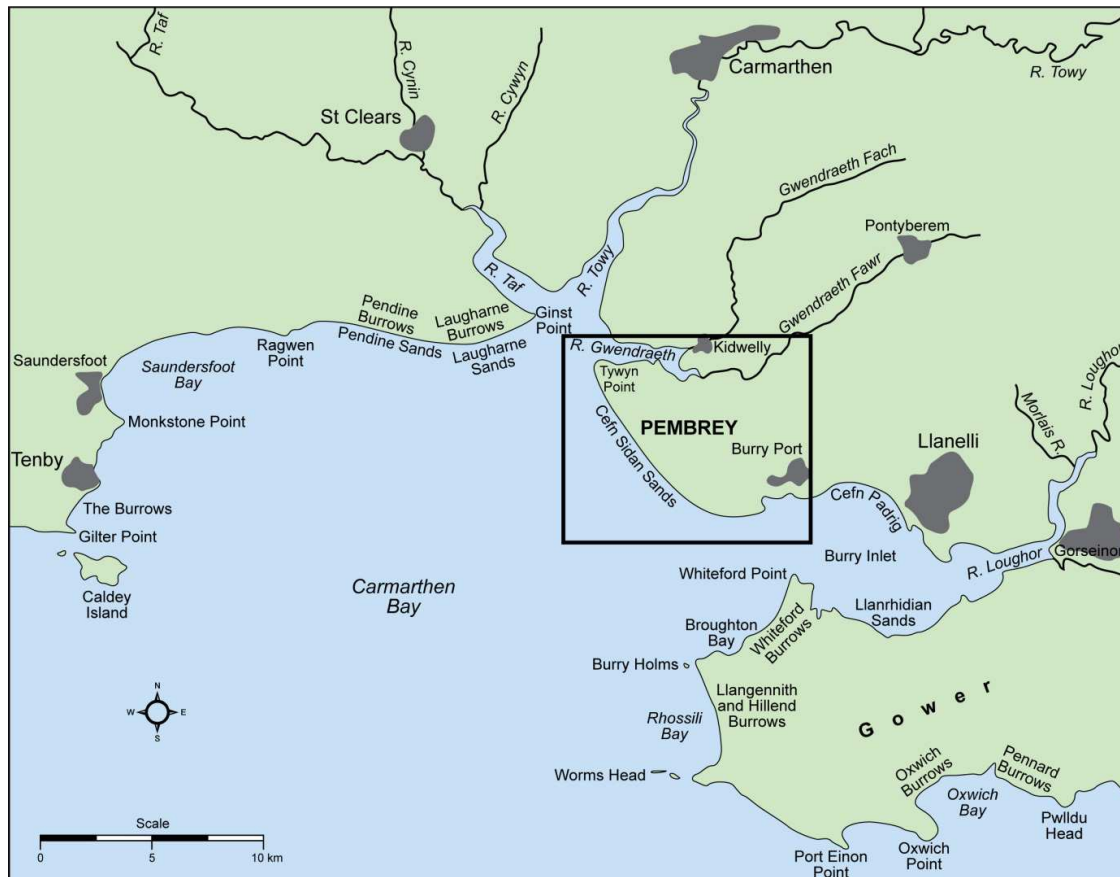


Figure 1: Map showing the location Pembrey Burrows within the wider context of Carmarthen Bay.

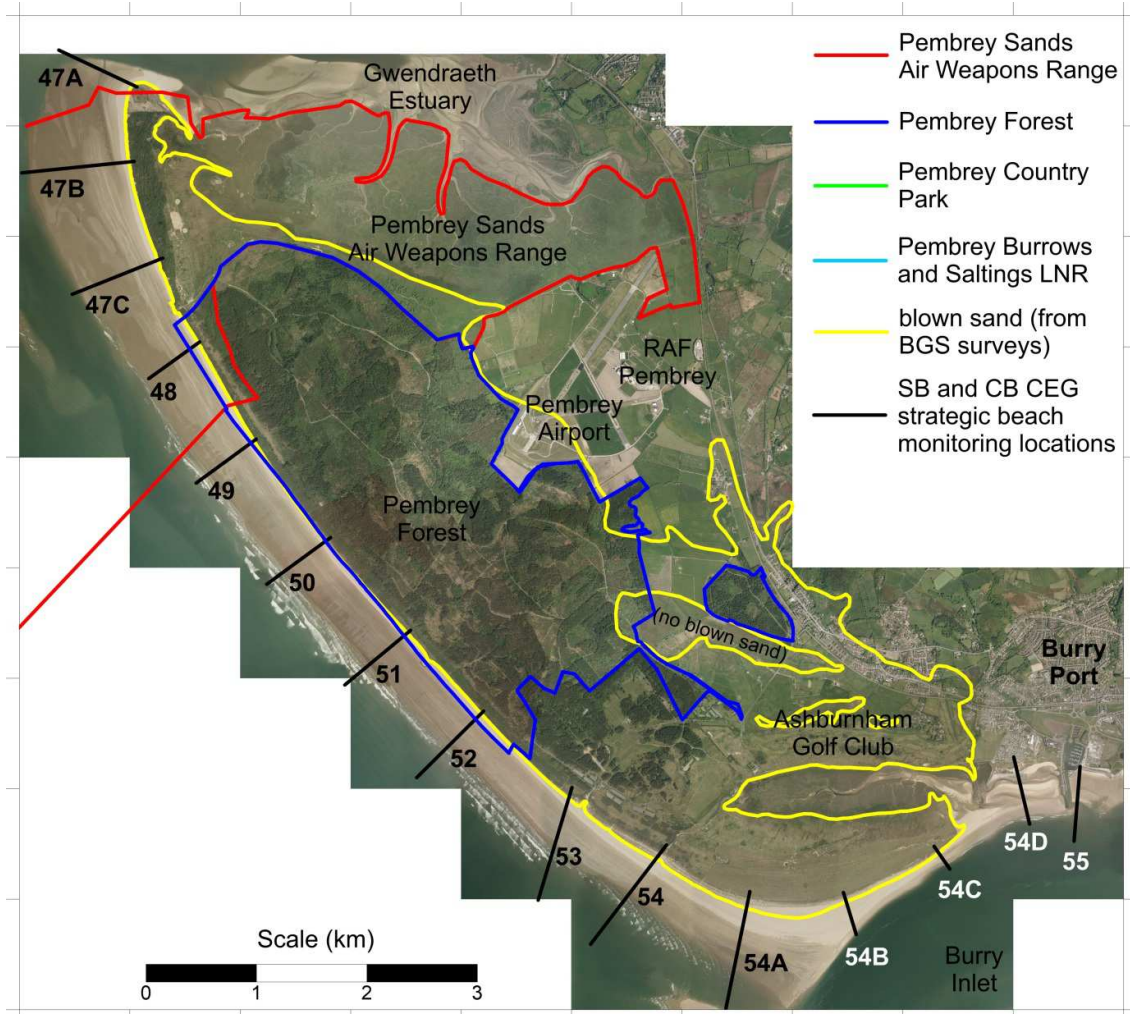


Figure 2: Composite aerial photograph (2010) of Pembrey Burrows showing boundaries of the MOD Air Weapons Range, Pembrey Forest, Pembrey Country Park, the landward limit of blown sand and locations of Swansea Bay & Carmarthen Bay Coastal Engineering Groups strategic beach monitoring profiles, superimposed on 2010 aerial photography.

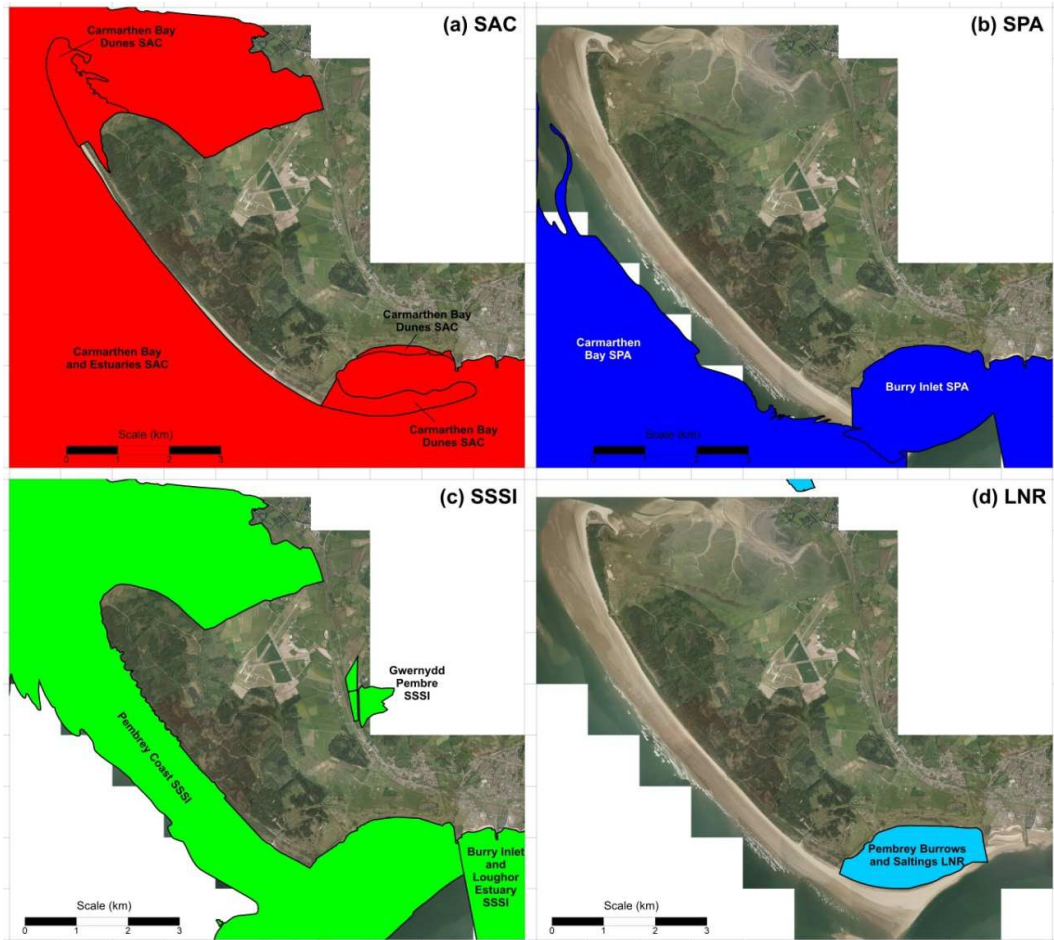


Figure 3: Conservation designations in the Pembrey coast: (a) Special Areas of Conservation (SAC); (b) Special Protection Areas (SPA); (c) Sites of Special Scientific Interest (SSSI); and (d) Local Nature Reserve (LNR).

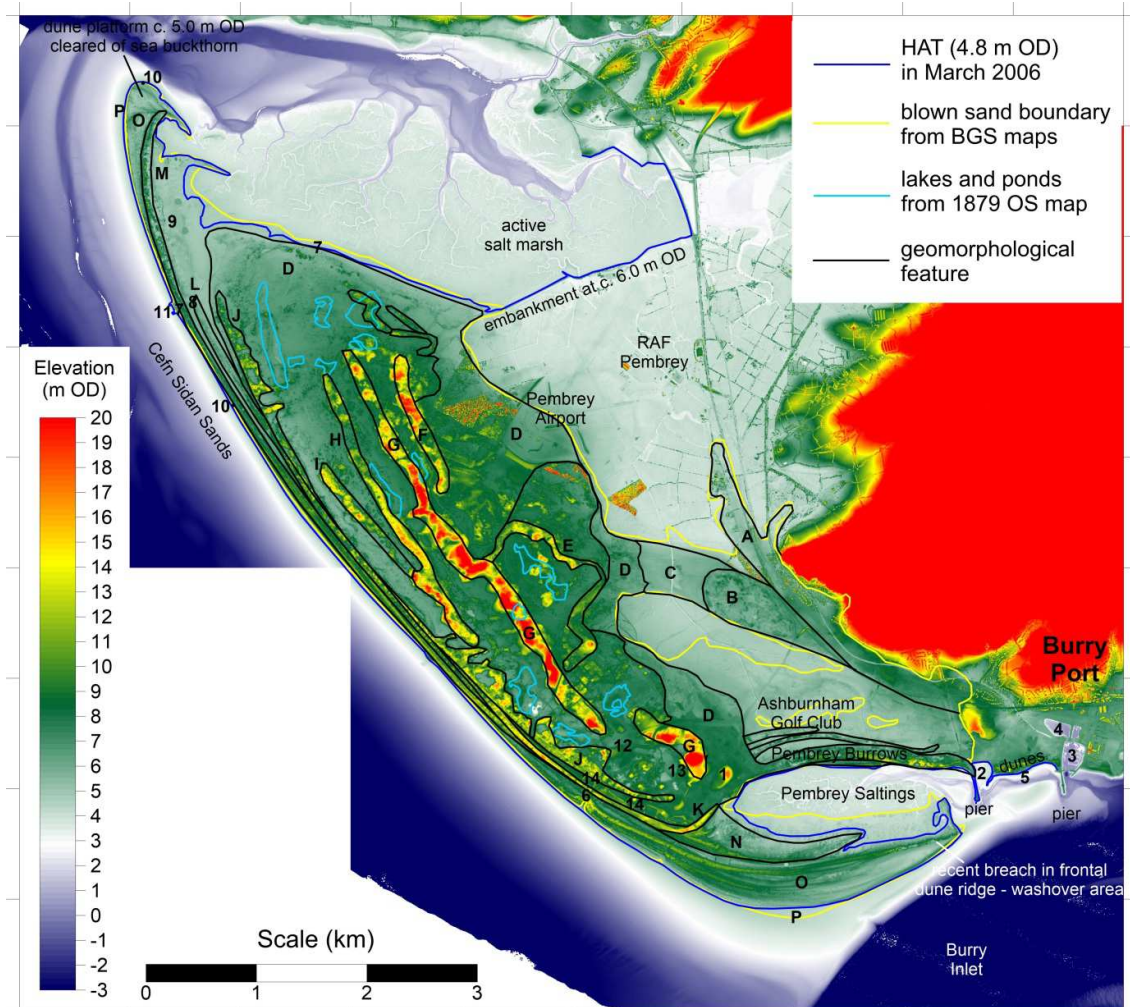


Figure 4: Geomorphological units in the Pembrey area, defined using 2003 and 2006 LiDAR data and aerial photography. LiDAR data have been filtered to remove vegetation and buildings. See Table 1 for descriptions of geomorphological units.



Figure 5: Geomorphological units in the Pembrey area, superimposed on 2010 aerial photography. See Table 1 for unit descriptions.

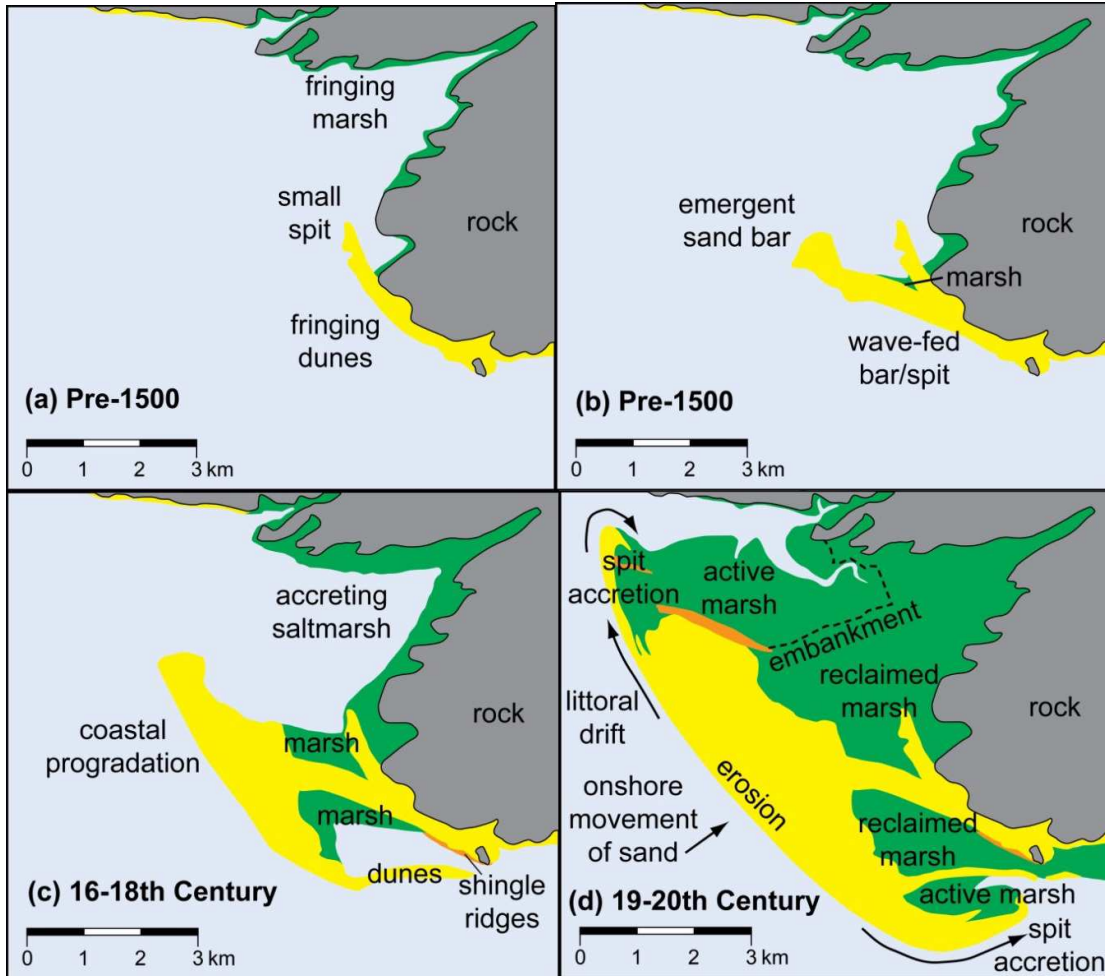


Figure 6: Schematic diagram showing stages in the geomorphological evolution of the Pembrey area.

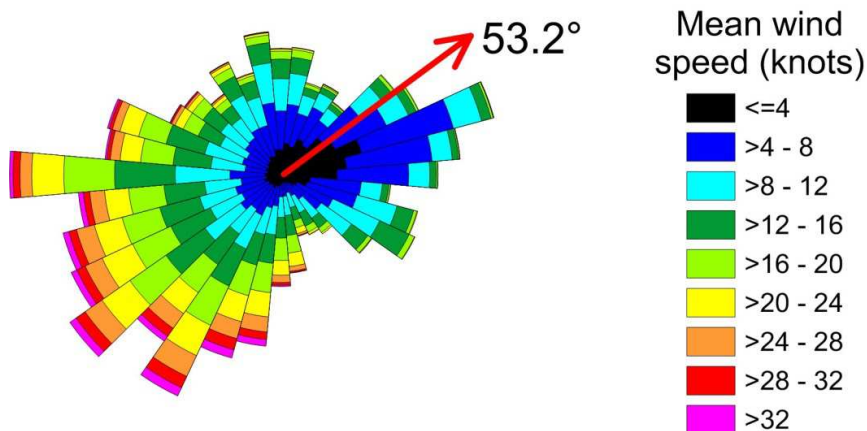


Figure 7: Wind rose constructed from hourly mean wind speeds and direction recorded at Pembrey Sands (December 1993 to January 2014). Data supplied by the UK Met Office The resultant drift direction (RDD) calculated for winds > 12 knots is also shown.

