Dune rejuvenation AfterLIFE options for Twyni Penrhos, Newborough

Report No: 787

Author Name: Prof. Kenneth Pye and Dr Simon Blott

Author Affiliation: Kenneth Pye Associates Ltd.

SoLIFE: LIFE 17 NAT/UK/000023
The Twyni Byw-Sands of LIFE project has received funding from the LIFE Programme of the European Union
Part funded by the Welsh Government

About Natural Resources Wales

Natural Resources Wales' purpose is to pursue sustainable management of natural resources. This means looking after air, land, water, wildlife, plants and soil to improve Wales' well-being, and provide a better future for everyone.

Evidence at Natural Resources Wales

Natural Resources Wales is an evidence-based organisation. We seek to ensure that our strategy, decisions, operations and advice to Welsh Government and others are underpinned by sound and quality-assured evidence. We recognise that it is critically important to have a good understanding of our changing environment.

We will realise this vision by:

- Maintaining and developing the technical specialist skills of our staff;
- Securing our data and information;
- Having a well-resourced proactive programme of evidence work;
- Continuing to review and add to our evidence to ensure it is fit for the challenges facing us; and
- Communicating our evidence in an open and transparent way.

This Evidence Report series serves as a record of work carried out or commissioned by Natural Resources Wales. It also helps us to share and promote use of our evidence by others and develop future collaborations. However, the views and recommendations presented in this report are not necessarily those of NRW and should, therefore, not be attributed to NRW.

Report series:	NRW Evidence Report
Report number:	787
Publication date:	July 2024
Contract number:	SoLIFE A2024-03
Contractor:	Kenneth Pye Associates Ltd.
Contract Manager:	I. Fairley
Title:	**Dune rejuvenation AfterLIFE options for Twyni Penrhos, Newborough**
Author(s):	K. Pye, S.J. Blott
Technical Editor:	I. Fairley
Quality assurance:	Tier 3
Peer Reviewer(s):	Julie Creer, Suzie Jackson
Approved By:	N. Thomas
Series editor(s):	K. Hewitt
Restrictions:	None

Recommended citation for this volume:

K. Pye, S.J. Blott 2024. Dune rejuvenation AfterLIFE options for Twyni Penrhos, Newborough. NRW Evidence Report Series; Report No: 787, 74pp, Natural Resources Wales, Bangor.

Cover photograph: Ground photograph of Forestry Commission fencing along Traeth Penrhos, Niwbrwch/Newborough taken in the 1950s. Source: NRW

Contents

List of Figures

List of Tables

Crynodeb Gweithredol

Cynhyrchwyd yr adroddiad hwn fel rhan o brosiect Twyni Byw LIFE a arweinir gan CNC ac a gefnogir gan gyllid o raglen LIFE yr UE a Llywodraeth Cymru. Ei brif bwrpas yw nodi opsiynau adnewyddu twyni tywod ar gyfer ardal y twyni blaen yn Nhwyni Penrhos a fydd yn llywio datblygiad cynllun Ar ôl LIFE ar gyfer y rhan hon o safle Niwbwrch. Mae Twyni Penrhos yn cynnwys crib twyni blaen cyfansawdd, sydd â rhannau artiffisial a naturiol, wedi'i leoli y tu ôl i Draeth Penrhos. Mae'n rhan o Safle o Ddiddordeb Gwyddonol Arbennig (SoDdGA) Tywyn Niwbwrch – Ynys Llanddwyn ac Ardal Cadwraeth Arbennig (ACA) Twyni Tywod Abermenai i Aberffraw.

Nododd y contract dair tasg gysylltiedig fel a ganlyn: (1) Dehongli amcanion cadwraeth natur yr ACA o safbwynt geomorffolegol; (2) defnyddio llenyddiaeth a data cyfredol o safleoedd twyni tywod 'cysefin' presennol i ddisgrifio graddfeydd hyd ac amrediad ar gyfer trawsnewid llawn o draeth uwchlanw i dwyni sefydlog; (3) datblygu opsiynau rheoli ac ymyriadau a awgrymir i gyflawni set wydn o gynefinoedd trosiannol.

Y cynefinoedd sy'n peri'r pryder mwyaf yn yr adroddiad presennol yw H2110 Egin-dwyni symudol, H2120 Twyni symudol ar hyd y draethlin, ac H2130 Twyni arfordirol sefydlog gyda llystyfiant llysieuol. Disgrifir yr amcanion cadwraeth yn y fersiwn ddiweddaraf (2022) o Gynllun Rheoli Craidd yr ACA. Mae'r amcanion ar gyfer egin-dwyni symudol yn cynnwys y canlynol: "Bydd y parthau twyni nodweddiadol, o'r traeth (trwy egin-dwyni symudol, twyni gwyn, llaciau twyni) i dwyni sefydlog, yn gyfan ar hyd 95% o'r tir blaen arfordirol meddal. Dylai fod erydiad a dyddodiad gweithredol o'r egin-dwyni symudol gydag o leiaf 50% o dywod noeth ar y blaendwyni hyn."Mae'r amcanion cadwraeth ar gyfer twyni symudol ar hyd y draethlin gydag Ammophila arenaria yn cynnwys: "Dylai eu maint fod yn sefydlog yn yr hirdymor, neu eu cynyddu lle bo'n briodol. Ni fydd unrhyw ostyngiad yng nghyfanswm arwynebedd (cydgrynhoi) y cynefinoedd twyni cymhwysol y dynodwyd y safle hwn ar eu cyfer (h.y. ni ddylai'r cyfanswm o 675 hectar o gynefin twyni cymwys leihau). Gall maint a lleoliad nodweddion cynefin twyni unigol fod yn destun amrywiadau cyfnodol a thymhorol. Yn ddelfrydol, dylai twyni symudol fod yn 30% o gyfanswm cynefin y twyni ac nid llai na 15%. Dylai tywod noeth fod yn bresennol dros o leiaf 20% o gynefin y twyni symudol. Dylai hyn gynnwys chwythbantiau gweithredol 'achlysurol' o leiaf a thywod symudol." Mae'r amcanion cadwraeth ar gyfer twyni sefydlog gyda llystyfiant llysieuol yn cynnwys: "Ni ddylai maint nodwedd cynefin glaswelltir twyni sefydlog ddisgyn o dan 40% o gyfanswm arwynebedd y twyni… Dylai tir moel fod yn bresennol dros 5–15% o'r cynefin twyni sefydlog ar ffurf chwythbantiau bach a chreithiau erydu. Dylai pob cam olynol o laswelltir twyni sefydlog fod yn bresennol, o laswelltir twyni lled-sefydlog cynnar i brysgwydd gwasgaredig (dim mwy na 5% o orchudd) a rhostir twyni lle mae'r amodau'n caniatáu hynny."

Mae presenoldeb planhigfeydd coedwigoedd tua'r tir o Dwyni Penrhos, ynghyd â thueddiad parhaus o erydu arfordirol ar hyd dwy ran o dair o'r lan a ddechreuodd ar ddechrau'r 1970au, yn golygu bod cynefinoedd twyni H2120 ac H2130 yn cael eu 'gwasgu' (cynefinoedd yn cael eu lleihau mewn lled o'r draethlin i'r gefnwlad) o fewn parth cul, a gall y parth hwn ond fynd yn gulach os bydd y duedd erydu, yn ôl y disgwyl, yn parhau i'r dyfodol gyda chodiad yn lefel y môr a chynnydd posibl mewn stormydd. Ar hyn o bryd, mae traean gogleddol Twyni Penrhos yn parhau i brofi allraddiad arfordirol ac yn dangos dilyniant llawn o draethlin, egin-dwyni, blaendwyni lled-symudol a thwyni sefydlog. Fodd bynnag, mae blaen yr erydiad yn symud tua'r gogledd, gan leihau maint y lan lle mae'r amcanion cadwraeth yn cael eu diwallu ar hyn o bryd.