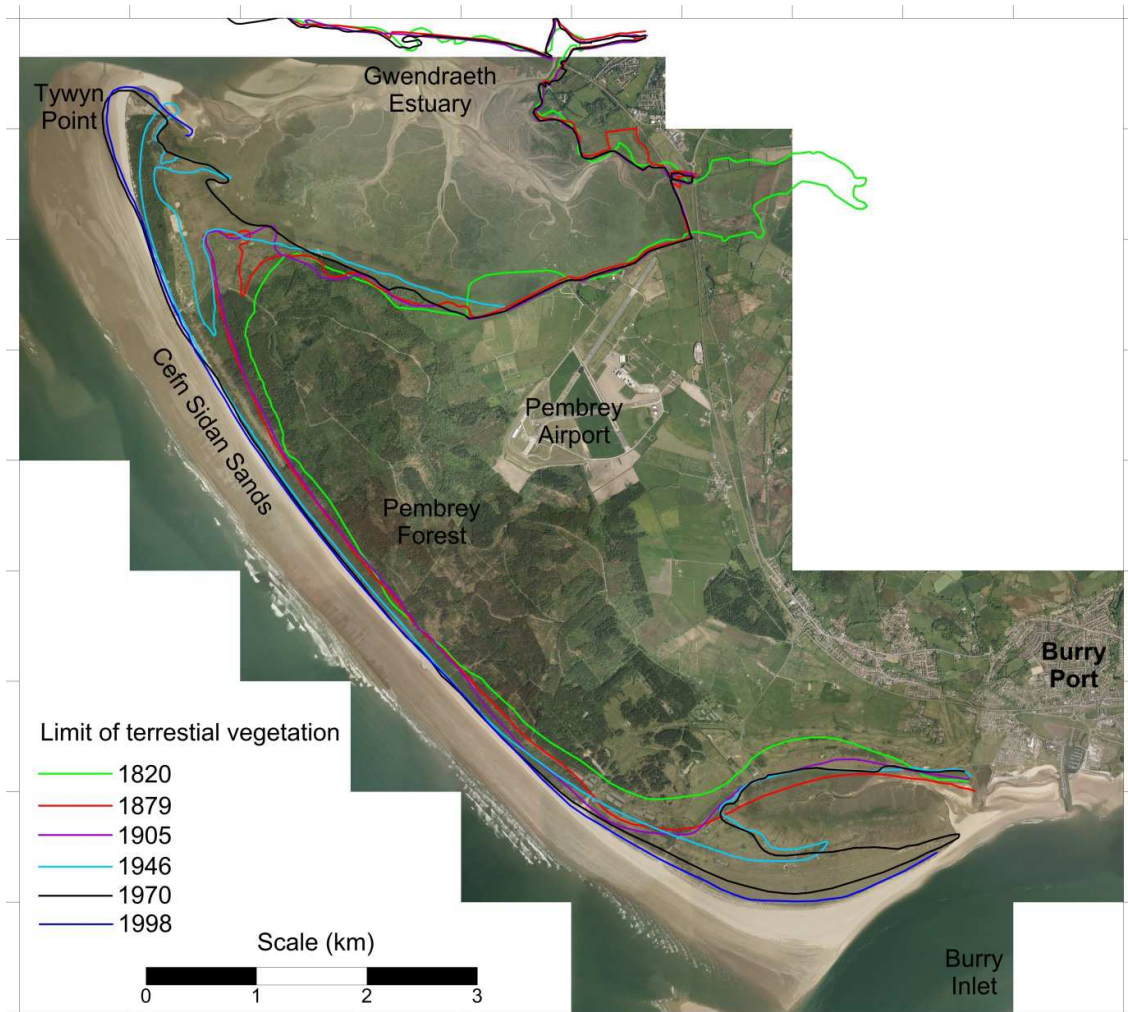


Figure 8: 2010 aerial photography of the Pembrey area with lines indicating the limits of terrestrial vegetation, based on historical OS maps (surveyed in 1820, 1879, 1905 and 1970), aerial photographs (1946 and 1998) and GPS ground surveys in February 2014.

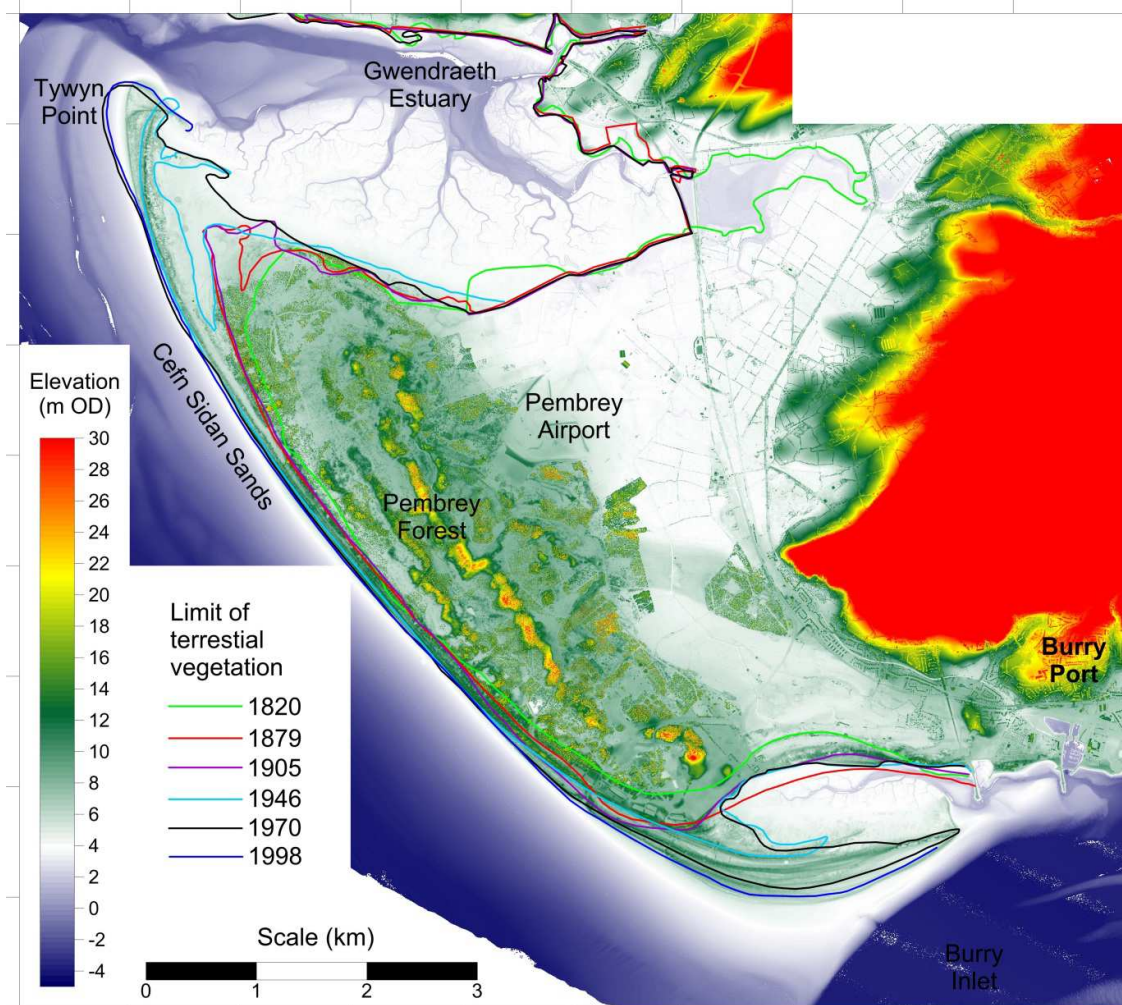


Figure 9: DEM of the Pembrey Burrows area generated from March 2006 LiDAR data. Lines indicate the positions of the limit of terrestrial vegetation based on historical OS maps (surveyed in 1820, 1879, 1905 and 1970), aerial photographs (1946 and 1998) and GPS ground surveys in February 2014.

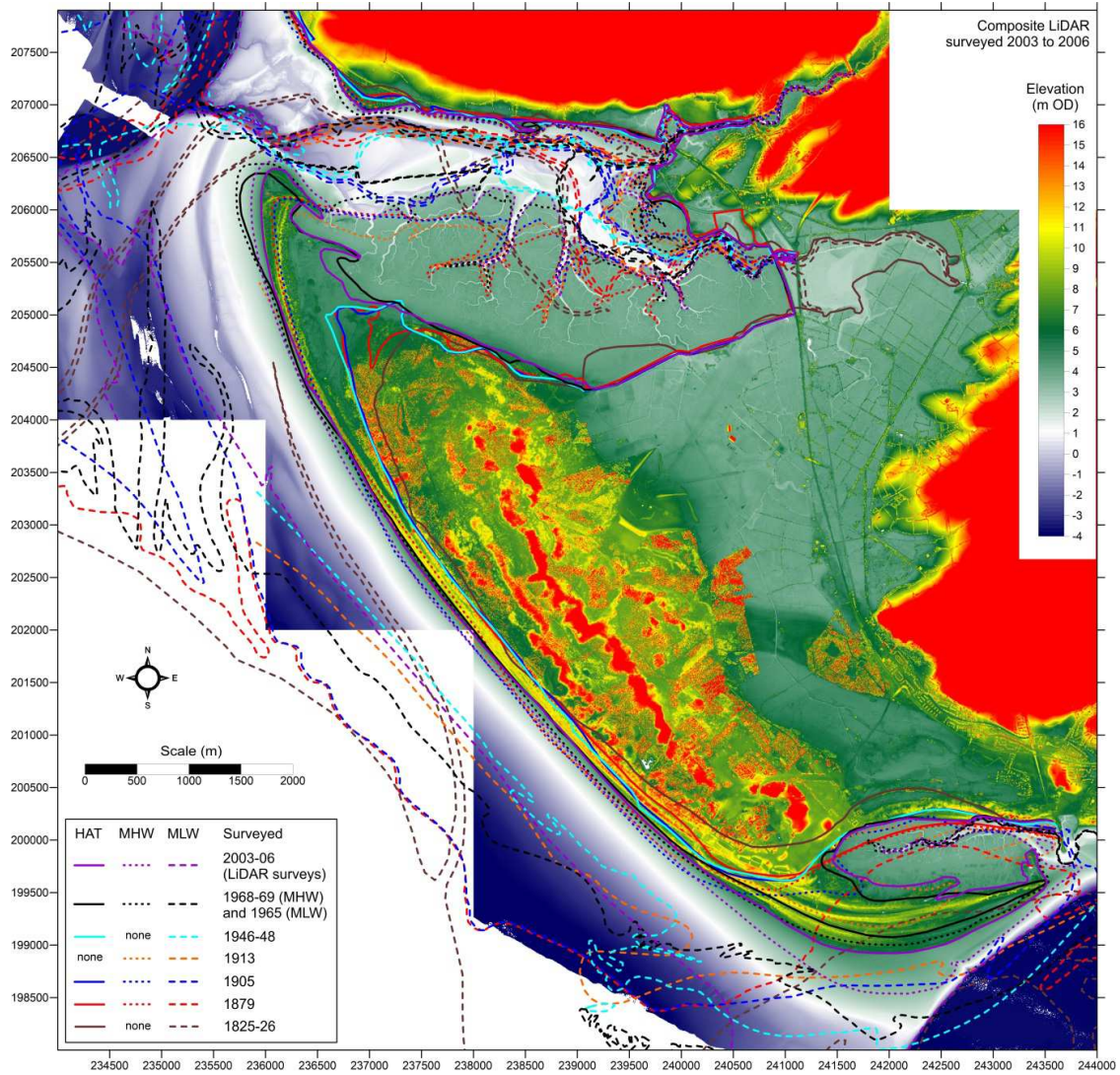


Figure 10: LiDAR DEM of Pembrey Burrows and adjoining areas and historical positions of intertidal channels. Tide lines have been digitized taken from OS maps.

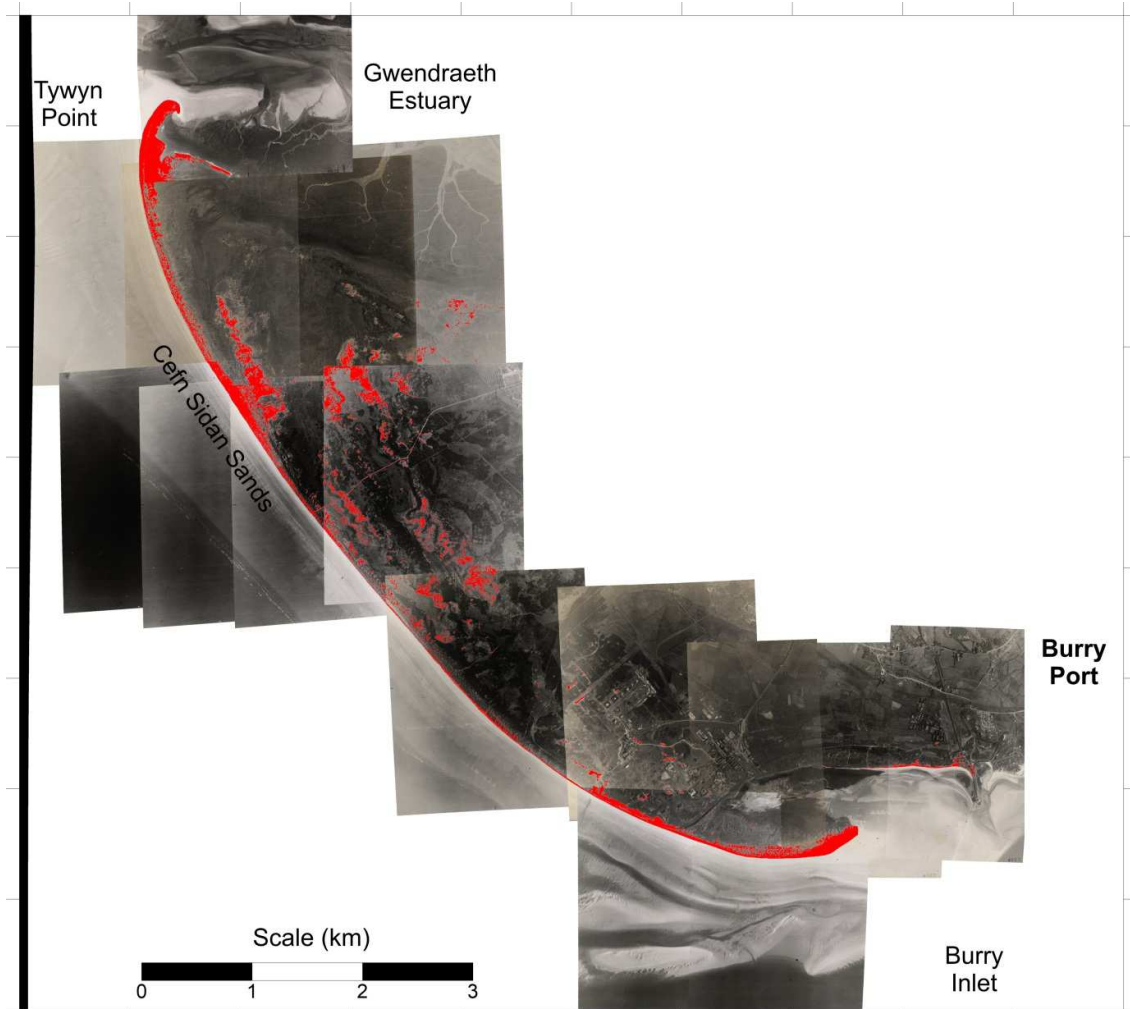


Figure 11: Bare sand areas (shown in red) mapped from the aerial photographs flown by the RAF in 1946.



Figure 12: Bare sand areas (shown in red) mapped from the aerial photographs flown in 2010.

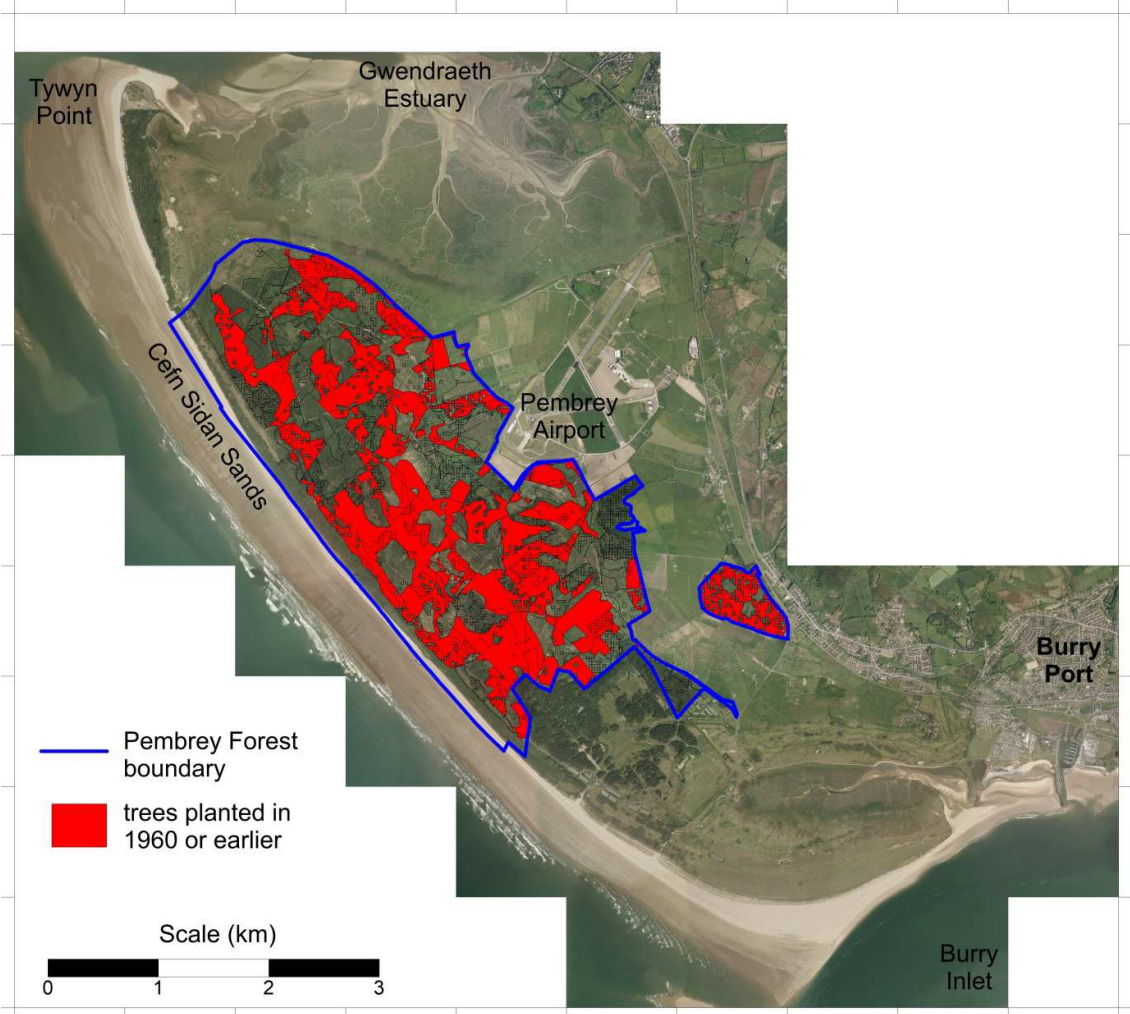


Figure 13: Areas of trees planted in 1960 or earlier, overlain on 2010 aerial photographs.

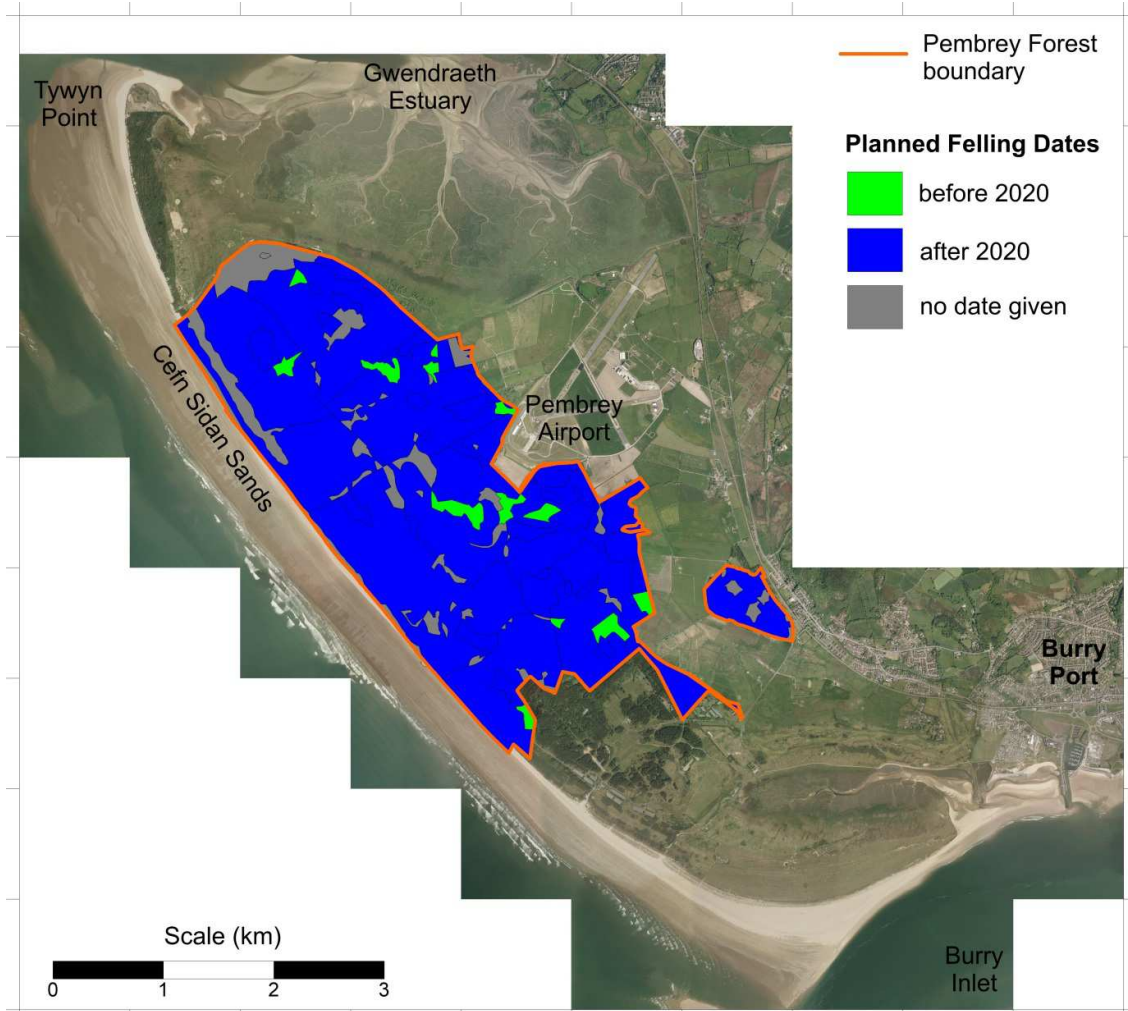


Figure 14: Planned tree felling dates, before or after 2020, identified in the current Forest Development Plan. Some level of replanting is currently envisaged in most of the areas.

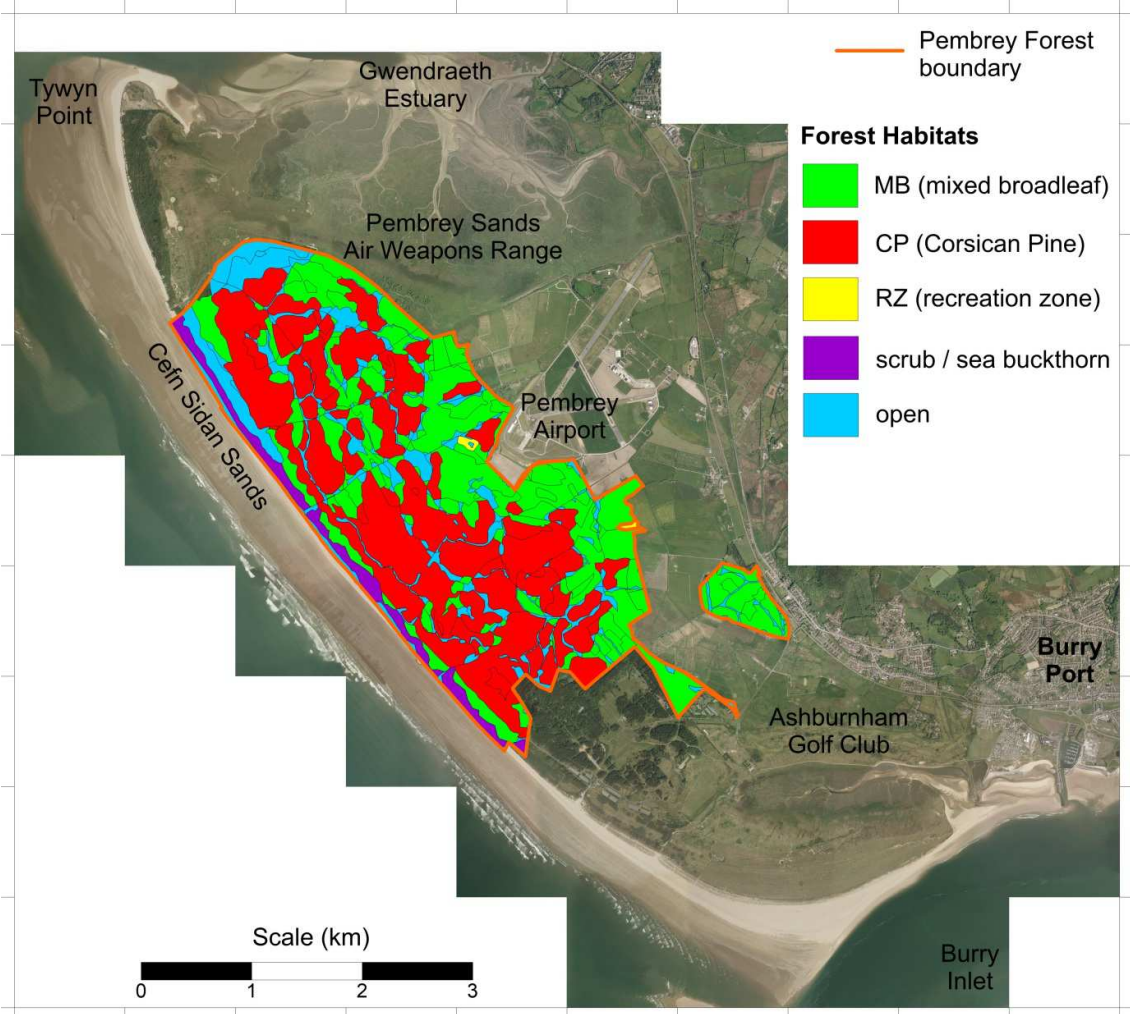


Figure 15: Habitat types at Pembrey Forest, overlain on 2010 aerial photographs.

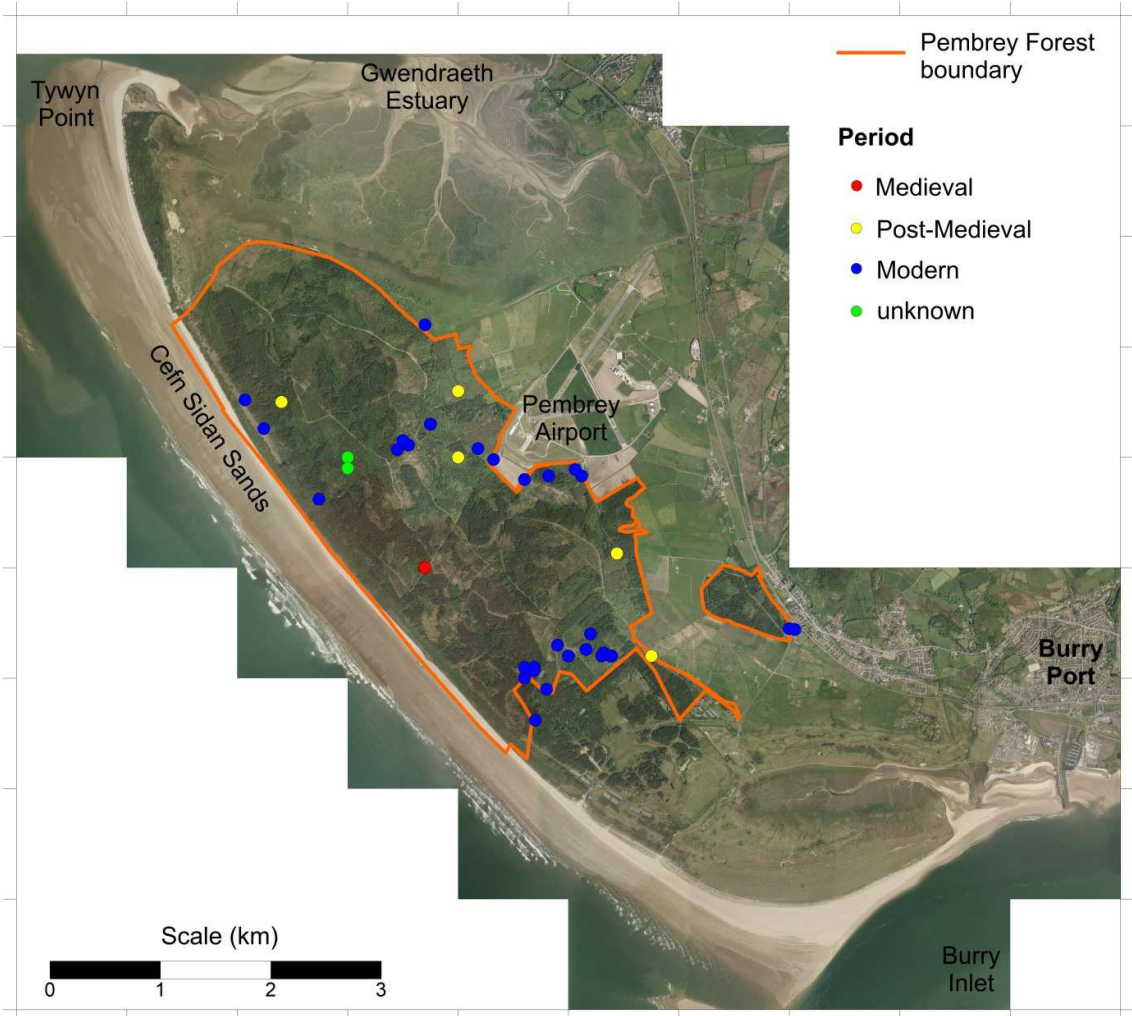


Figure 16: Archaeological sites at Pembrey Forest, overlain on 2010 aerial photographs.

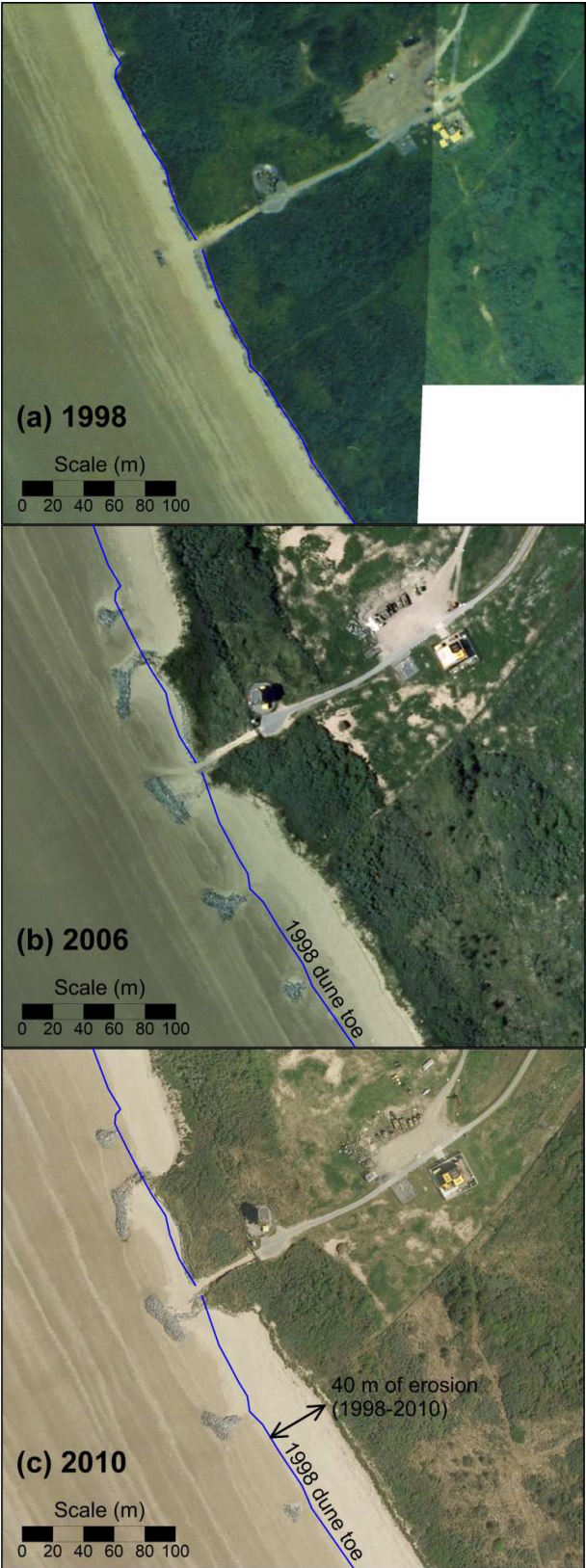


Figure 17: The effect of coast protection works on shoreline evolution south of Tywyn Point.

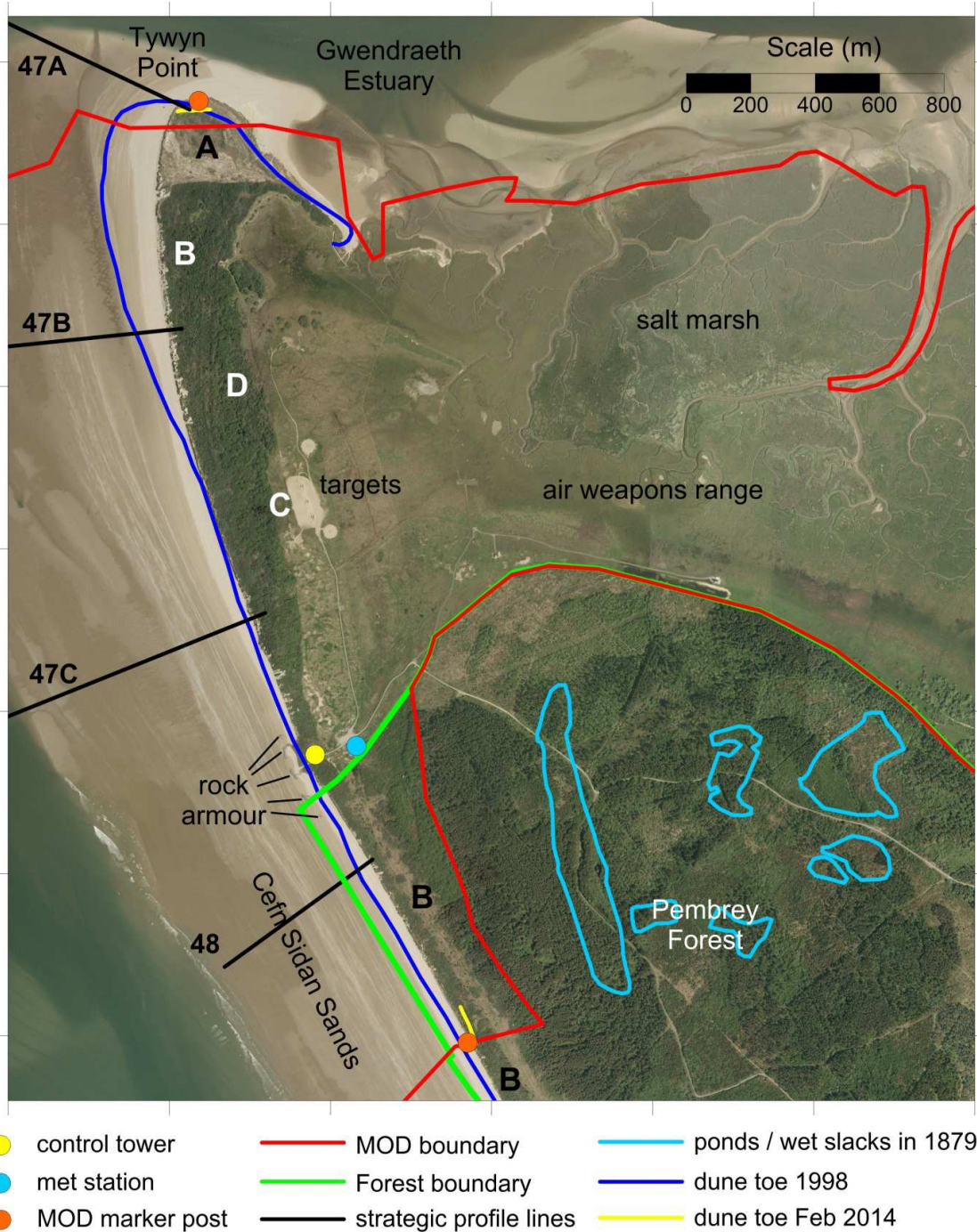


Figure 18: The northern part of the Pembrey frontage (2010 aerial photography). A: area of scrub clearance 2008-2012; B: area of scrub clearance 2013-2014; C: wet slack; D: Alder dominated mixed woodland on landward side of sea buckthorn scrub.

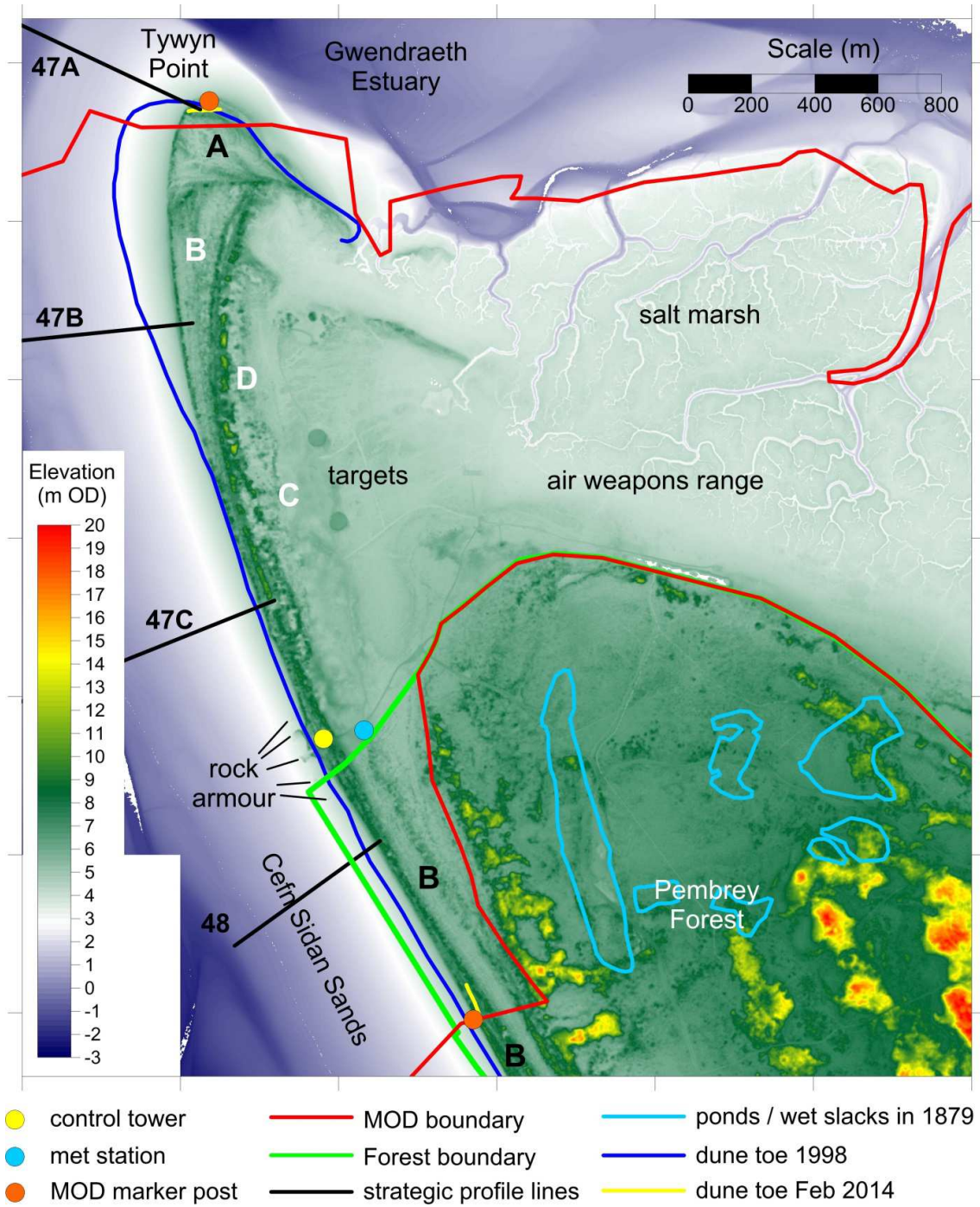


Figure 19: The northern part of the Pembrey frontage (2006 LiDAR DEM). A: area of scrub clearance 2008-2012; B: area of scrub clearance 2013-2014; C: wet slack; D: Alder-dominated woodland.

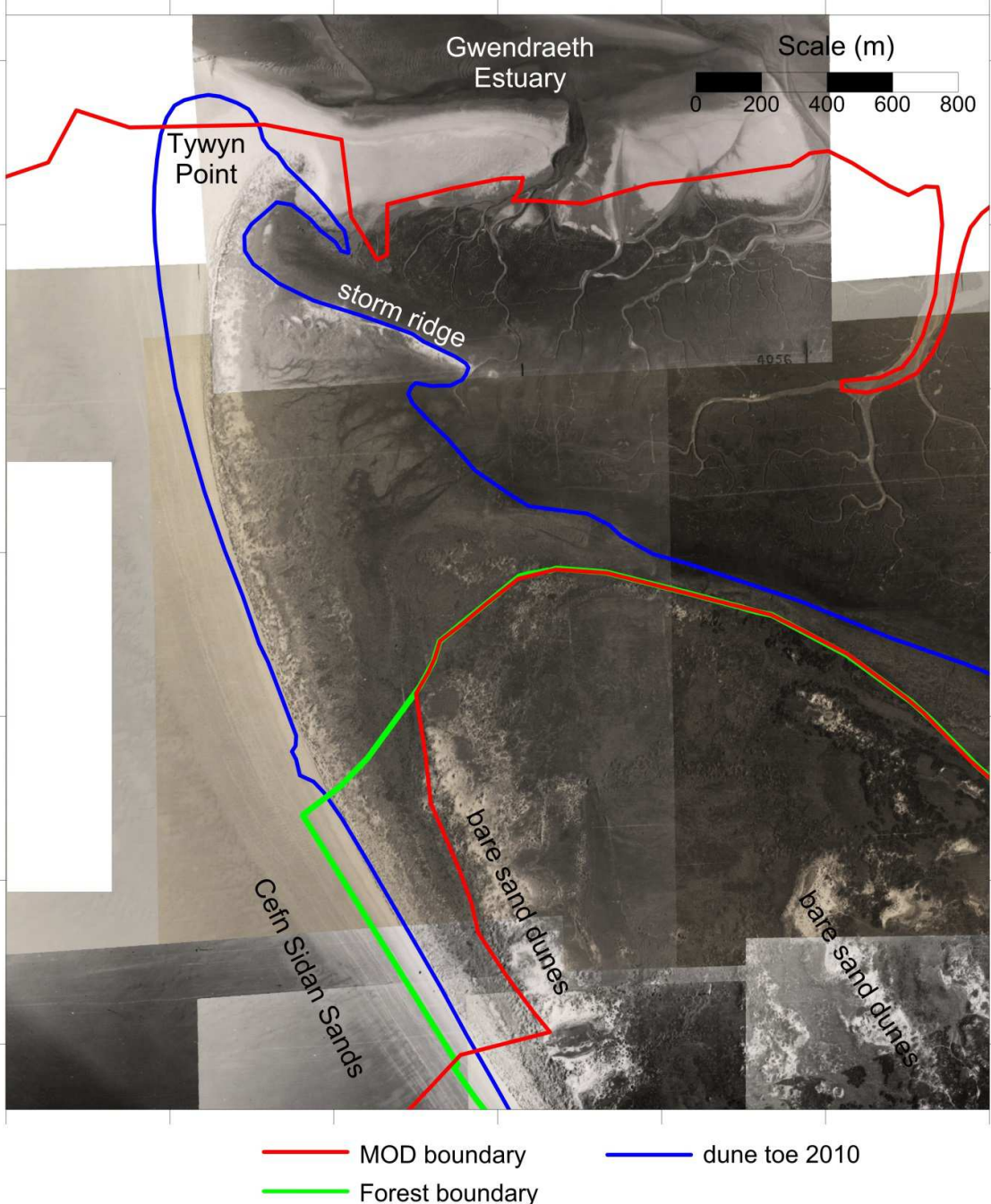


Figure 20: The northern part of the Pembrey frontage (1946 aerial photography).