Mae'r adroddiad hwn yn nodi ac yn ystyried nifer o opsiynau i (a) gynyddu maint y twyni lled-symudol a symudol ar hyd rhan ganolog y lan, a (b) lleihau neu ddileu'r 'wasgfa' ar y cymunedau twyni sefydlog trwy ddarparu mwy o le, a fydd yn caniatáu i'r cynefinoedd â blaenoriaeth ddatblygu a symud tua'r tir yn wyneb lefel y môr yn codi a'r draethlin yn cilio. Daethpwyd i'r casgliad, er mwyn darparu digon o le i alluogi hyn i ddigwydd, ac i gwrdd â'r amcanion cadwraeth ar hyd y rhan fwyaf os nad y cyfan o flaen Twyni Penrhos, fod angen torri coed ymhellach. Yn yr hir dymor, dylid symud ymyl y goedwig tua'r môr yn ôl 300m–500m dros gyfnod o 30 mlynedd.

Executive Summary

This report has been produced as part of the Sands of Life (SoLIFE) project led by NRW and supported by funding from the EU LIFE programme and Welsh Government. Its main purpose is to identify dune rejuvenation options for the frontal dune area at Twyni Penrhos which will inform the development of an AfterLIFE plan for this part of the Newborough site. Twyni Penrhos consists of a composite frontal dune ridge, part artificial, part natural, located behind Traeth Penrhos. It forms part of the Newborough Warren – Ynys Llanddwyn Site of Special Scientific Interest (SSSI) and the Y Tywyn o Abermenai i Aberffraw Special Area of Conservation (SAC).

The contract identified three related tasks: (1) interpret the SAC nature conservation objectives from a geomorphological perspective; (2) use current literature and data from existing 'pristine' sand dune sites to describe range and length scales for full transition from supratidal beach to fixed dune; (3) develop suggested management options and interventions to achieve a resilient set of transitional habitats.

The habitats of principal concern in the current report are *H2110 Embryonic shifting dunes*, *H2120 Shifting dunes along the shoreline* and *H2130 Fixed coastal dunes with herbaceous vegetation*. The conservation objectives are described in the most recent (2022) version of the SAC Core Management Plan. The objectives for *Embryonic shifting dunes* include "the typical dune zonation, from beach (through embryonic shifting dunes, white dunes, dune slacks) to fixed dune), shall be intact along 95% of the soft coastal frontage. There should be active erosion and deposition of the embryonic shifting dunes with at least 50% bare sand on these foredunes". The conservation objectives for *Shifting dunes along the shoreline with Ammophila arenaria* include: "extent should be stable in the long term, or where appropriate increasing. There shall be no decrease in the total (aggregate) area of qualifying dune habitats for which this site was designated (i.e., the sum total of 675 ha of qualifying dune habitat should not diminish). The extent and location of individual dune habitat features may be subject to periodic and seasonal variation. Shifting dunes should ideally be 30% of the total dune habitat and not less than 15%. Bare sand should be present over at least 20% of the shifting dune habitat. This should include at least "occasional" active blow-outs and mobile sands." The conservation objectives for *Fixed dunes with herbaceous vegetation* include "the extent of fixed dune grassland habitat feature should not fall below 40% of total dune area.... Bare ground should be present over 5-15% of the fixed dune habitat comprising small blowouts and erosion scars. All successional stages of fixed dune grassland should be present, from early semi-fixed dune grassland to scattered scrub (no more than 5% cover) and dune heath where conditions allow".

The presence of forest plantations to landward of Twyni Penrhos, combined with a sustained trend for coastal erosion along the southern two thirds of the frontage which began in the early 1970s, means that H2120 and H2130 dune habitats are being 'squeezed' (habitats reduced in width from the shoreline to the hinterland) within a narrow zone which can only become narrower if, as expected, the erosion trend continues into the future with sea level rise and possible increases in storminess. At the present time the northern third of Twyni Penrhos continues to experience coastal progradation and to display a full sequence of strandline, embryo dune, semi-mobile foredunes and fixed dunes. However, the erosion front is moving northwards, reducing the extent of the frontage where the conservation objectives are currently being met.

This report identifies and considers a number of options to (a) increase the extent of semi-mobile and mobile dunes along the central part of the frontage, and (b) to reduce or eliminate 'squeeze' on the fixed dune communities by providing additional accommodation space which will allow the priority habitats to develop and move landward in the face of sea-level rise and shoreline recession. It is concluded that to provide sufficient accommodation space to allow this to happen, and to meet the conservation objectives along most if not all of the Twyni Penrhos frontage, it is necessary to undertake further tree felling. In the long term, the seaward forest margin should be moved back by 300 – 500 m over a 30 year period.

1. Introduction: report purpose and scope

This report has been produced as part of the Sands of LIFE (SoLIFE) project led by NRW and supported by funding from the EU LIFE programme and Welsh Government. The SoLIFE project, started in 2018, aims to achieve favourable condition for five Habitats Directive Annex I habitats and three Annex II species by improving a total sand dune area in Wales of 2400 ha. A major objective is to restore natural geomorphological and ecological processes, recreating mobility in the dune landscape and allowing establishment of early successional stages. Methods include turf stripping, dune reprofiling, frontal dune notching, removal of invasive species and promotion of sustainable grazing practices (NRW, 2019). An important aspect is management of forestry to ensure appropriate accommodation area for dunes in the face of climate change.

The purpose of this technical advice report is to identify dune rejuvenation options for the frontal dune area at Twyni Penrhos (Newborough, southwest Anglesey) which will inform the development of an AfterLIFE plan for the site. The aim of the work undertaken is "to obtain evidence to ensure the site conservation objectives are met and the dune system is resilient to storm action and climate change".

The contract identified three related work packages:

1. **Interpret the conservation objectives from a geomorphological perspective.**

   Extract geomorphological aspects from each habitat's conservation objective as described in the 2022 version of the Y Twyni o Abermenai i Aberffraw SAC Core Management Plan, and describe the morphological attributes that each successional feature should be displaying. Explain the forcing mechanisms and environmental requirements for a healthy feature.

2. **Use current literature and data from existing 'pristine' sand dune sites to describe range and length scales for full transition from supratidal beach to fixed dune.**

   Quantify the range of cross-shore extent that zonation should cover to attain a favourable status with respect to the conservation objectives and ensure resilience of the various successional habitats.

3. **Develop suggested management options and interventions to achieve a resilient set of transitional habitats.**

   Use past evidence to suggest a range of (cost varying) appropriate management techniques (e.g. notching, reprofiling) to reinstate and facilitate the development of a natural transition of successional dune habitats in line with the conservation objectives for the site and the interpretation and analysis of points 1 and 2.

The project was conceived as a desk-based study but the report has also drawn on field observations made during site visits by the first author.

2. Nature and environmental context of Twyni Penrhos

2.1 Coastal evolution and morphology

The Niwbwrch (Newborough) dune system (Figure 1) is the largest in Wales with a sand-covered area of approximately 1289 ha. Morphologically it consists of four main parts: (1) a large but relatively low-lying cuspate foreland of partly afforested dunes and slacks (Gwningaer Fawr) which lies adjacent to the southeast corner of the Cefni estuary; (2) a Pre-Cambrian rock ridge which runs in a SW – NE direction through the middle of the site, capped by a number of rocky crags including Cerrig-mawr; (3) an area of open dunes and slacks (Tywyn Niwbwrch / Newborough Warren) located to the east of the central rock ridge, and (4) a dune-capped spit (Braich Abermenai) which extends from the southeast corner of Tywyn Niwbwrch towards the Menai Strait.