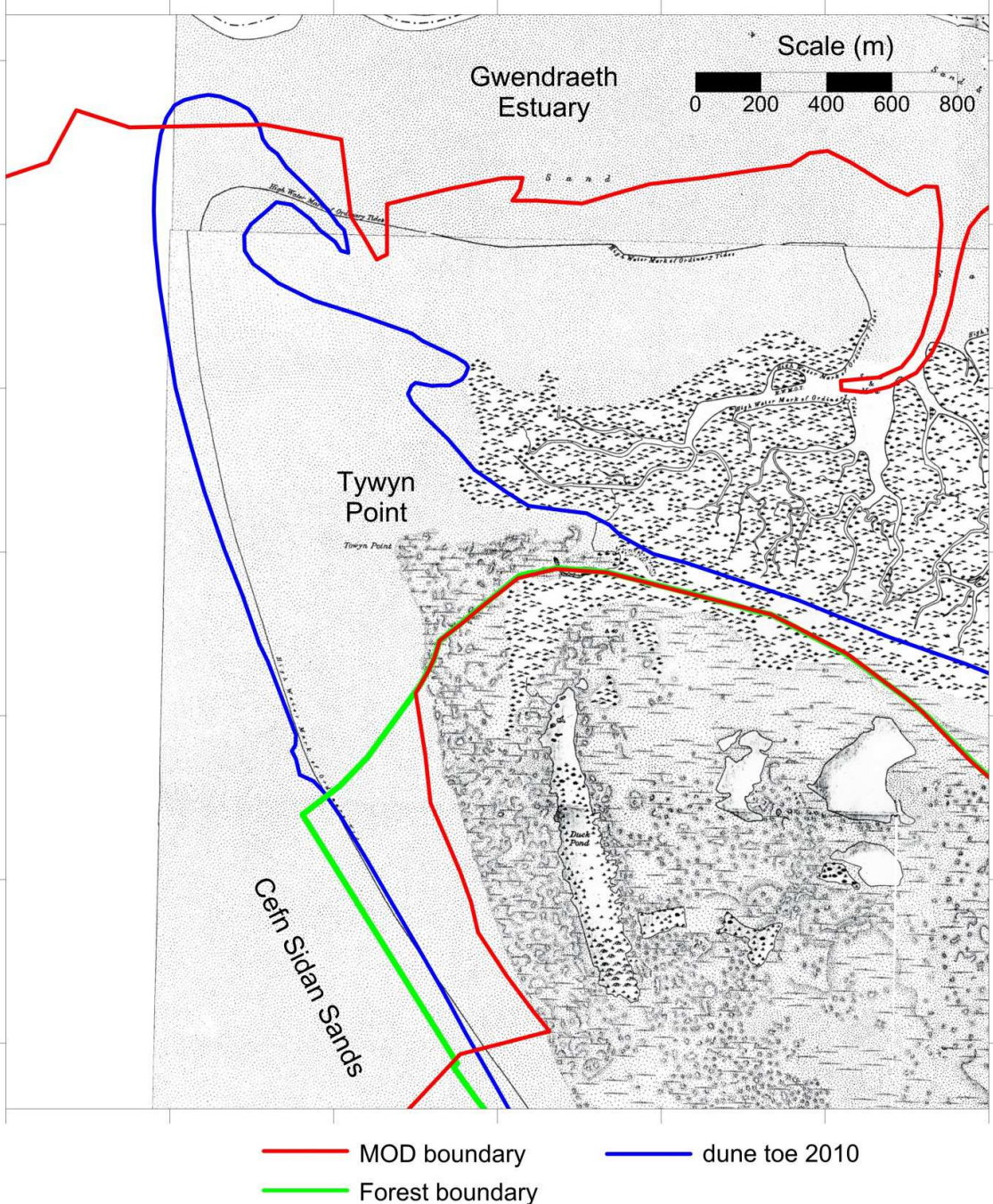


Figure 21: The northern part of the Pembrey frontage (First edition Six Inch OS map surveyed in 1879).

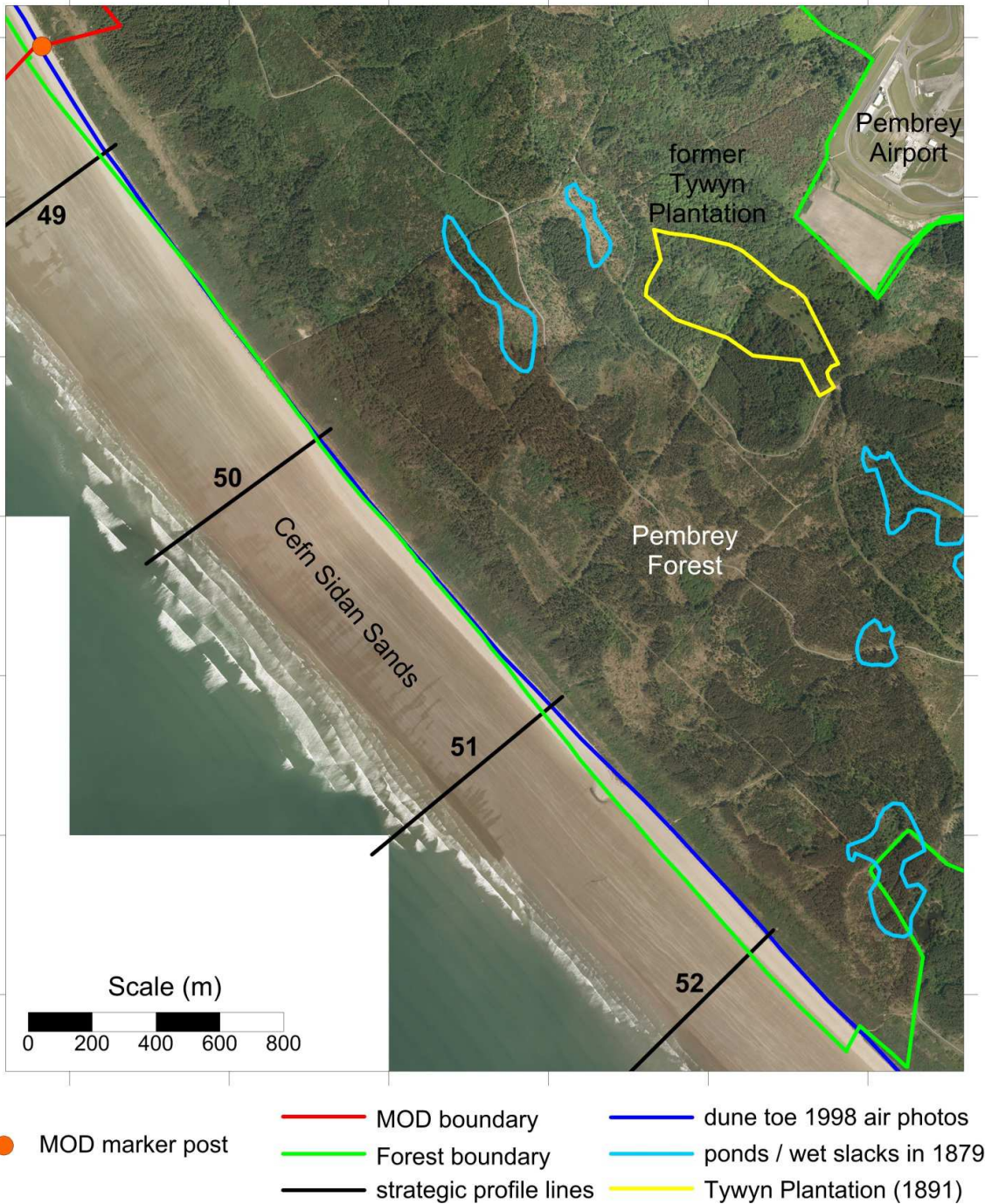


Figure 22: The central part of the Pembrey frontage (2010 aerial photography).

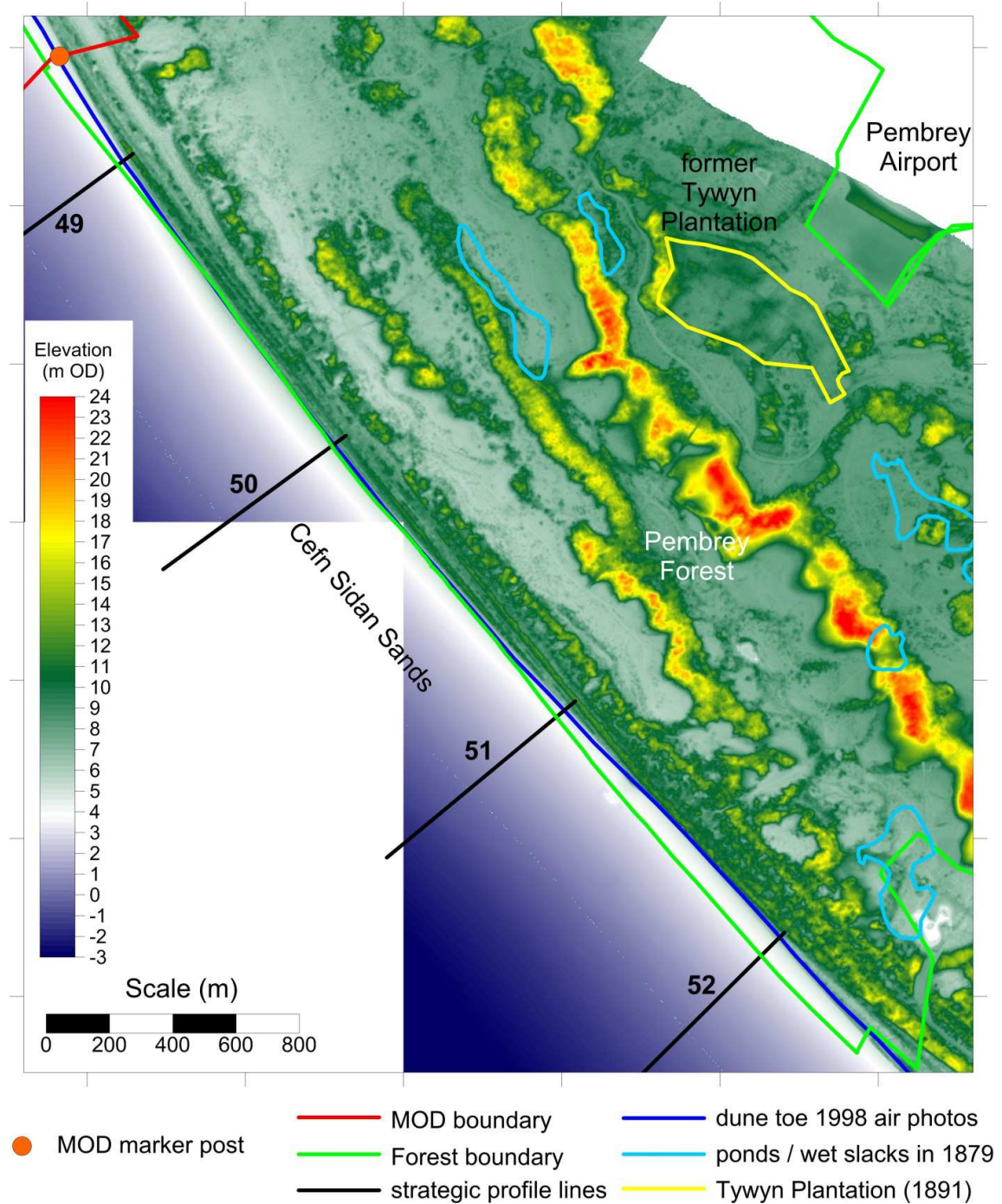


Figure 23: The central part of the Pembrey frontage (2006 LiDAR DEM).

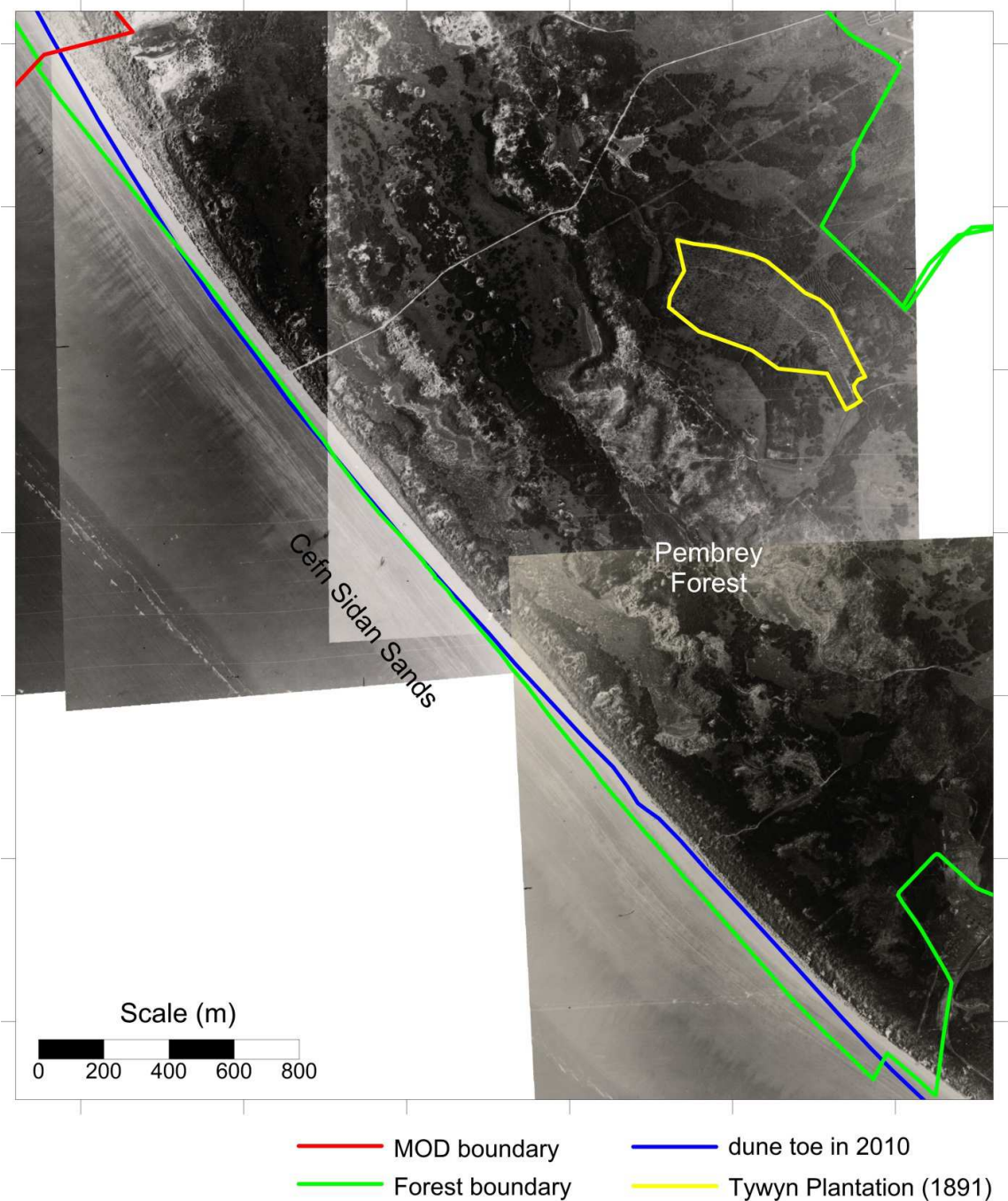


Figure 24: The central part of the Pembrey frontage (1946 aerial photography).

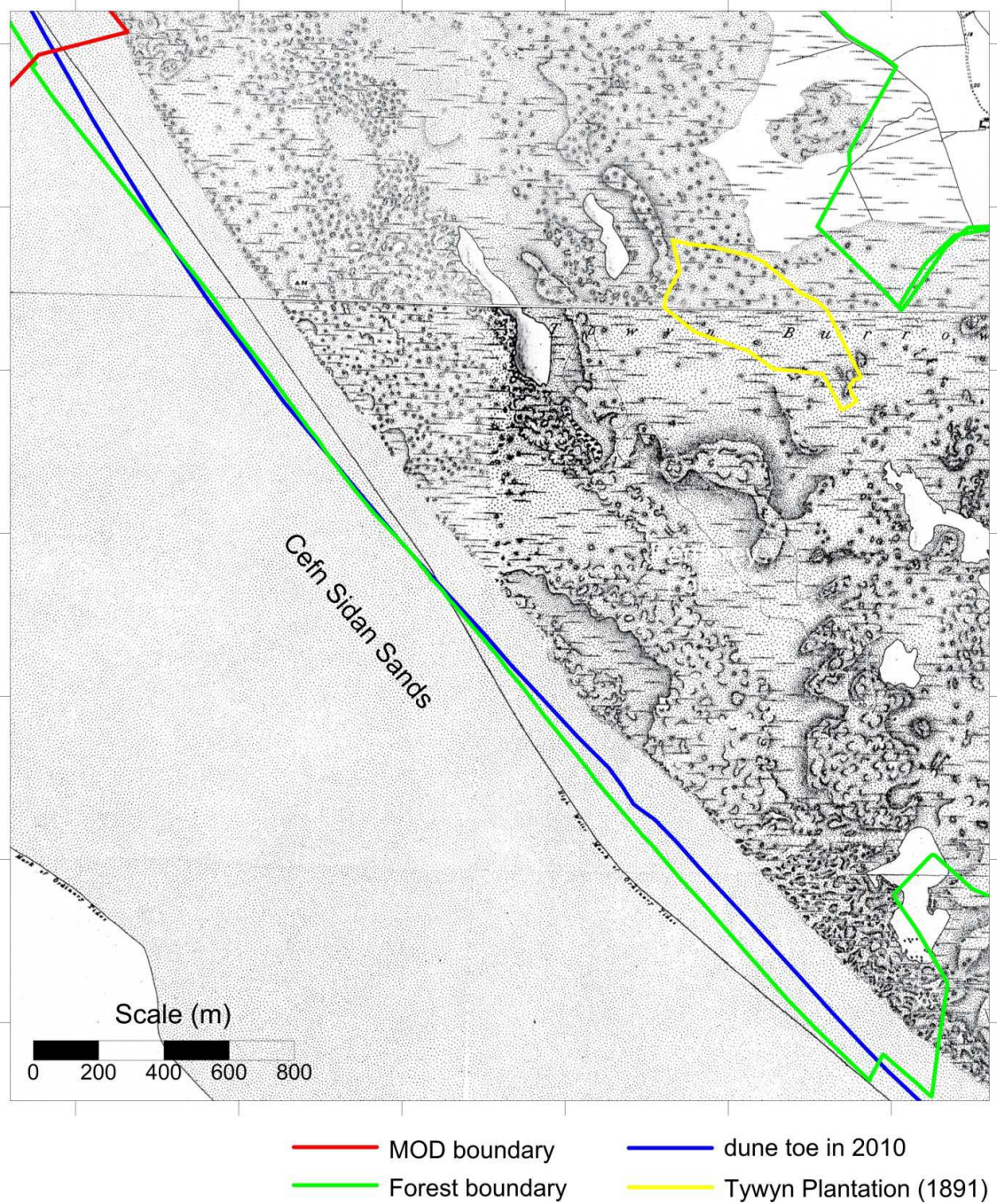


Figure 25: The central part of the Pembrey frontage (First Edition Six Inch OS map surveyed in 1879).