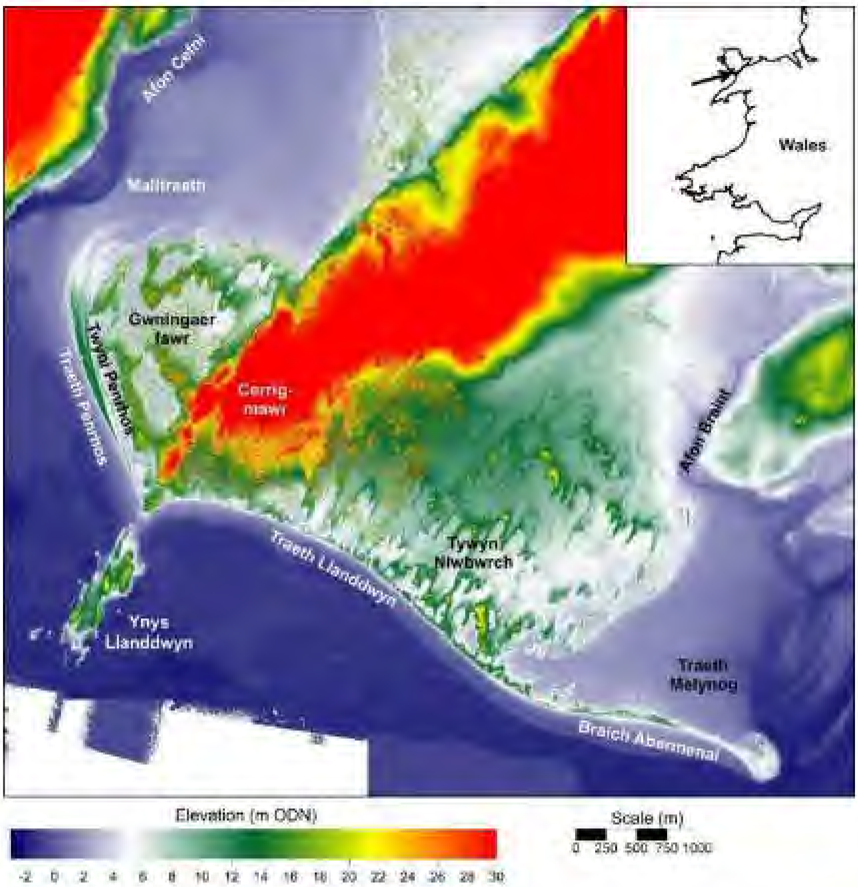

Figure 1. LiDAR DSM showing the main morphological features of the Niwbwrch area, flown in 2023. Data source: Data Map Wales (Open Government Licence)

Twyni Penrhos is a composite frontal dune and slack system, part artificial, part natural, located along the seaward side of Gwningaer Fawr. The name Penrhos refers to a location at the seaward extremity of the rhos (heath) which was once a prominent feature of the rock ridge. The ridge has been partly buried by climbing dunes and sand sheets, and in the early 20th century much of this area was covered by bare sand through which a number of rock outcrops protruded (Greenly, 1919). Large parts of Gwningaer Fawr and Tywyn Niwbwrch consisted of semi-vegetated mobile dunes at this time. However a trend towards increased vegetation cover and dune stabilization began in the late 1940s, driven partly by natural factors and partly by afforestation following acquisition of the western part of the dune system by the Forestry Commission in 1947 (Ranwell, 1955, 1959, 1960; Mayhead, 1989; Hill & Wallace, 1989; Rhind et al., 2001; Pye & Blott, 2012; Pye et al., 2014).

The Gwningaer Fawr dunes and slacks have formed on a sedimentary foreland located on the southern side of the former Malltraeth tidal inlet. The age of the inner part of the foreland has not been established by dating, but it may have originated in the mid-Holocene period. Following construction of an embankment (the 'Cob') across the inlet near the village of Malltraeth (completed in 1813), the course of the main low water channel of the Afon Cefni was diverted to the northern side and the old channel on the southern side silted up. The Ordnance Survey (OS) First Edition One-inch map published in 1841 (Figure 2a) shows that Gwningaer Fawr was then much smaller; however, it significantly increased in size by the 1950s (Figure 2b). After this time progradation at the northern end of the foreland continued, involving the development of a series of spit recurves supplied with sand from intertidal and subtidal areas, and by northward alongshore drift along Traeth Penrhos.

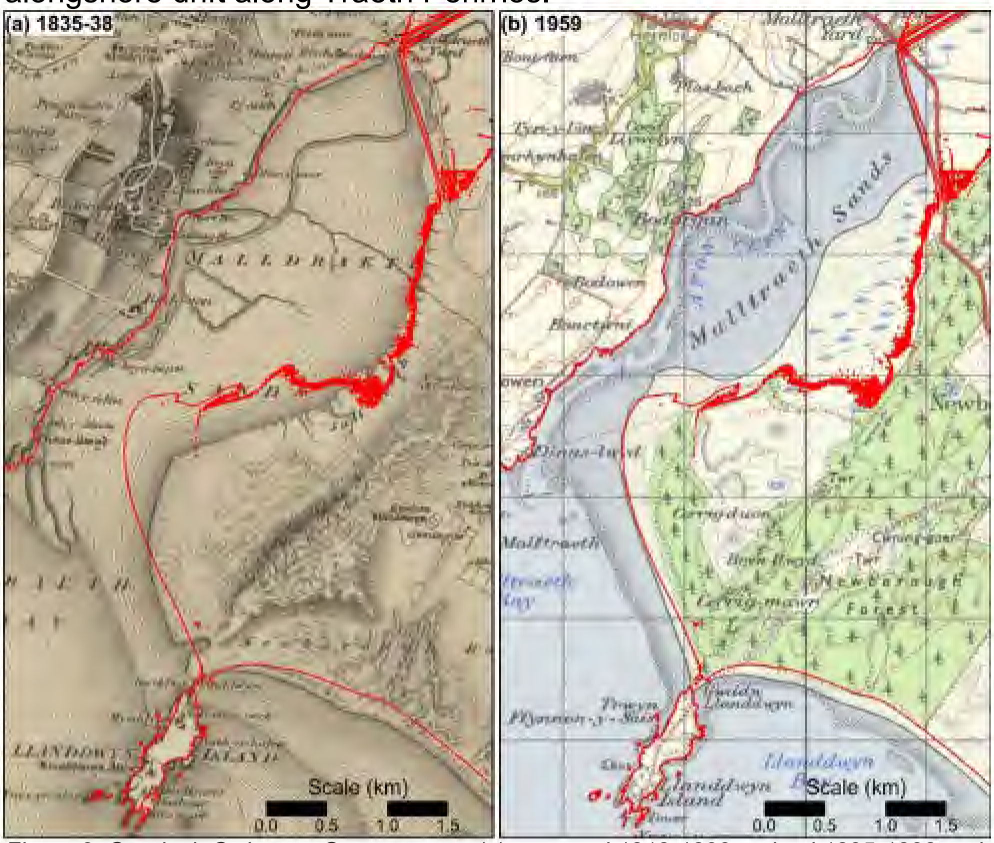

Figure 2. One-inch Ordnance Survey maps: (a) surveyed 1818-1823 revised 1835-1838 and published in 1842; (b) revised 1959 and published in 1962. Both are overlaid with the 2022 2.72 m ODN contour (approximately HAT level) shown as a red line

2.2 Coastal processes

The area experiences a macro-tidal regime with a mean spring tidal range of approximately 4.9 m (Table 1). Consequently, a wide foreshore is exposed at low tide and much of the intertidal Malltraeth embayment is dry. The level of the predicted Highest Astronomical tide (HAT) at Ynys Llanddwyn is approximately 2.71 m above Ordnance Datum Newlyn (ODN) and the estimated 1-in-1 year return period still water level is approximately 2.84 m ODN (Table 2).