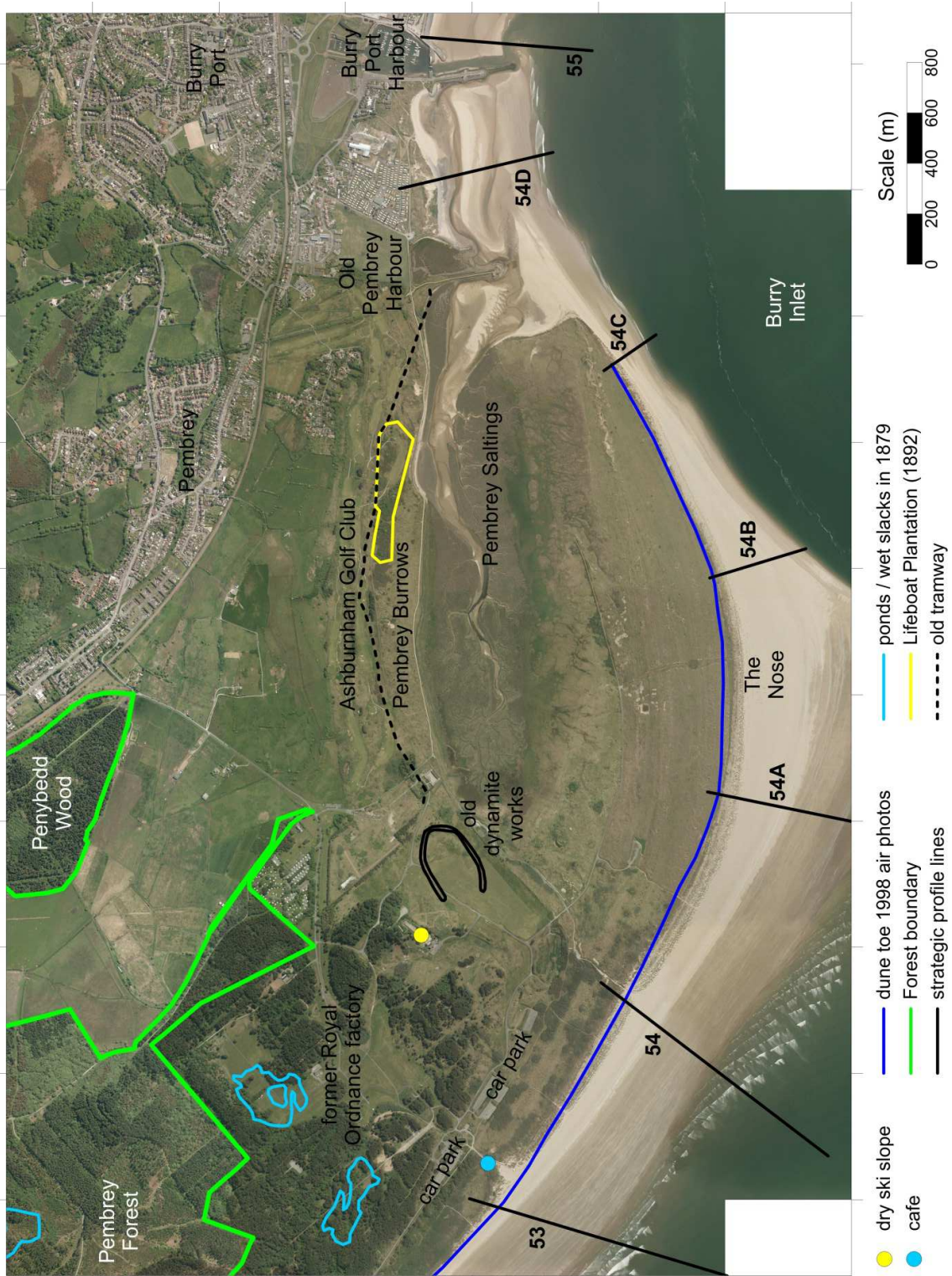


Figure 26: The southern part of the Pembrey frontage (2010 aerial photography).

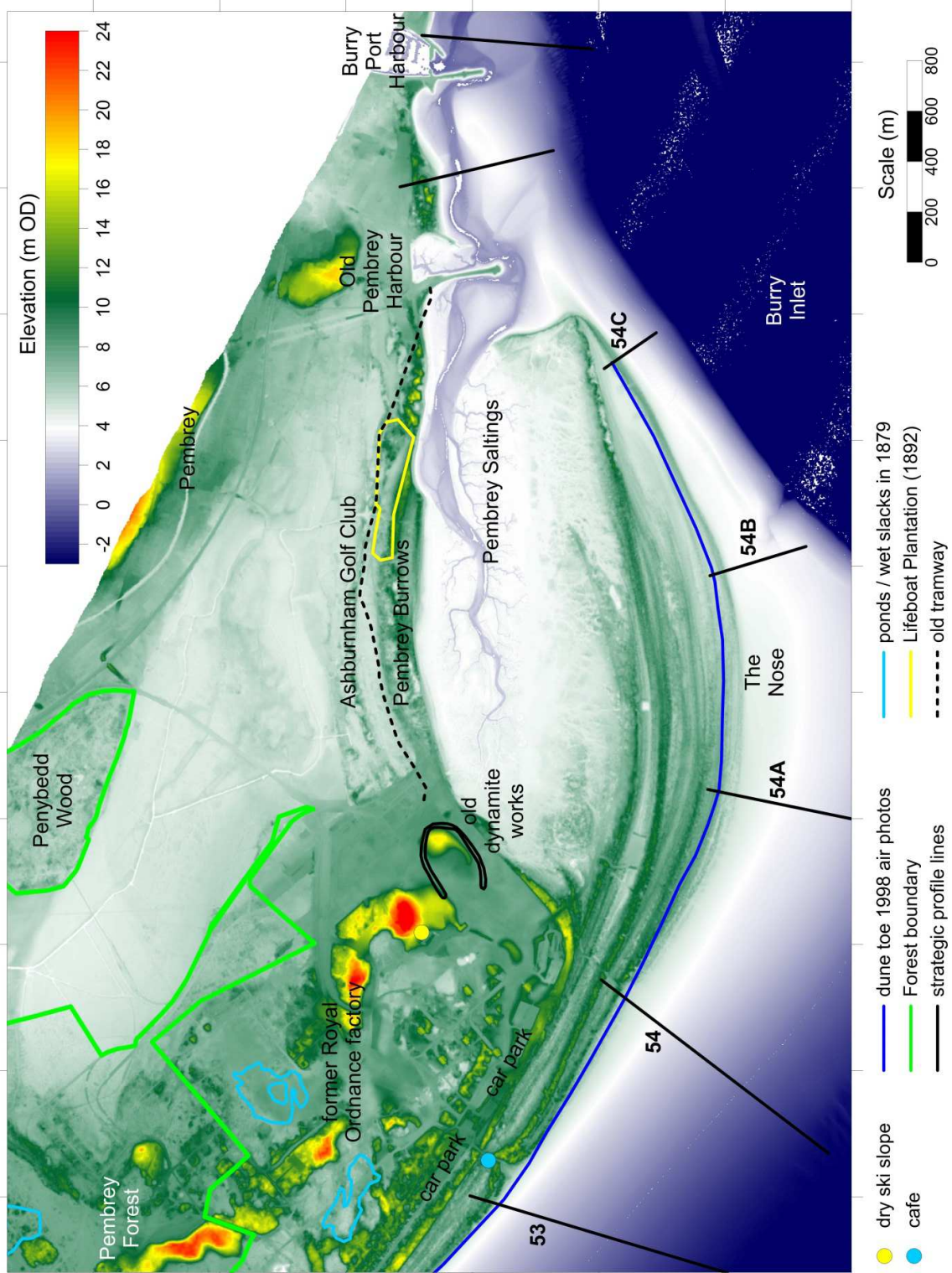


Figure 27: The southern part of the Pembrey frontage (2006 LiDAR DEM).

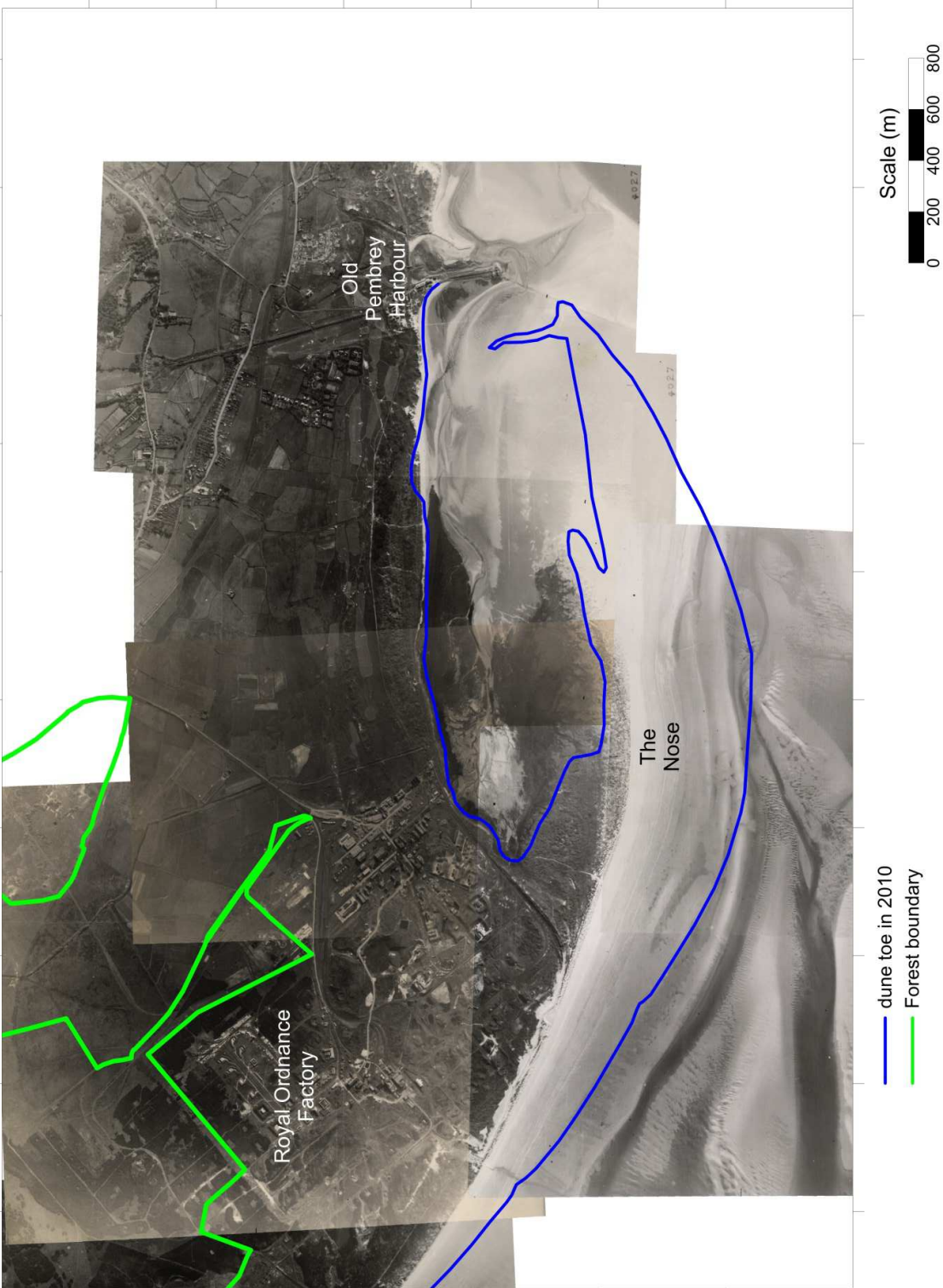


Figure 28: The southern part of the Pembrey frontage (1946 aerial photography).

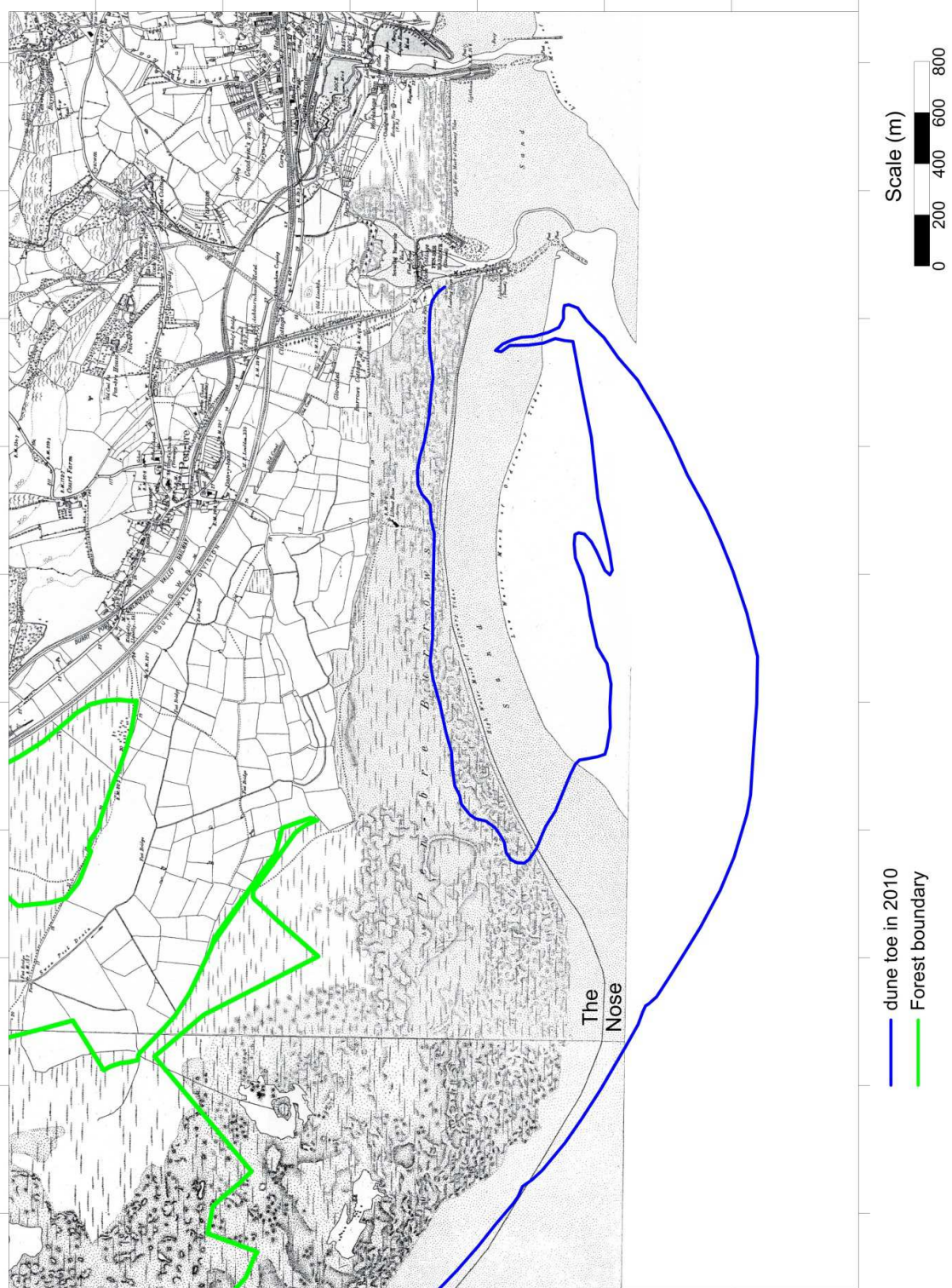


Figure 29: The southern part of the Pembrey frontage (First edition Six Inch OS map surveyed in 1879).



Figure 30: Sediment sampling locations.

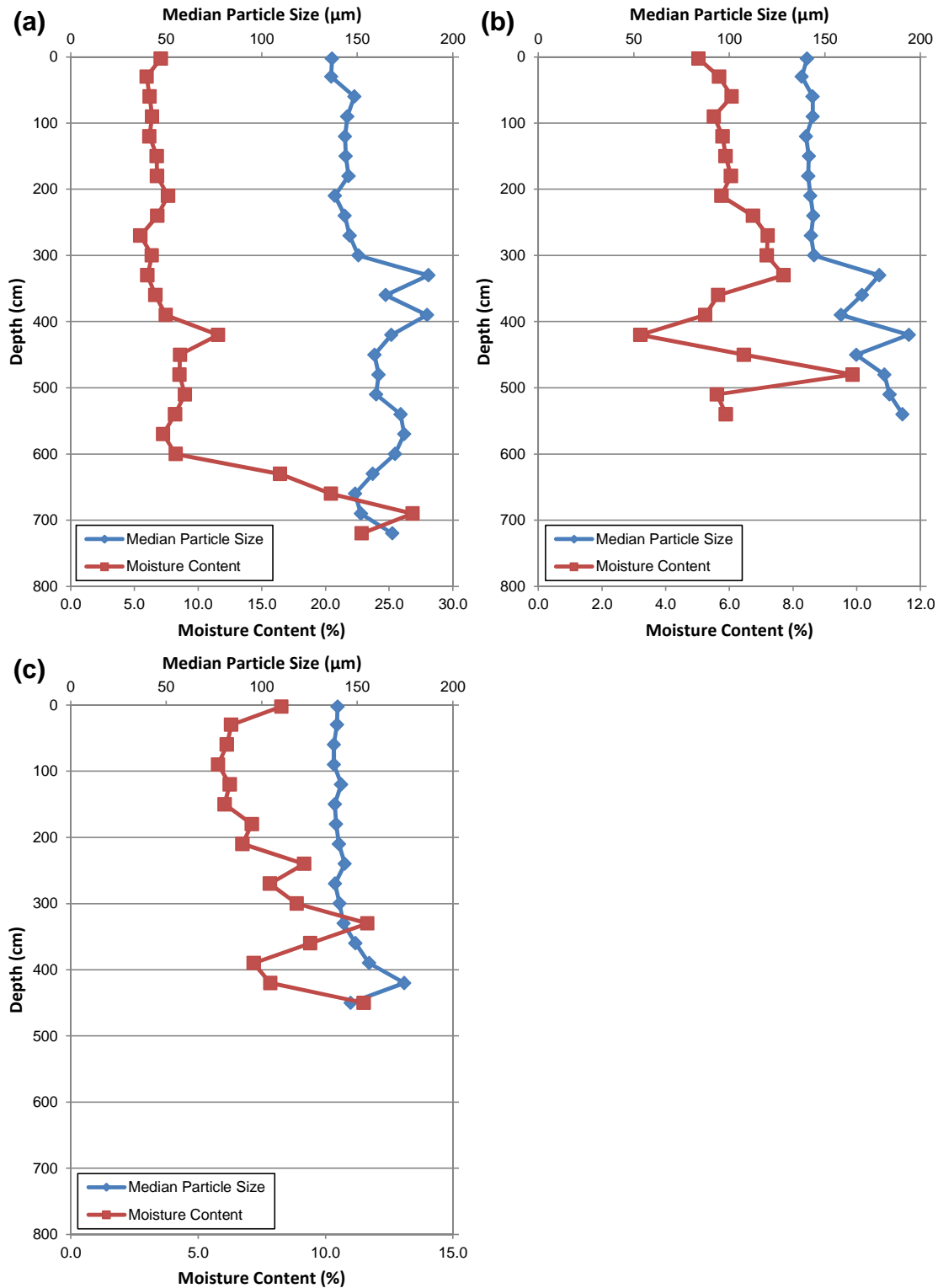


Figure 31: Depth variation in median sand particle size and moisture content in three boreholes c.50 m inland from the beach south of the Pembrey Country Park Visitor Centre, sampled on 17-09-2008: (a) Borehole 1; (b) Borehole 2; and (c) Borehole 3. Particle size determined by dry sieving; moisture content determined by weight loss following oven drying.