Long-term wind records for Valley, located approximately 15 km to the north, show that the prevailing wind direction is southwesterly and the resultant drift direction (RDD) for sand moving winds > 11 knots is towards the north-northeast (Figure 3). No measured wave data are available for the area but modelled data indicate dominant offshore waves from the west-southwest (Figure 4). Wave refraction and shoaling takes place as waves approach the shore and are modified by the nearshore bathymetry and coastal geomorphology.

Table 1. Tidal levels (in m relative to Ordnance Datum, Newlyn), taken from the nearest Secondary Ports listed in the 2020 Admiralty Tide Tables. The reported levels at Ynys Llanddwyn have been assumed to apply to the whole of the frontage in this study

	Holyhead	Porth Trecastell	Ynys Llanddwyn	Fort Belan
HAT	3.25	2.90	2.71	2.70
MHWS	2.55	2.20	2.11	2.00
MHWN	1.35	1.00	1.11	0.90
MSL	0.22	0.17	0.16	0.24
MLWN	-1.05	-0.80	-0.89	-0.80
MLWS	-2.35	-2.10	-2.09	-2.00
LAT	-3.05	nd	nd	nd
CD	-3.05	-2.80	-2.79	-2.60

Table 2. Return period of extreme water levels for offshore point 968 located approximately 2.5 km SW of Newborough (EA, 2019)

Return Period (years)	Level (m OD)	95% Confidence Interval (m OD)
1	2.84	2.83 to 2.89
2	2.93	2.91 to 2.98
5	3.05	3.02 to 3.10
10	3.14	3.09 to 3.19
20	3.22	3.16 to 3.29
25	3.25	3.19 to 3.32
50	3.33	3.25 to 3.43
75	3.38	3.28 to 3.50
100	3.42	3.31 to 3.55
150	3.47	3.34 to 3.63
200	3.51	3.37 to 3.69
250	3.54	3.39 to 3.73
300	3.56	3.41 to 3.77
500	3.63	3.45 to 3.88
1000	3.73	3.52 to 4.04
10000	4.12	3.76 to 4.73

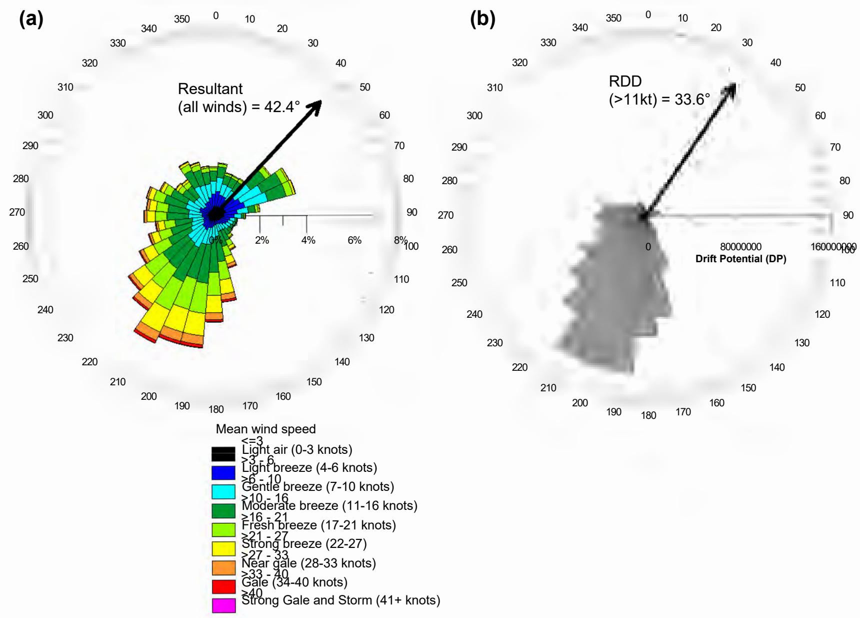

Figure 3. (a) Wind rose calculated for all winds recorded at Valley during the period January 1957 to February 2020 inclusive; (b) sand rose calculated for winds >11 knots for the same period: Primary data source: MIDAS

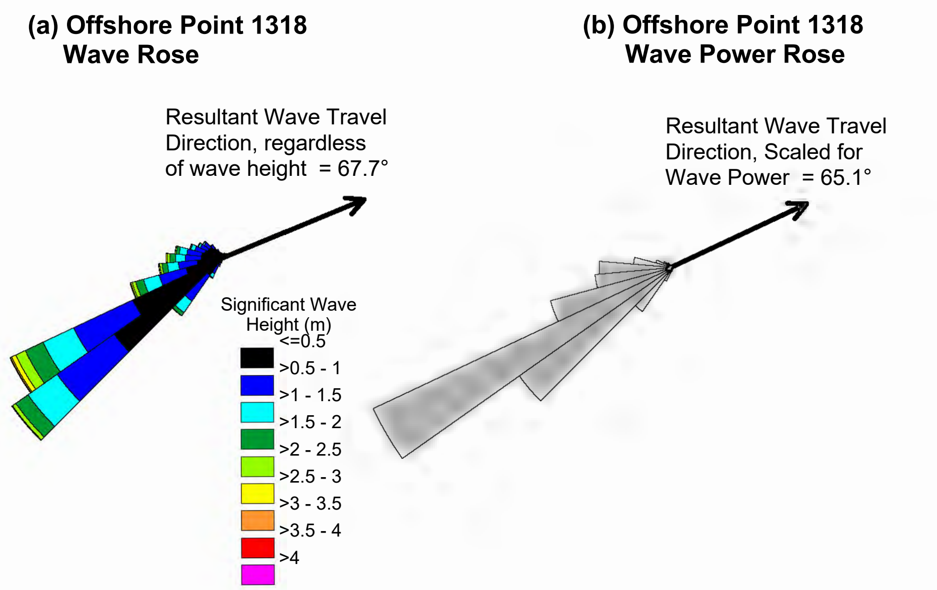

Figure 4 .(a) hindcast wave rose and (b) hindcast wave power rose calculated at offshore point 1318 for the period 1980-2016, using CEFAS Hindcast Wavenet data. Offshore point approximately 2.5 km west of Ynys Llanddwyn

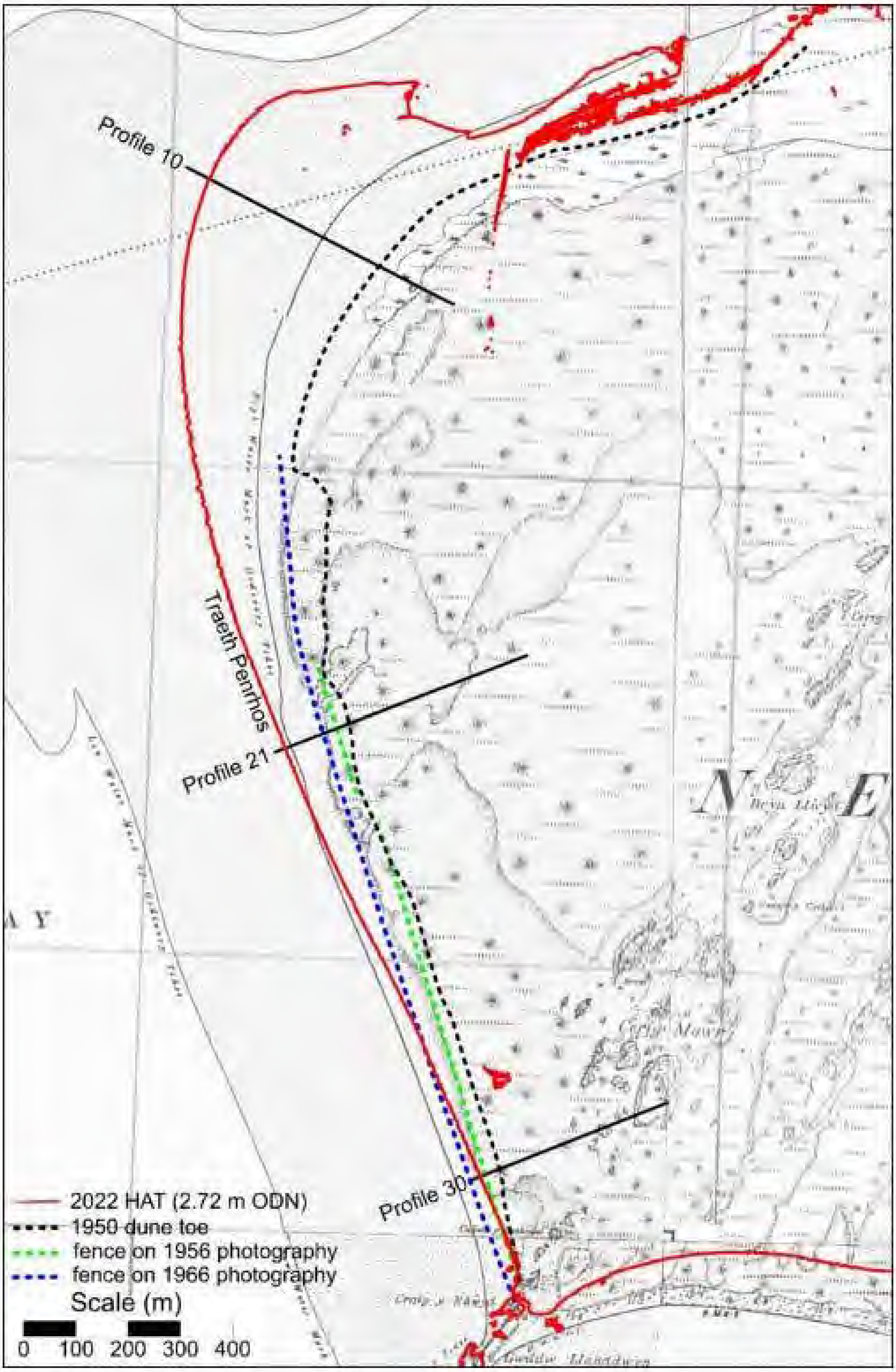

Figure 5. Six-inch Ordnance Survey map surveyed and published in 1888, overlaid with the position of fences in 1956 and 1966, the dune toe from 1950 aerial photographs, and the HAT contour from the 2022 LiDAR DTM.

2.3 Dune morphology and effects of Forestry Commission interventions

Three compound parabolic dune ridges (made up of a number of interlinked parabolic dune elements) are present on Gwningaer Fawr, separated by low-lying deflation plains. All three ridges have been formed mainly by dominant south-southwesterly winds, although the third ridge on the northern side of the foreland appears also to have been influenced by northeasterly winds blowing down the Afon Cefni valley.

Aerial photographs from the period 1940 - 1950 show that prior to acquisition by the Forestry Commission the area behind Traeth Penrhos consisted of a largely unvegetated sand sheet, with scattered patches of vegetation. The works undertaken by the Forestry Commission between 1947 and 1965 included construction of artificial foredune ridges to protect the newly planted forest behind. Two main fence lines were constructed along the backshore of Traeth Penrhos to trap sand (Figures 5 - 11). Construction of the first (most inland) fence had begun by early 1951 and by 1956 it had been extended north as far as Pant Gwylan (Gull Slack), which at one time hosted a gullery (J. Ratcliff pers. comm). The fencing consisted of brushwood attached to wire strands and/or wire mesh and supported at intervals by wooden posts (Figure 6). A second (outer) fence was erected between 1960 and 1965. During this period there was evidently a large supply of sand from the adjoining nearshore area. Fence construction slowed the drift of sand inland and encouraged sand deposition to seaward of, as well as along and behind, each fence line.

Figure 6. Ground photograph of Forestry Commission fencing along Traeth Penrhos taken in the 1950s. Source: NRW

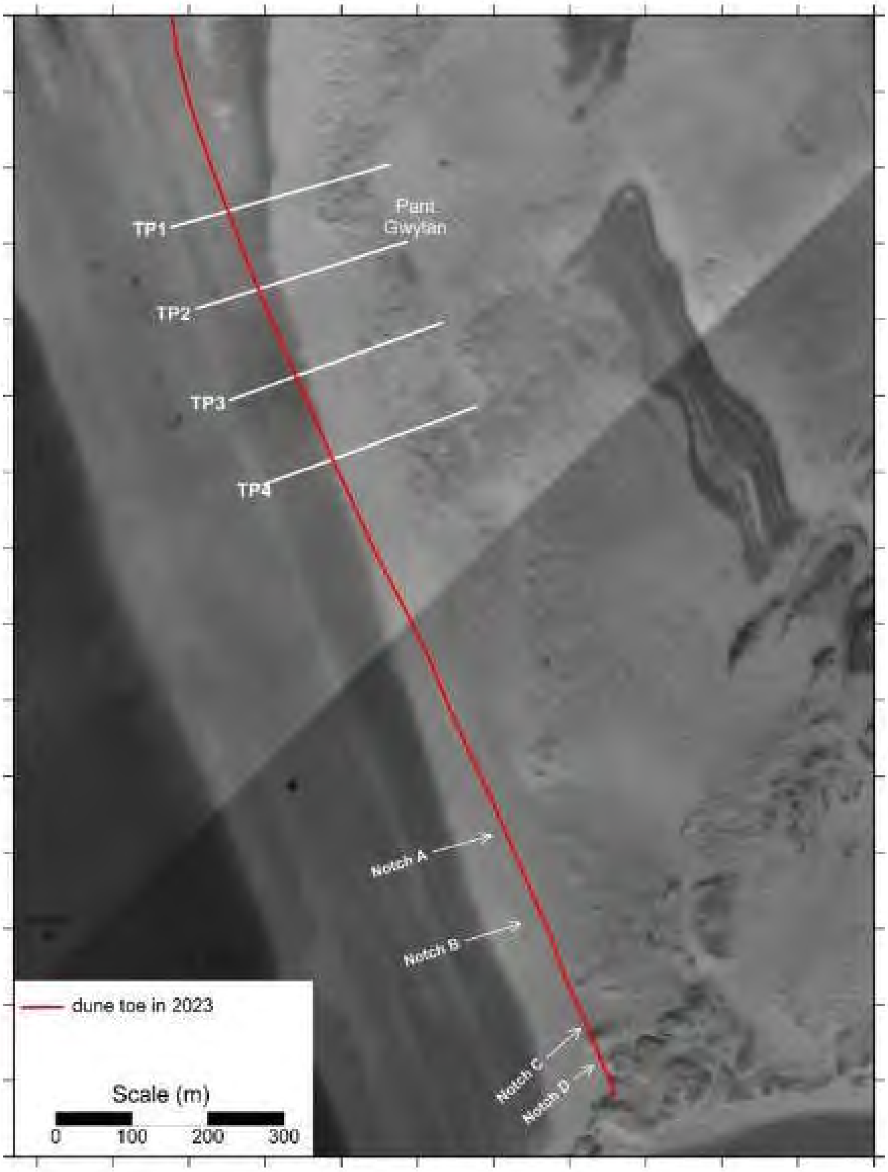

Figure 7. Aerial photography flown 12/05/1950 (sortie 5004 541RAF517 IR), prior to the construction of the first fenced line at the back of the beach. The dune toe line extracted from a 2023 LiDAR DTM is shown as a red line. The positions of shore-normal profiles and frontal dune notches referred to later in the report are also shown for reference. Source: Welsh Government Cartographics Dept