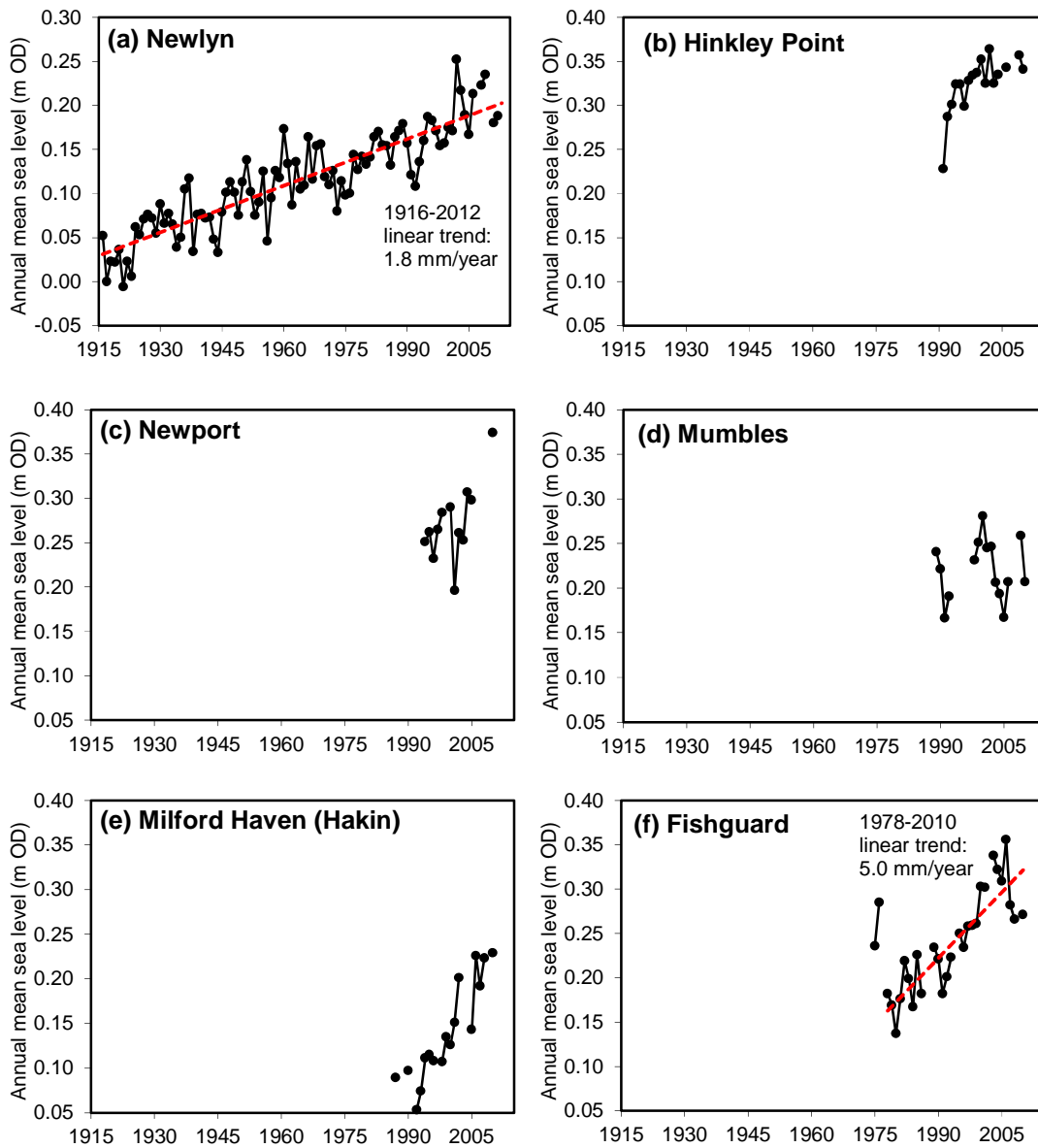


Figure 32: Changes in annual mean sea level recorded at six tide gauge stations in south-west Britain: (a) Newlyn (1916-2012); (b) Hinkley Point (1991-2010); (c) Newport (1994-2010); (d) Mumbles (1989-2010); (e) Milford Haven (Hakin) (1987-2010); and (f) Fishguard (1975-2010). Data source: PSMSL, revised to May 2014 (data from PSMSL).

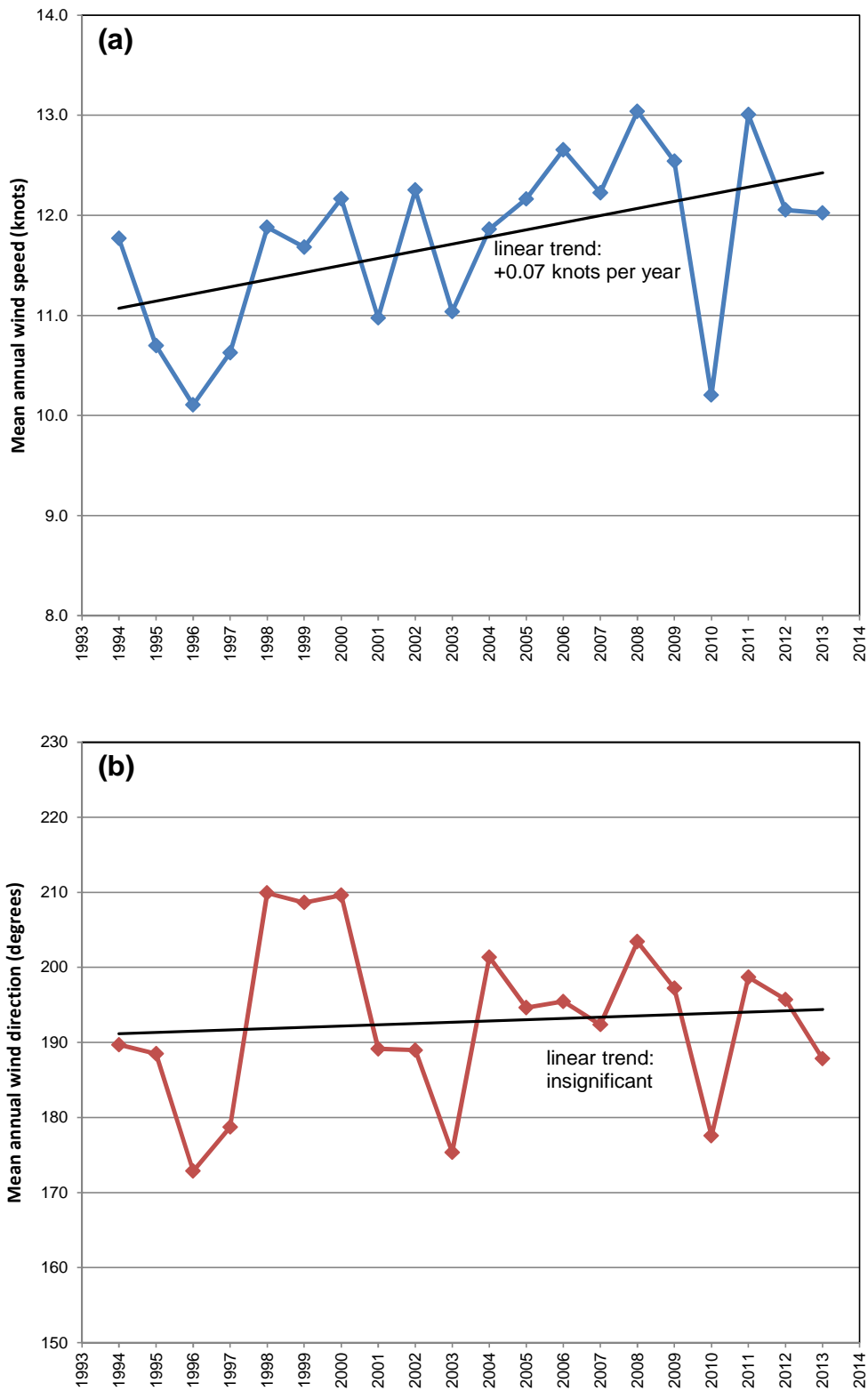


Figure 33: Temporal variation in (a) mean annual wind speed and (b) mean annual wind direction at Pembrey Sands, determined on hourly mean wind speeds and direction between January 1994 and December 2013. Data source: UK Met Office.

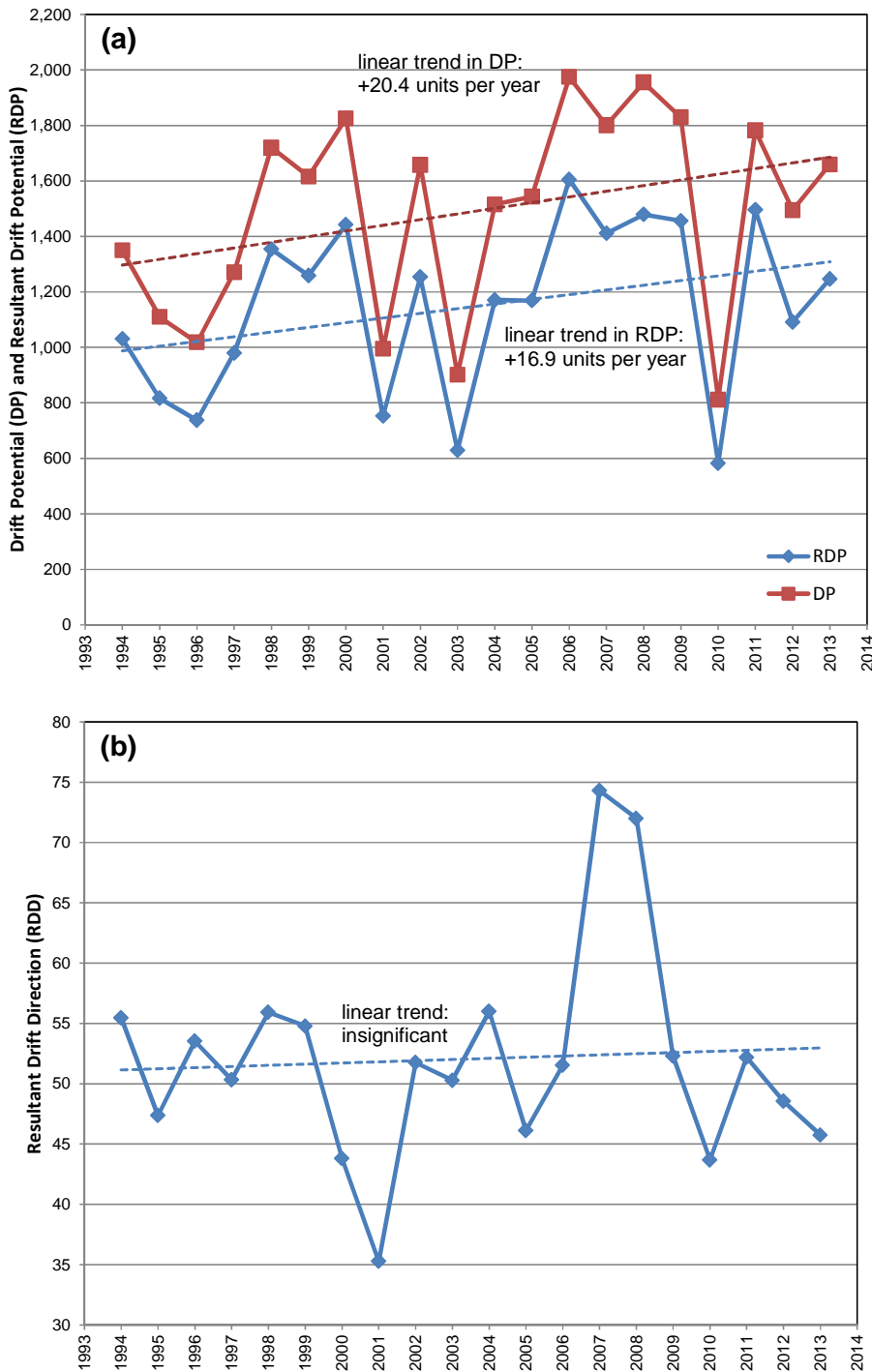


Figure 34: Temporal variation in (a) annual Drift Potential (DP), and Resultant Drift Potential (RDP), and (b) Resultant Drift Direction (RDD), constructed from hourly mean wind speeds and direction recorded at Pembrey Sands between January 1994 and December 2013. Data source: UK Met Office.

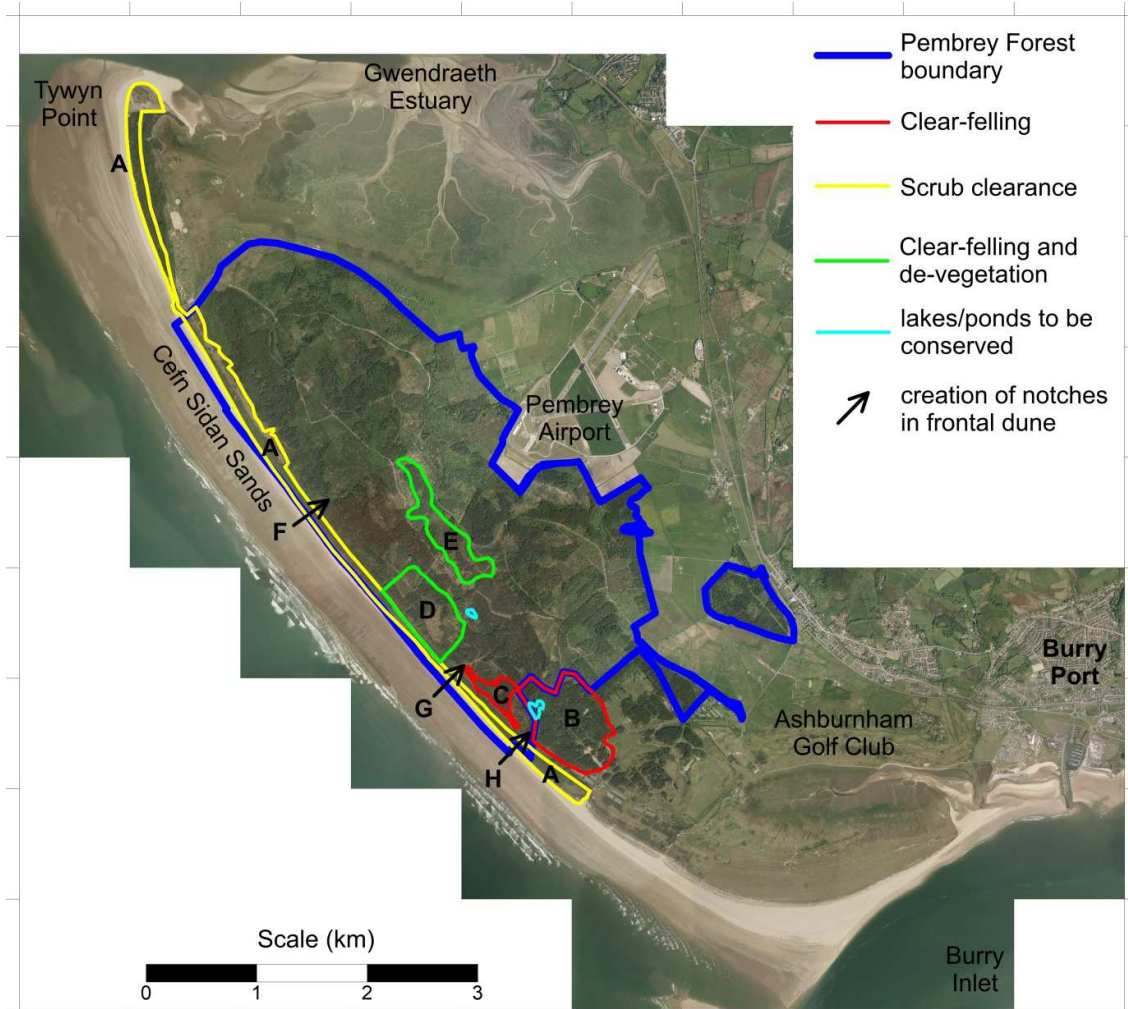
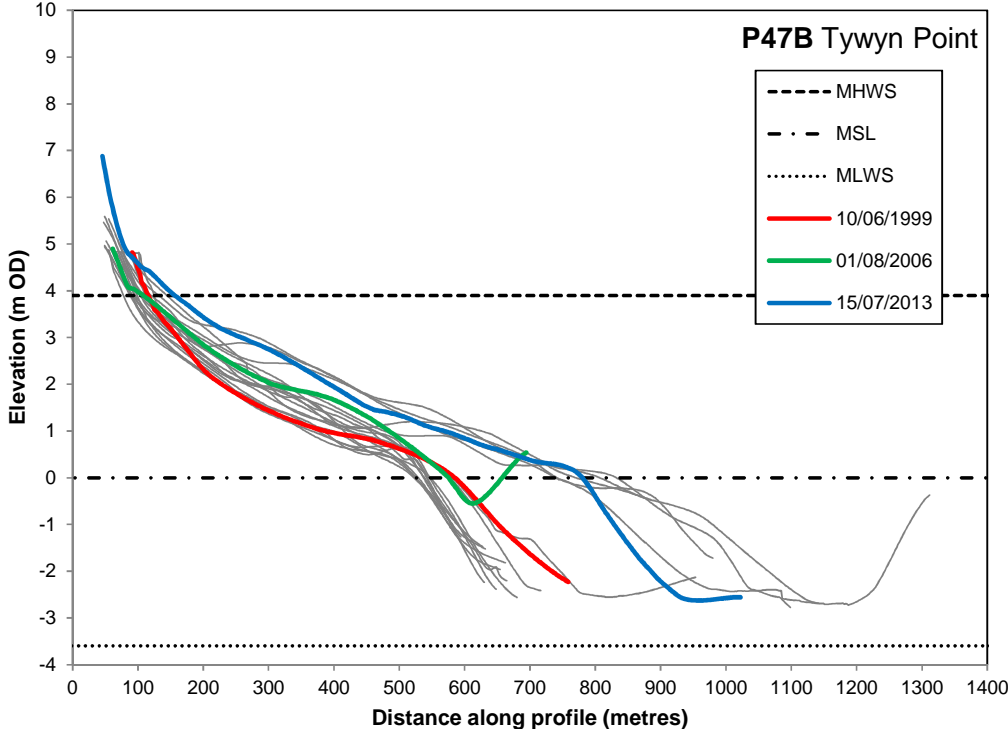
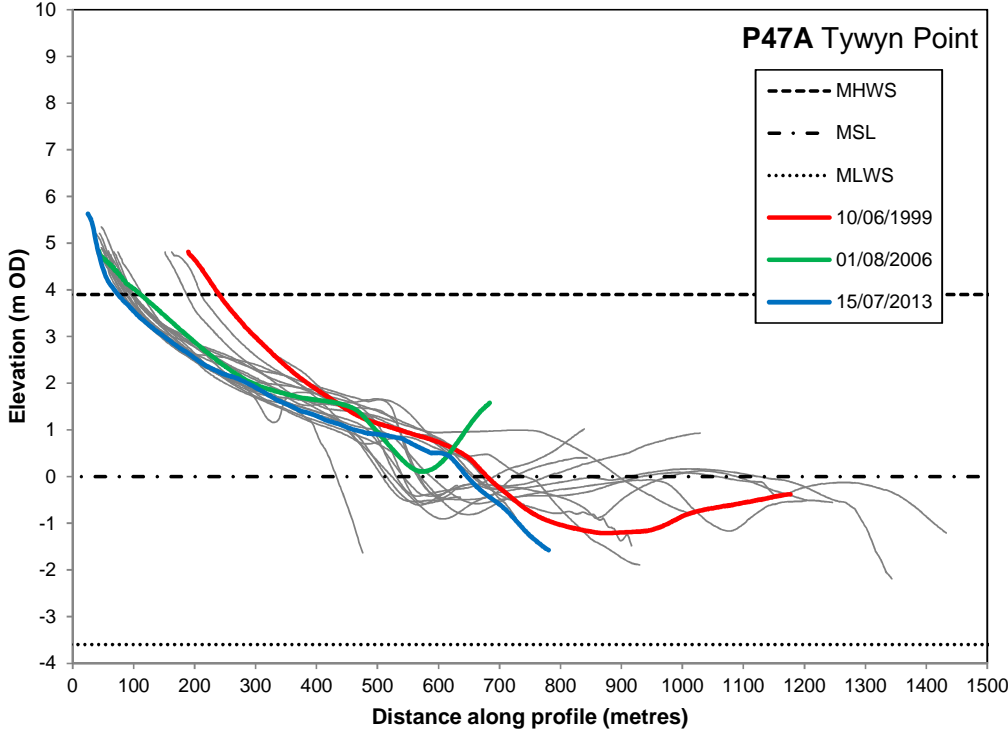
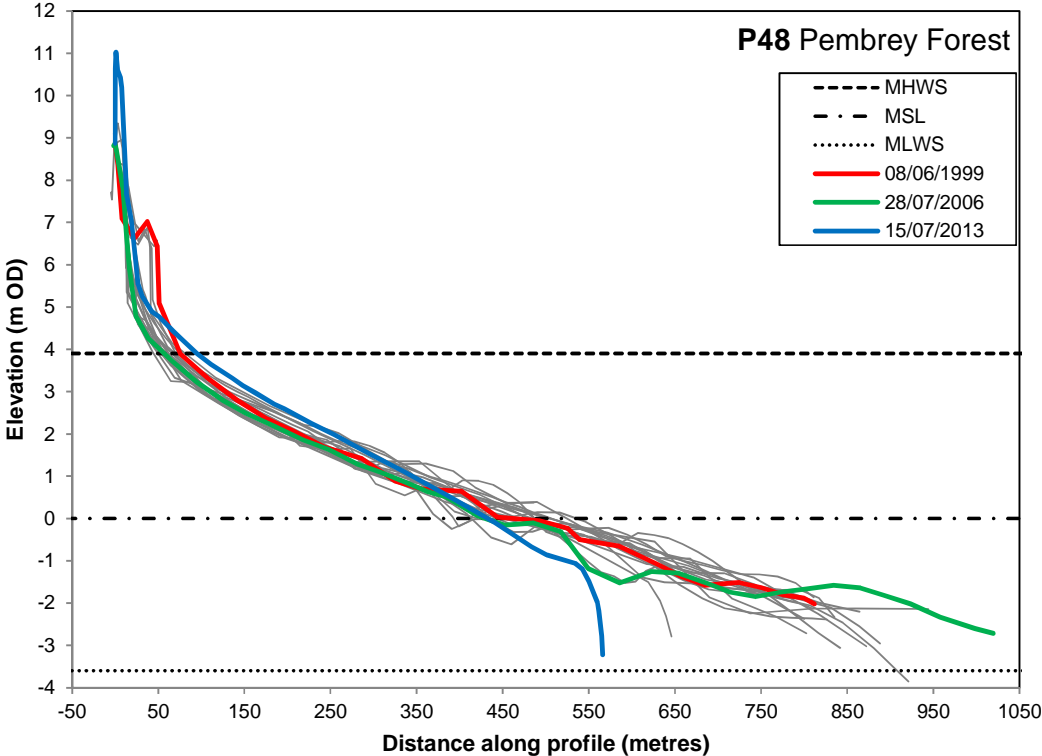
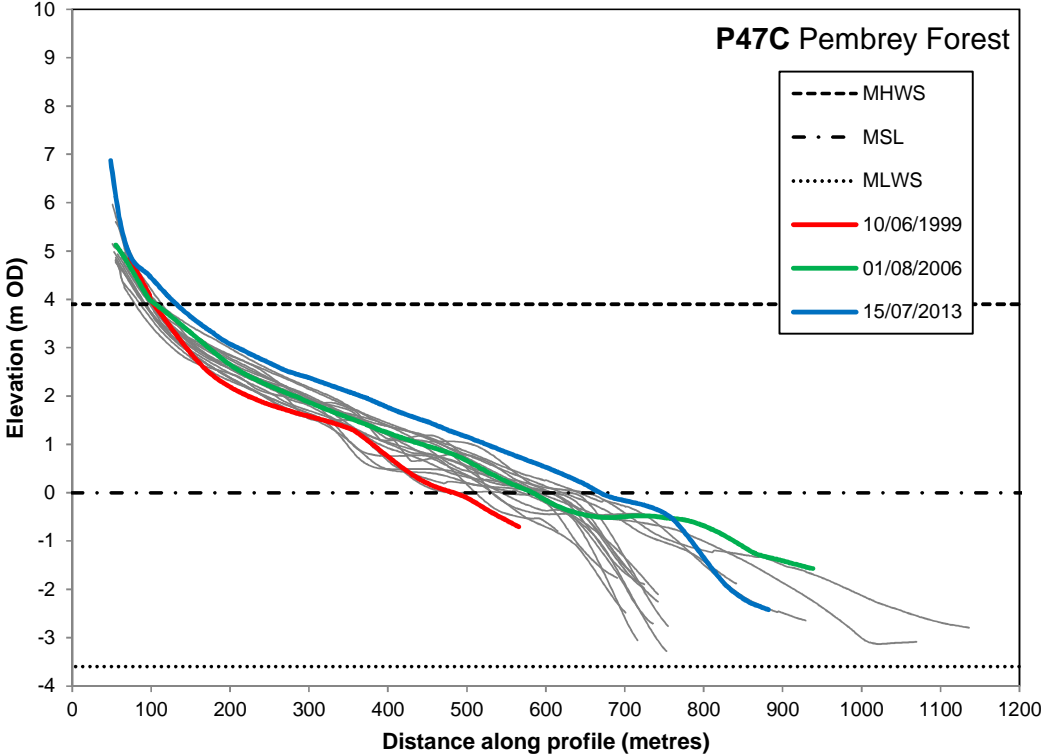