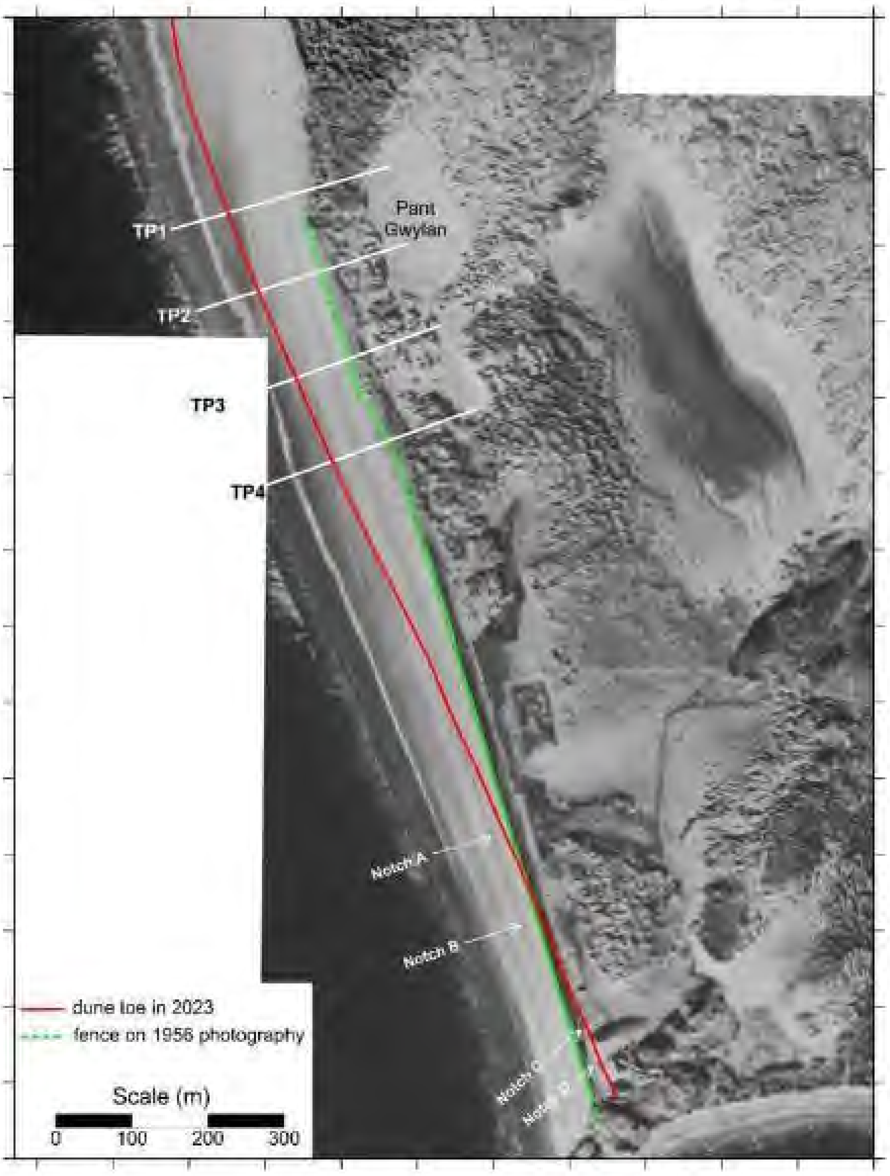

Figure 8. Aerial photography flown 02/02/1956 (sorti5608 58_RAF_1931 F21). The dune toe line extracted from a 2023 LiDAR DTM is shown as a red line, the 1956 fence line is also shown (green dotted line). The positions of shore-normal profiles and frontal dune notches referred to later in the report are also shown for reference. Source: Welsh Government Cartographics Dept.

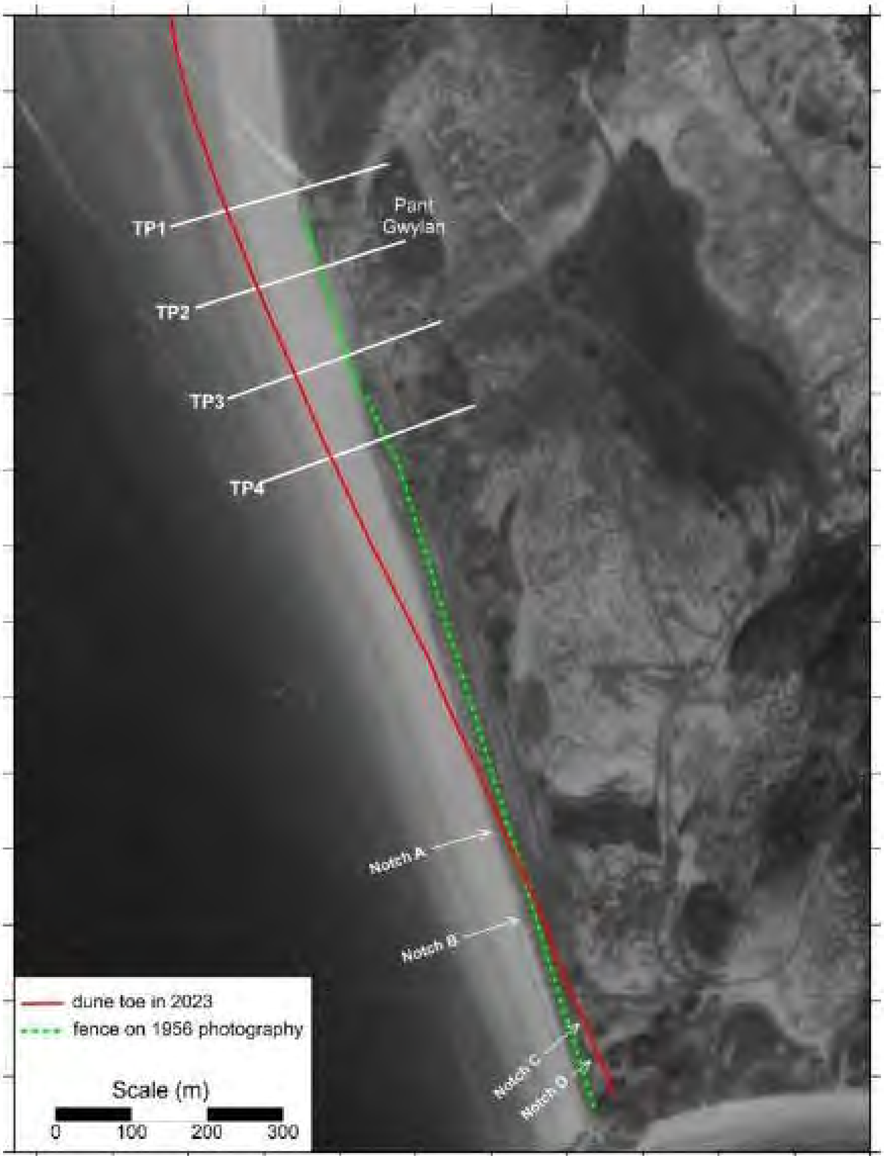

Figure 9. Aerial photography flown 31/05/1960 (sortie 6004 58RAF3579 F22). The dune toe line extracted from a 2023 LiDAR DTM is shown as a red line, the 1956 fence line is also shown (green dotted line). The positions of shore-normal profiles and frontal dune notches referred to later in the report are also shown for reference. Source: Welsh Government Cartographics Dept.

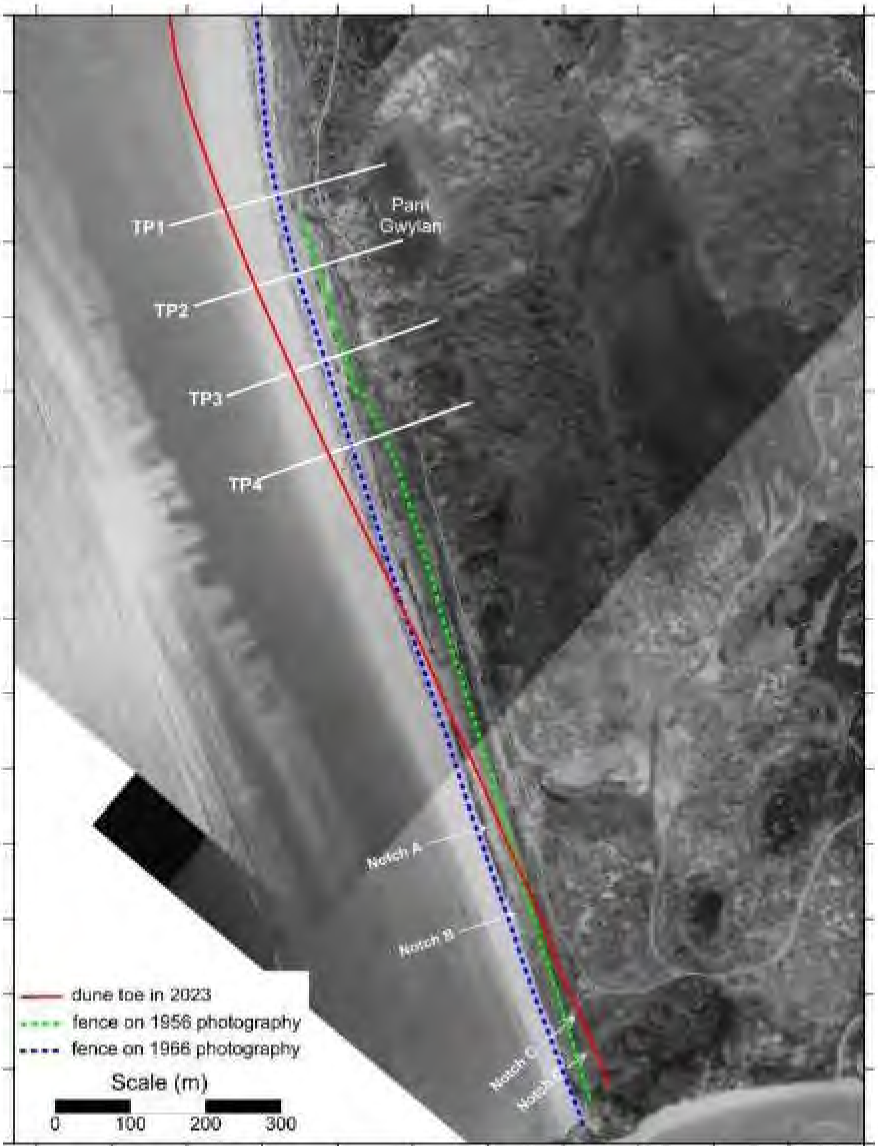

Figure 10. Aerial photography flown 01/06/1966 (sortie 6609 MAL29_66 100 10k). The dune toe line extracted from a 2023 LiDAR DTM is shown as a red line, the 1956 fence and 1966 fence/dune lines are also shown. The positions of shore-normal profiles and frontal dune notches referred to later in the report are also shown for reference. Source: Welsh Government Cartographics Dept.

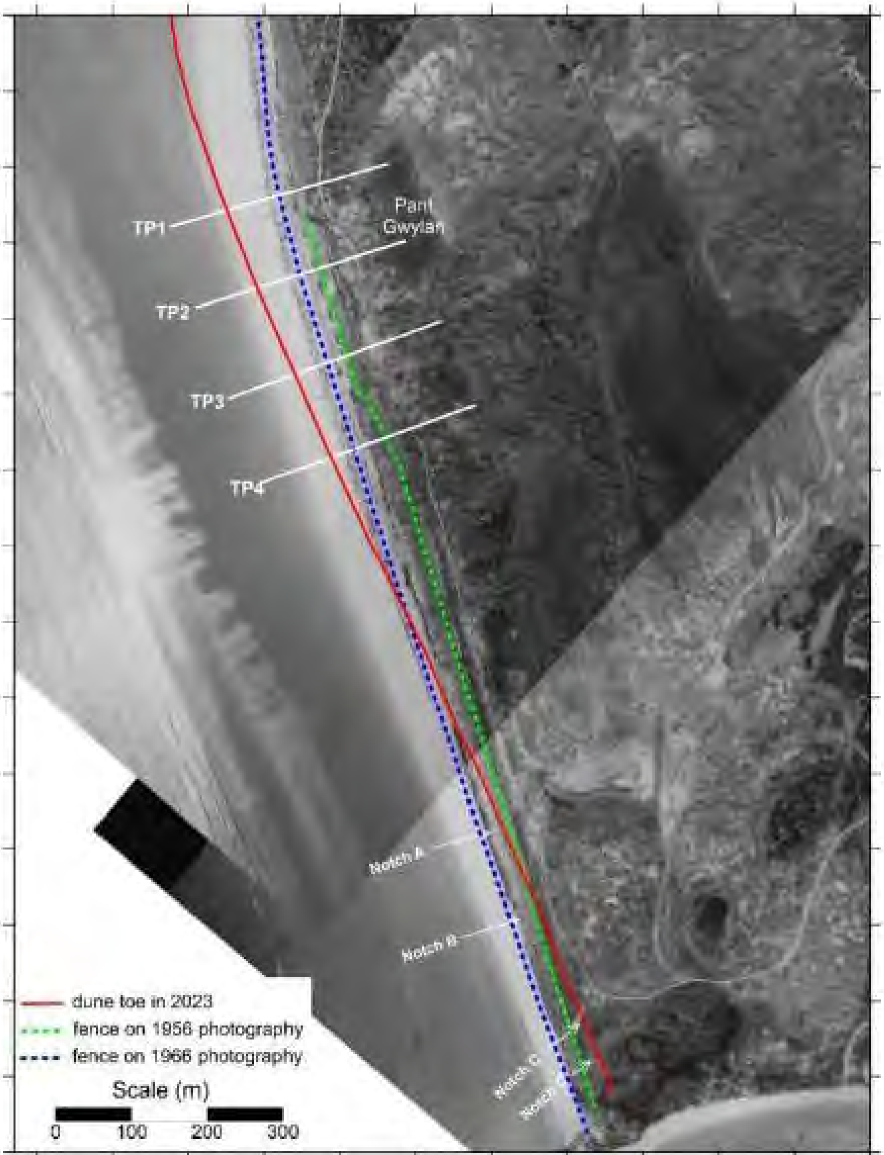

Figure 11. Aerial photography flown 10/08/1982 (sortie 8233 CUCAP RC8_EU). The dune toe line extracted from a 2023 LiDAR DTM is shown as a red line, the 1956 fence and 1966 fence/dune lines are also shown. The positions of shore-normal profiles and frontal dune notches referred to later in the report are also shown for reference. Source: Welsh Government Cartographics Dept.

2.4 Recent erosion and accretion patterns

Erosion began at the southern end of the Traeth Penrhos frontage during the 1970s and by 1982 approximately 400 m of frontal dunes had been lost in this area (Figure 12). Since then erosion in the south has continued and the erosion front has moved northwards. The onset of erosion has been associated with increased frequency of winds and waves from the south-southwest and decreased frequency of winds from the northwest, resulting in stronger net alongshore transport towards the north. There has also been a reduced tendency for onshore transport of sand from the subtidal zone (Pye & Blott, 2020). The period since 1990, and especially since 2007, has also been relatively stormy. Between 2013 and 2022 the 3.5 m OD contour, which approximates the dune toe position, retreated by up to 16.3 m at the southern end of Twyni Penrhos).

Figure 12. The position of the dune toe estimated from historical aerial photographs. Base satellite imagery flown 04/07/2023 (source: Google Earth). The positions of shore-normal profiles and frontal dune notches referred to later in the report are also shown for reference. Source: Welsh Government Cartographics Dept.