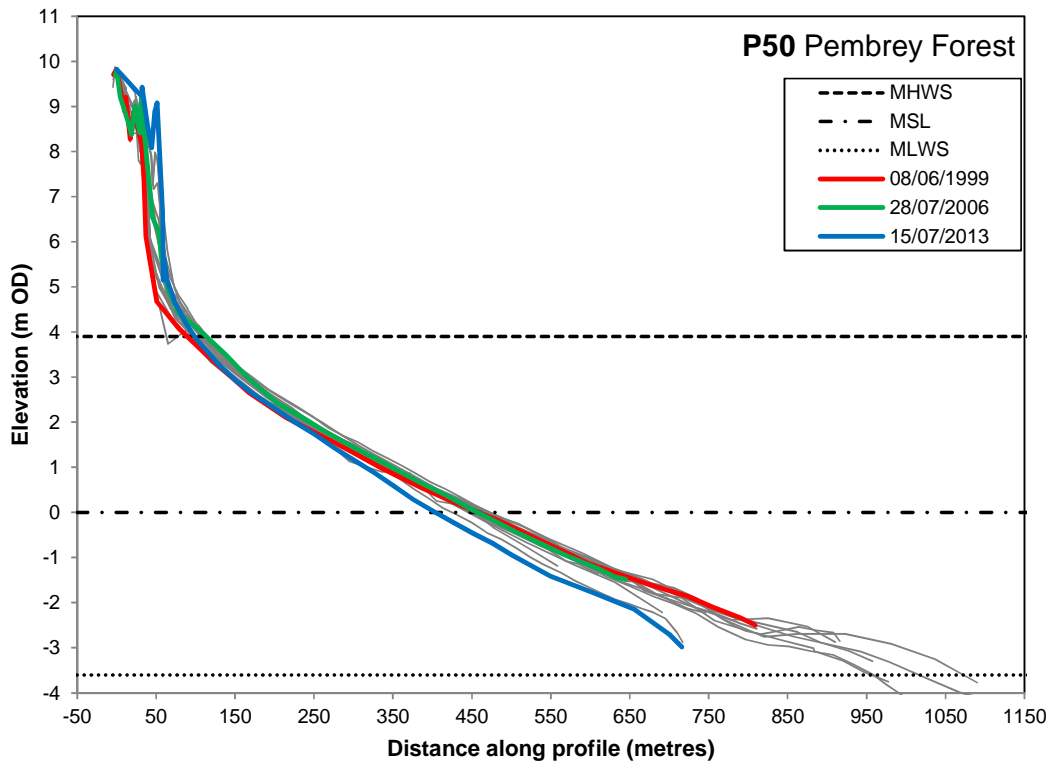
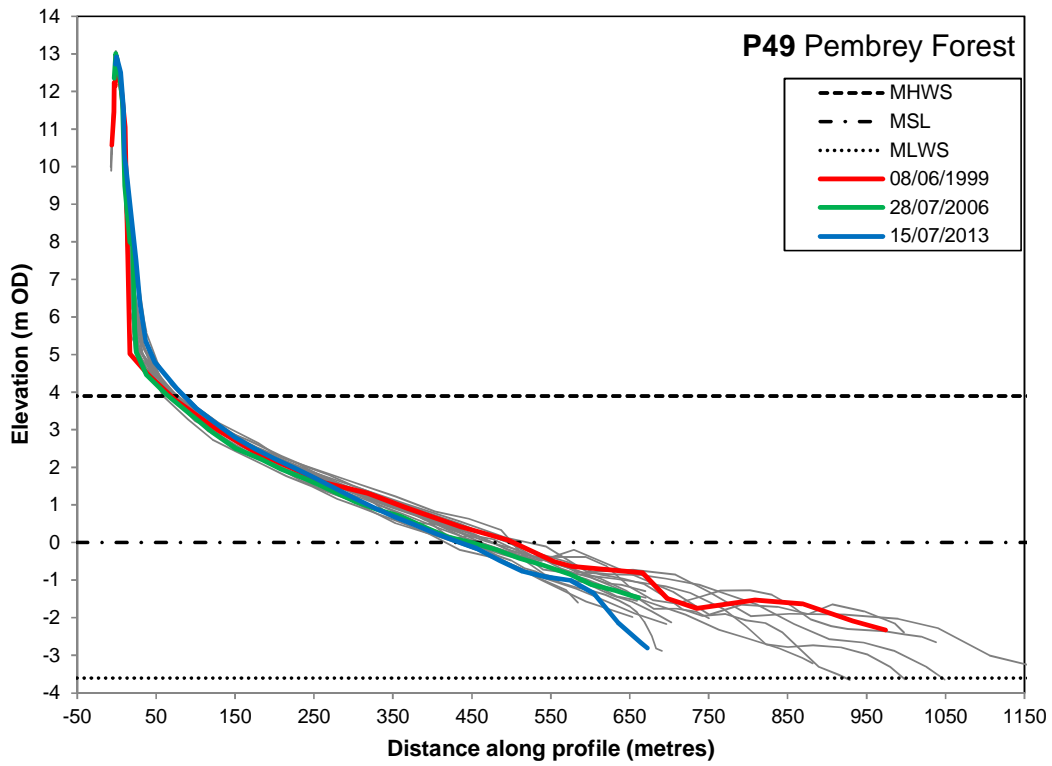
Figure 35: Suggested locations of dune rejuvenation works and trials: (A) clearance of all remaining buckthorn and other scrub from a 50 to 200 m wide zone along the frontal dunes, including control of regrowth in areas which have already been cleared; (B) clear-felling of poor quality coniferous forest area within Pembrey Country Park; (C) scrub clearance and turf stripping to connect part of the most seaward dune ridge with the foredune area within Pembrey Forest; (D) tree felling from the windward slope and crest areas of part of the highest inland dune ridge within Pembrey Forest.

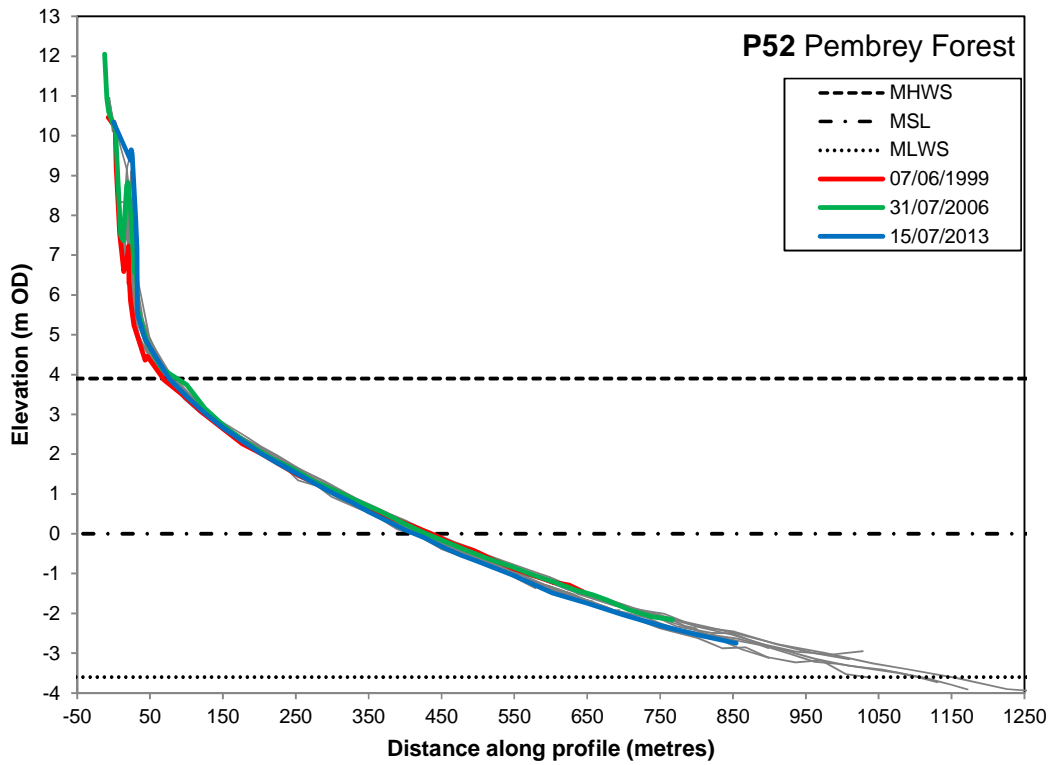
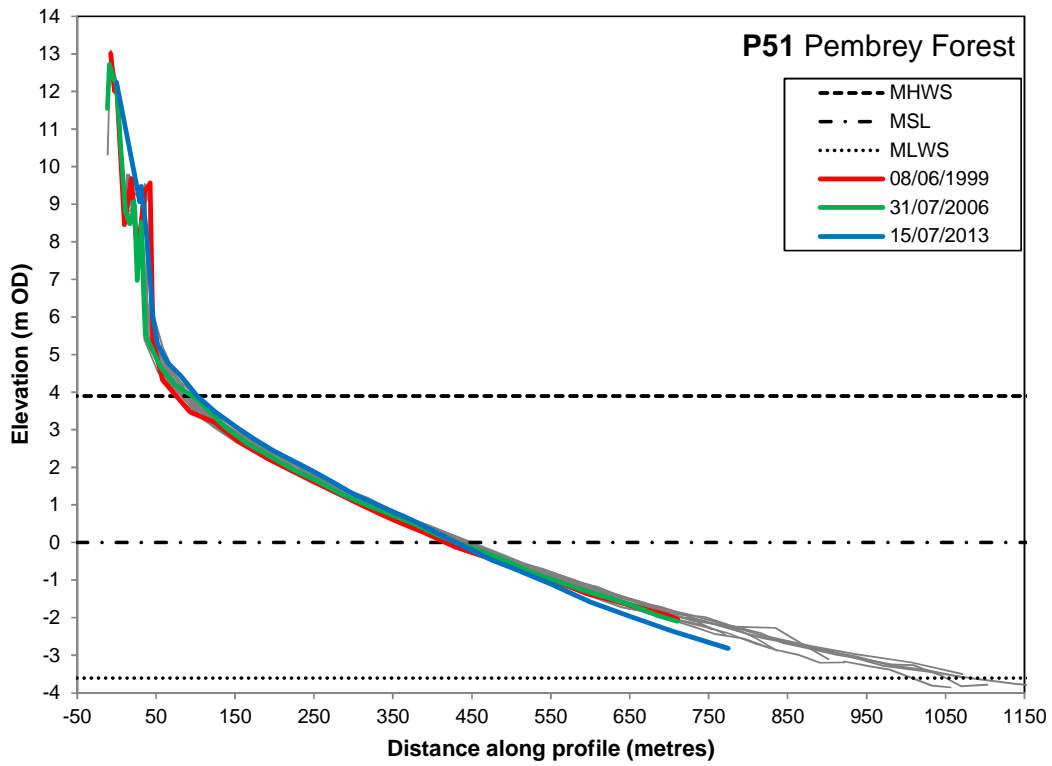
10. Appendices

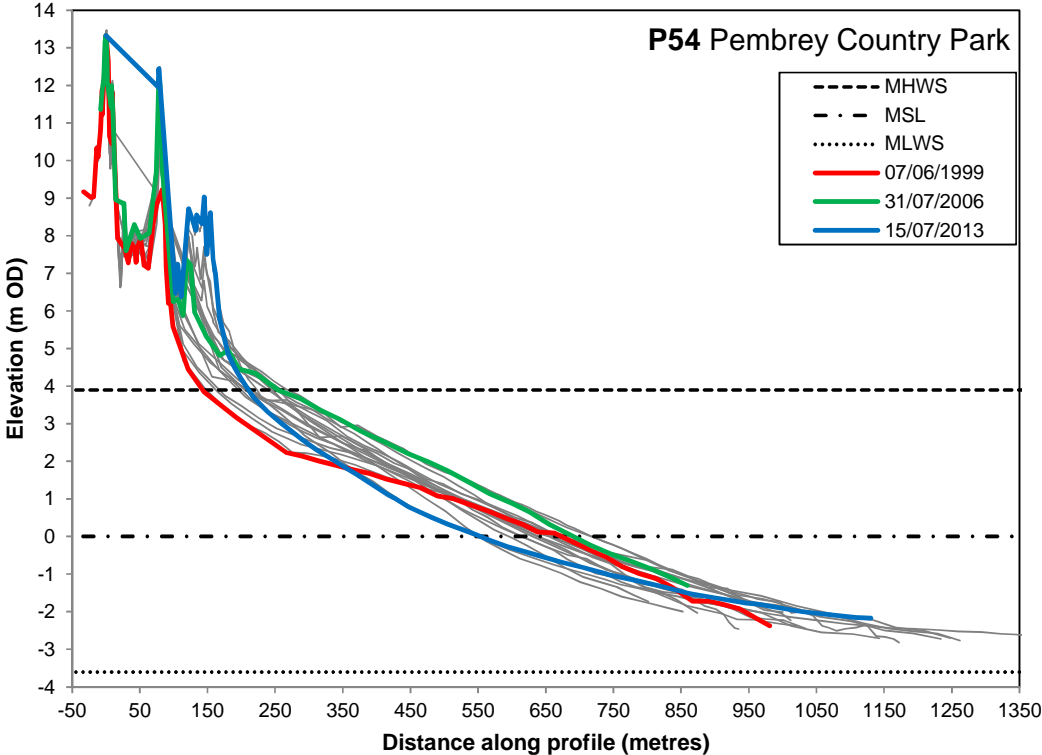
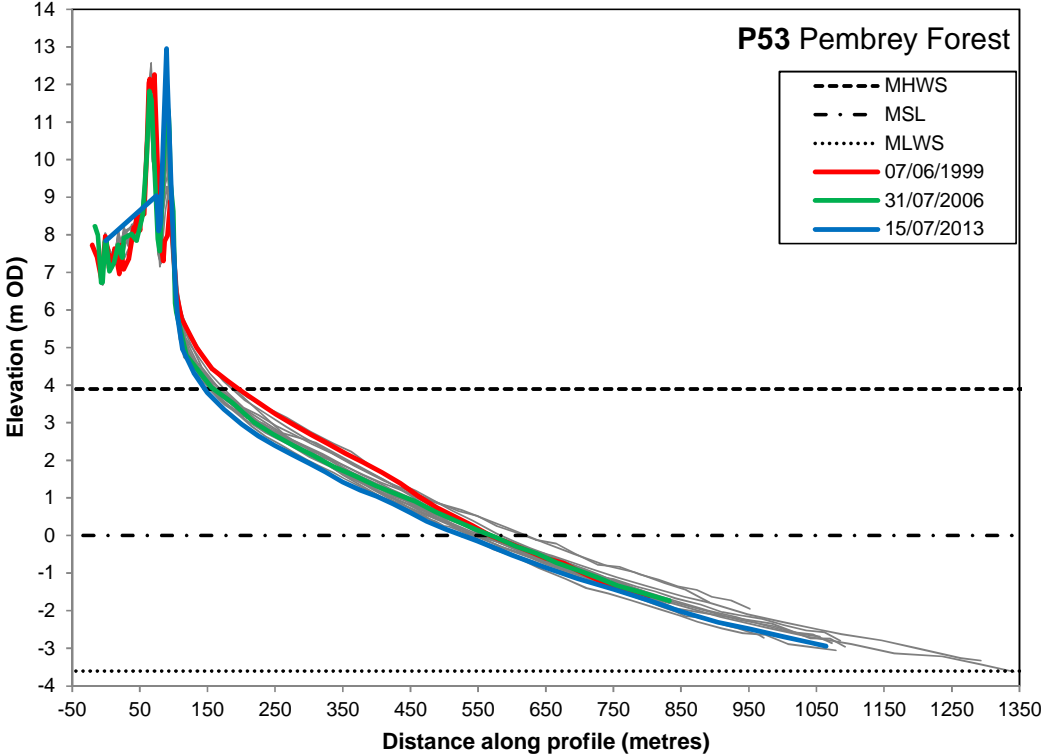
10.1. Swansea Bay and Carmarthen Bay Coastal Engineering Groups Strategic Coastal Monitoring. Beach profiles (Locations shown on Figure 3).

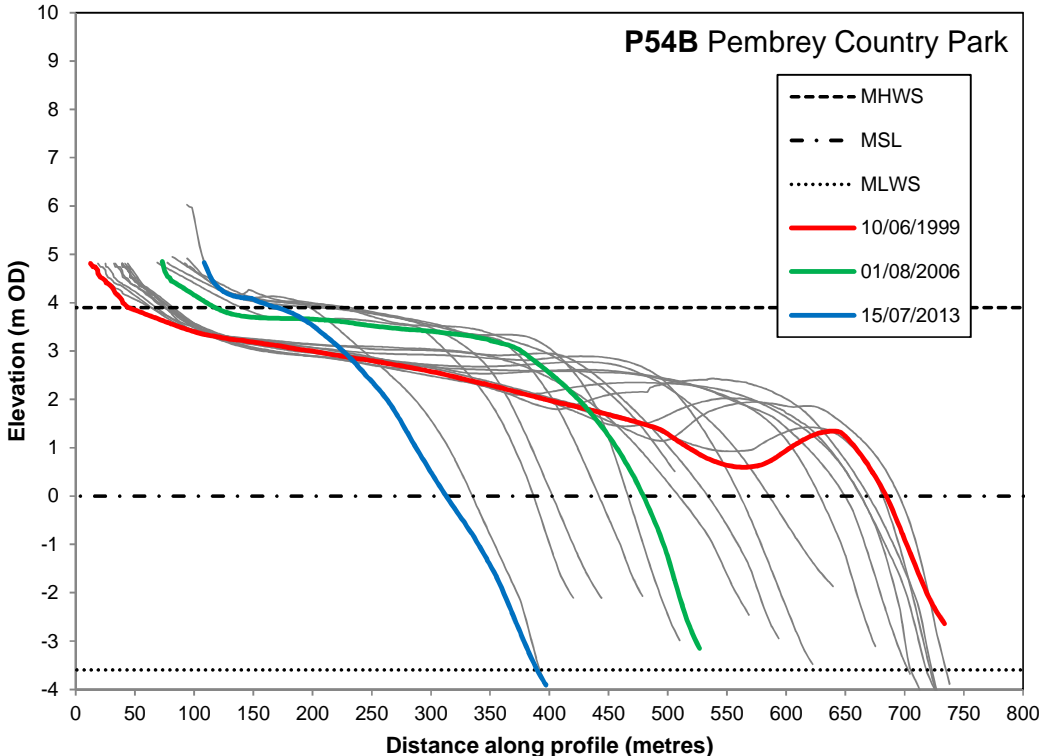
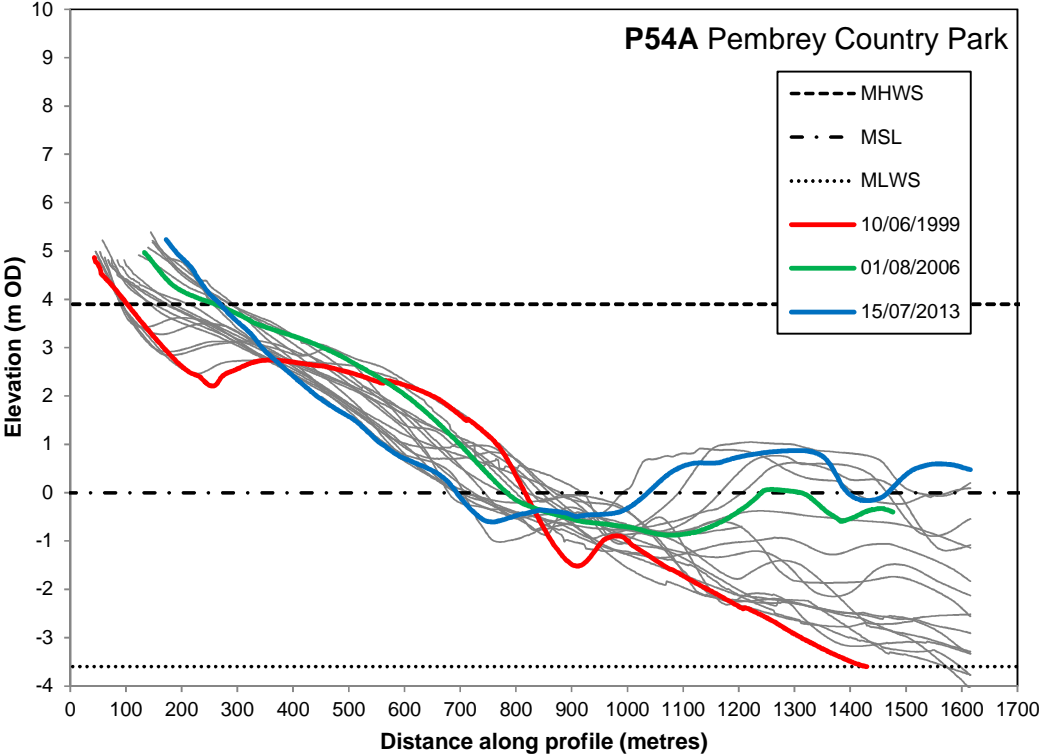


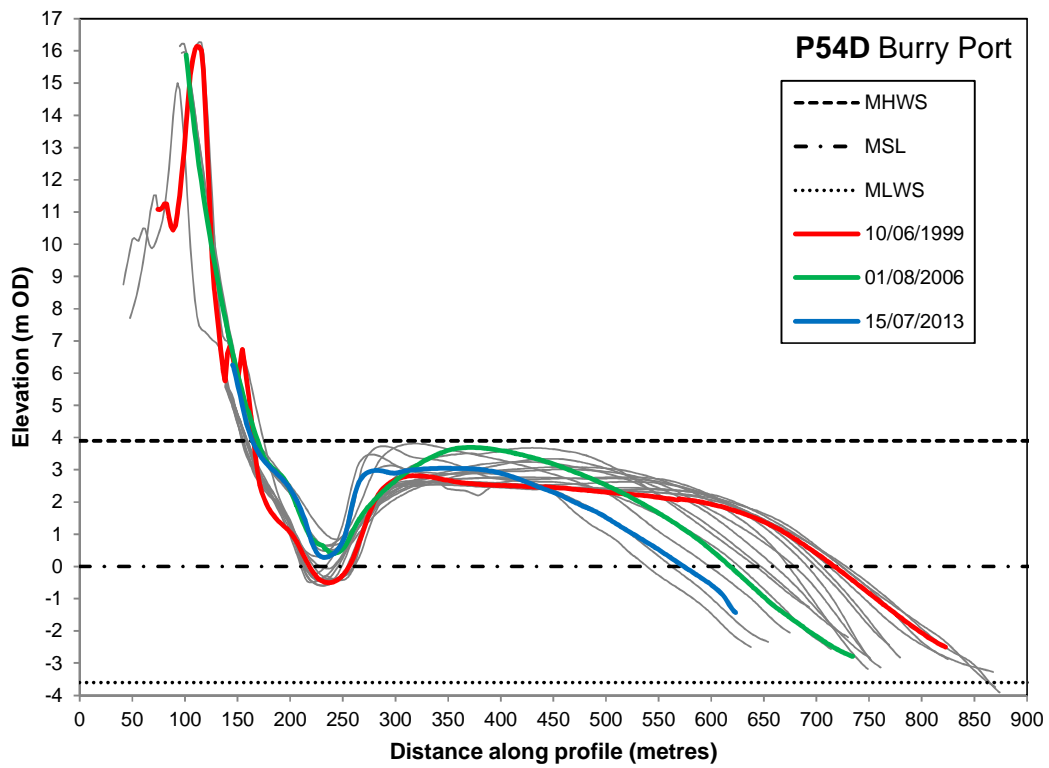
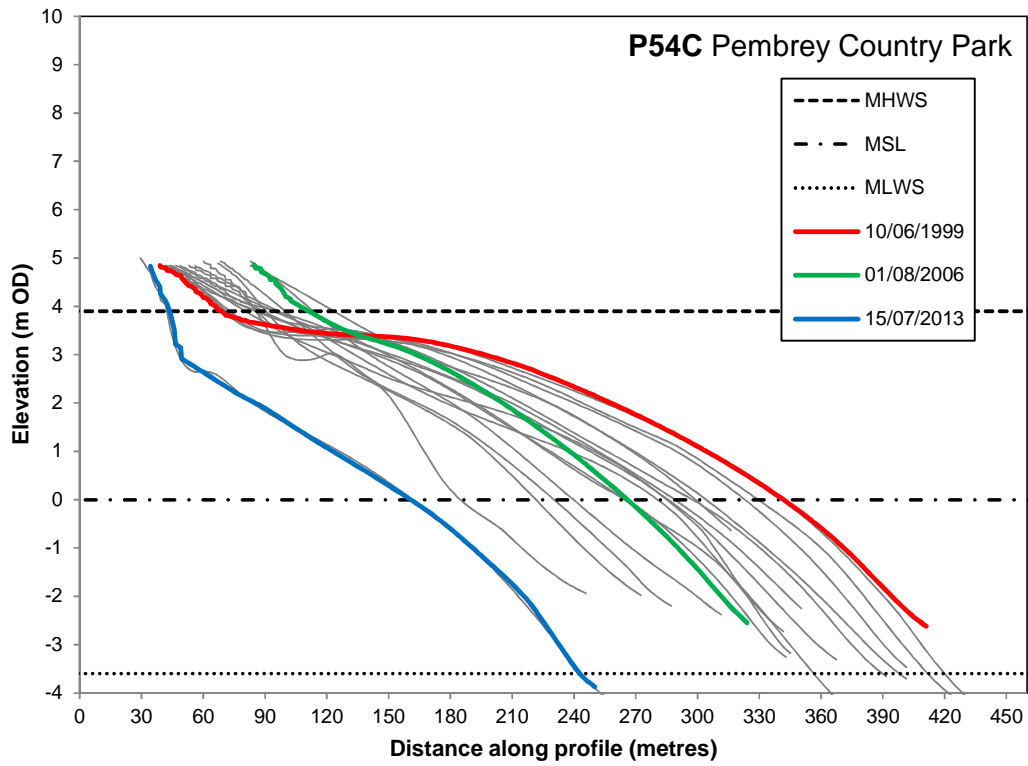


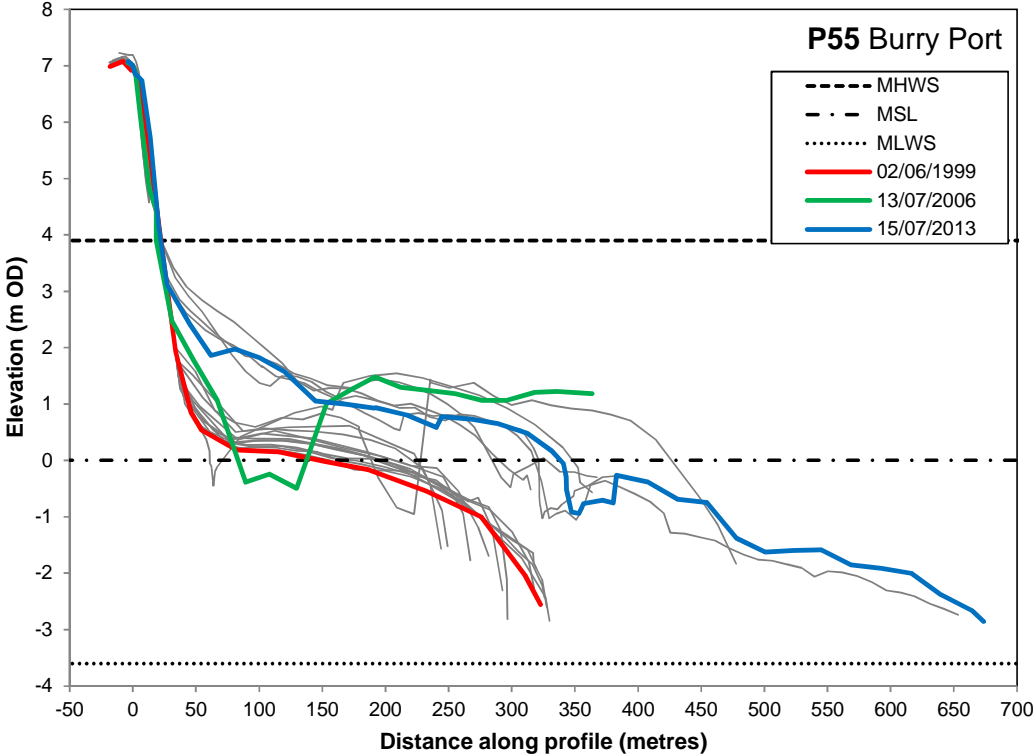












10.2. Digital elevation models of the Tywyn Point area and the southeastern end of Pembrey dunes (based on surveys commissioned by Swansea and Carmarthen Bay Engineering Groups).

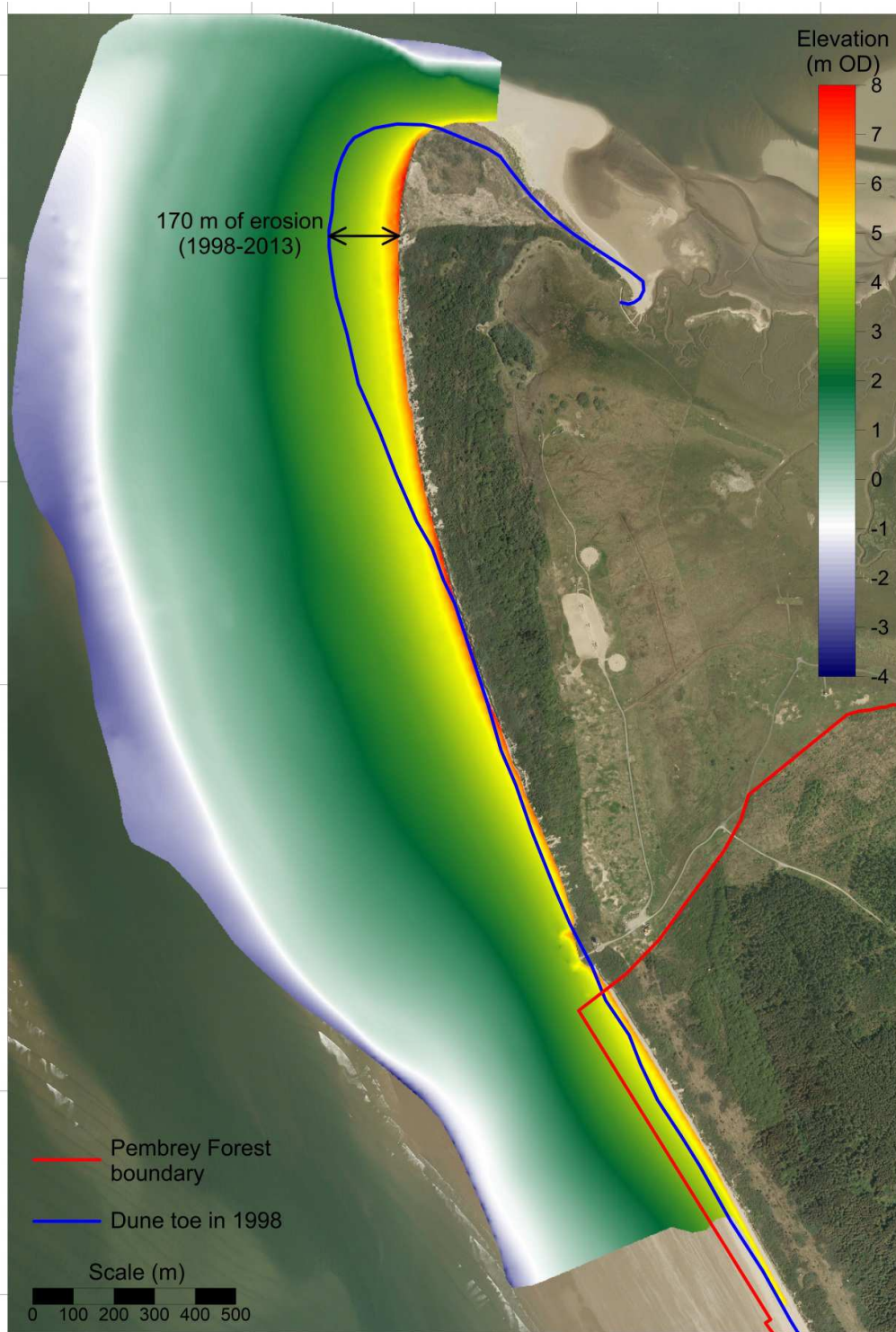


Figure A2.1: Summer 2013 DEM of the Tywyn Point area, superimposed on 2010 aerial photography. The position of the dune toe in 1998 is also shown.

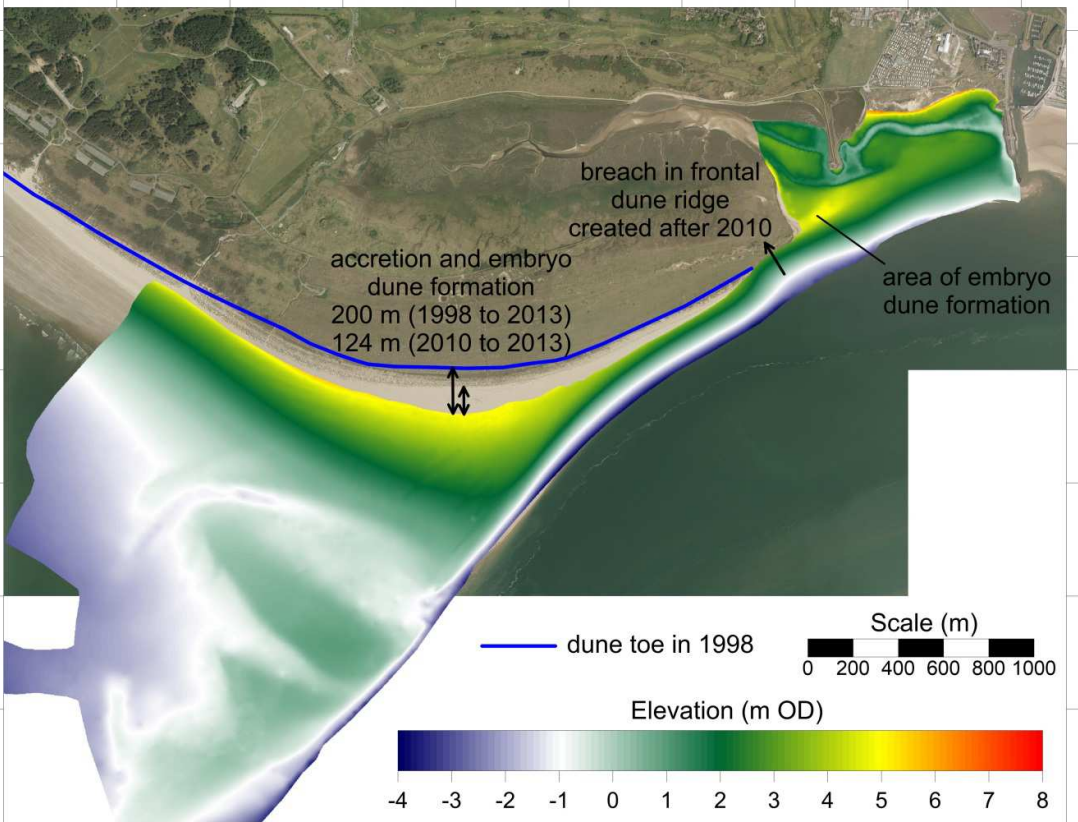


Figure A2.2: Summer 2013 DEM of the southeastern end of Pembrey Burrows, superimposed on 2010 aerial photography. The position of the dune toe in 1998 is also shown.

10.3. Ground photographs taken in February 2014.



Photograph 1: Wave-eroded dune cliffs at the northern end of Tywyn Point.



Photograph 2: Small area of embryo dunes just south of Tywyn Point which escaped erosion during the winter 2013-14 storms.



Photograph 3: Area of 2013-14 scrub clearance in the frontal dunes just south of Tywyn Point.



Photograph 4: Area of 2007-12 scrub clearance just south of Tywyn Point.



Photograph 5: Rabbit burrows in the hind-dunes just south of Tywyn Point.



Photograph 6: Wet relatively low-lying area on the west side of the target area, south of Tywyn Point, view looking northwards.



Photograph 7: View looking south across the target area south of Tywyn Point.



Photograph 8: View north from the control tower towards Tywyn Point.



Photograph 9: Rock armour protection near the Pembrey Sands control tower; view looking southwest.



Photograph 10: View looking SSW from the Pembrey Sands control tower; area of 2014 scrub clearance in the mid-picture.



Photograph 11: Wave-eroded dunes at the southern end of the beach landing area, south of Tywyn Point.



Photograph 12: Area cleared of buckthorn in the winter of 2013-14, south of the Air Weapons Range boundary.



Photograph 13: Forest high dune ridge in the mid part of Pembrey Forest – area suggested for clear-felling.



Photograph 14: The stoss slope of a high dune ridge in the mid part of Pembrey Forest – area suggested for clear-felling.



Photograph 15: Dense stand of pine forest north of Pembrey Country Park – suggested area for clear felling.



Photograph 16: Dense sea buckthorn scrub seaward of the pine plantation, north of Pembrey Country Park – area suggested for scrub clearance, partial turf stripping and possible creation of blow-through notches in the frontal dunes.



Photograph 17: Dense sea buckthorn scrub north of the Beach Kiosk and Visitor Centre, Pembrey Country Park – area suggested for scrub clearance.



Photograph 18: Area south at the southern end of Pembrey Country Park where buckthorn scrub has been cleared since 2010 to allow re-establishment of dune grassland.



Photograph 19: Ongoing scrub clearance in the frontal dunes towards the southern end of Pembrey Country Park.



Photograph 20: Migrating barchanoid megaripples and linear sand streaks on an area of accreting beach at the southern end of Pembrey Country Park; recent embryo dunes and accreting foredune ridge in the background - view looking east.



Photograph 21: Migrating barchanoid-lingoid magripples on the beach at the southern end of Pembrey Country Park - view looking west.



Photograph 22: Tidal / wave washover area where recent erosion has breached the frontal dune ridge at the eastern end of Pembrey Burrows LNR. This area was breached after 2010 due to landward movement of the low water channel, which has caused steepening of the beach, and was enlarged during the stormy winter of 2013-14 which brought a number of high tides and periods of strong wave action.



Photograph 23: View west at the point where the frontal dune ridge has been breached by recent erosion, Pembrey Burrows LNR.



Photograph 24: Well-vegetated stable dunes between Ashburnham Golf Course and Old Pembrey Harbour.



Photograph 25: Coast protection works and stabilized dunes to the west of Pembrey Old Harbour.



Photograph 26: Stabilised blowouts and areas of scrub on the seaward side of the dunes near Ashburnham Golf Club. The remaining part of the Lifeboat Plantation is visible in the top right of the photograph.



Photograph 27: A remaining active blowout on the seaward side of the dunes west of Pembrey Old Harbour.



Photograph 28: View eastwards along the stable dune ridge fronting Ashburnham Golf Course.



Photograph 29: The promenade fronting the dunes immediately west of Burry Port Harbour.

10.4. Data Archive Appendix

The data archive contains:

[A] The final report in Microsoft Word and Adobe PDF formats.

Metadata for this project is publicly accessible through Natural Resources Wales' Library Catalogue <http://194.83.155.90/olibcgi> by searching 'Dataset Titles'. The metadata is held as record no 115775.



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