The seaward side of the frontal dune ridge south of Profile 21 shown on Figure 13 is cliffed with an average slope of 36°- 42°. The dune ridge at the southern end of the frontage near profile 30 contains four artificial notches (labelled A to D) which were created in 2014 with the aim of increasing the flux of windblown sand from the beach into the hind-dune area (Pye & Blott, 2013). Immediately to the north of profile P21 the dune front is more gently sloping, the frontal dune ridge is higher and wider with a number of small blowouts developed in the crest. The northern end of the system around profile P10 consists of a series of dune-capped spit recurves which still show a trend for net progradation with alternating periods of storm erosion and recovery involving embryo dune and new foredune ridge development.

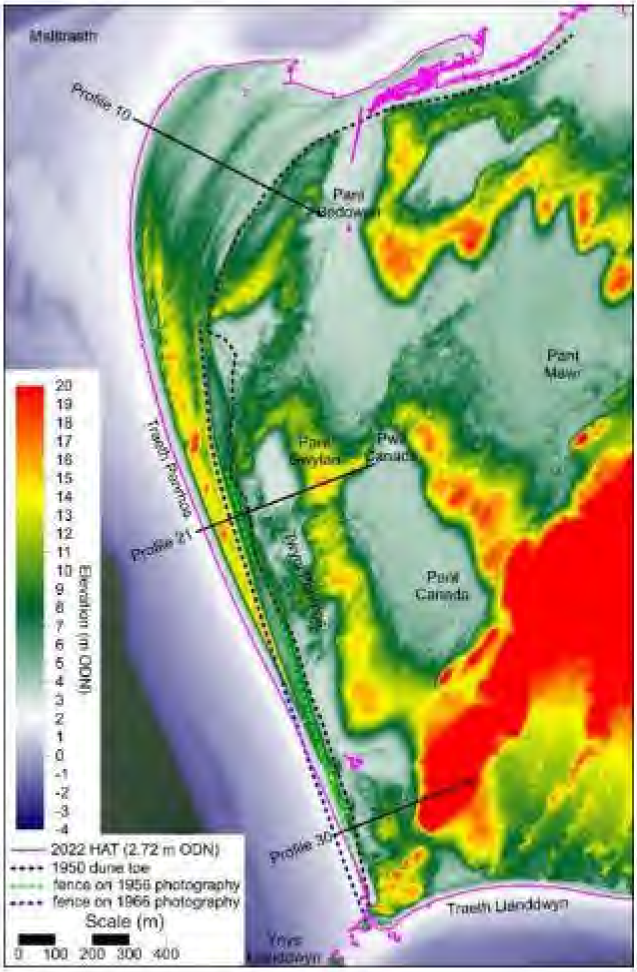

Figure 13. LiDAR digital terrain model (2022) showing the major topographical features, Forestry Commission fence lines, 1950 dune toe, interpolated 2022 HAT level and locations of cross shore profiles 10, 21 and 30

There is a close correspondence between the frontal dune morphology, accretion – erosion trends and the width / steepness of the adjoining beach. South of profile P21 the beach is relatively steep and the backshore (distance between MHWS and HAT) is relatively narrow, whereas to the north of profile 21 the average beach gradient progressively decrease and the backshore width increases (Figure 14).

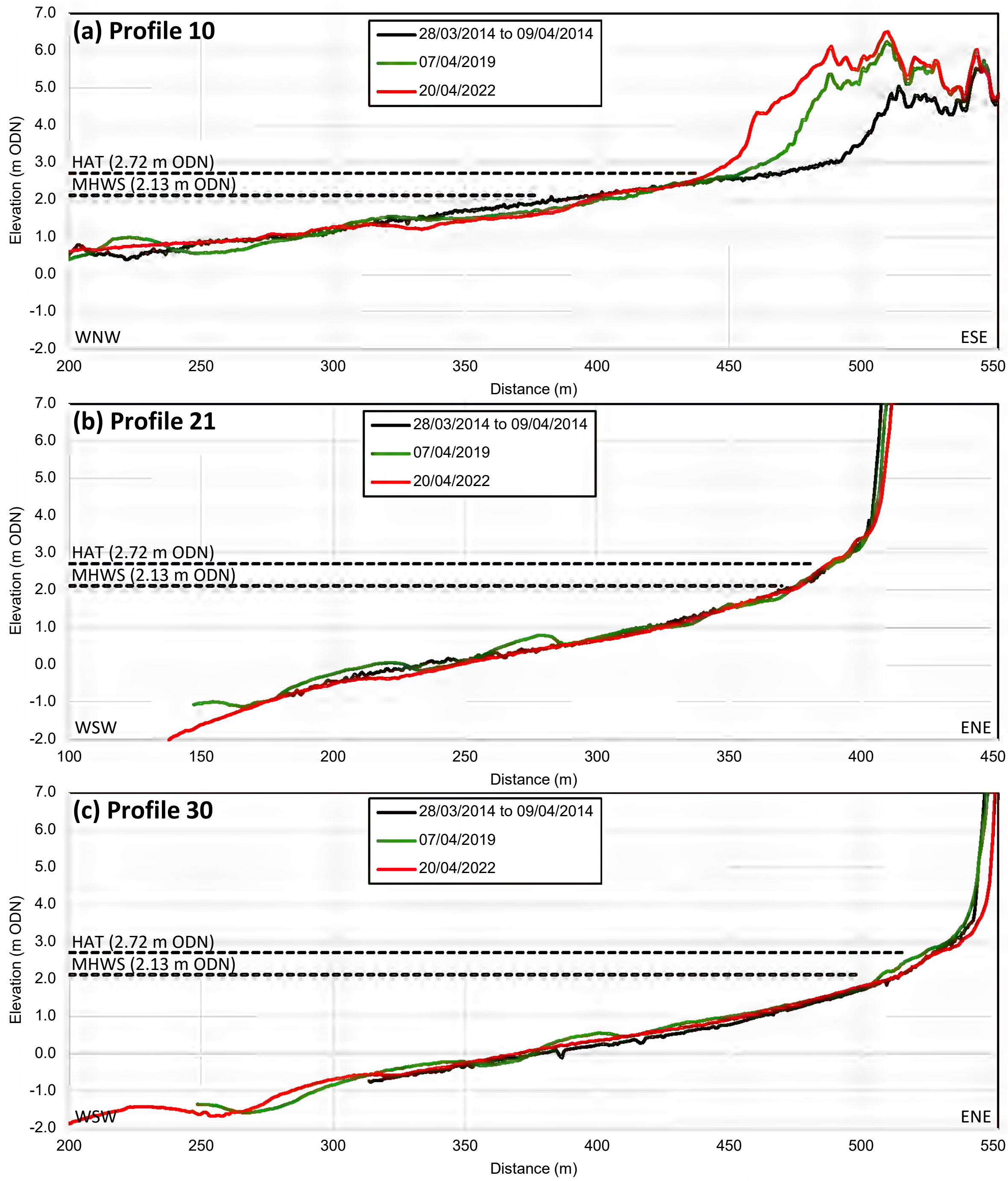

Figure 14. Profiles 10, 21 and 30 of the beach and frontal dunes, taken from LiDAR DTMs based on flights 28/03/2014-09/04/2014, 07/04/2019 and 20/04/2022

Analysis of historical maps and aerial photographs has shown that the shoreline at profiles P21 and P30 showed a slow net erosional trend between 1888 and 1950 (Figure 15). During this period there was very little vegetation present to trap sand supplied to the upper beach from the nearshore zone and much of it migrated inland to feed mobile dunes. The effect of the Forestry Commission intervention works in reversing this erosional trend between 1951 and 1965 is very clear from Figure 15. However, at profile P30 the effect was short-lived; erosion resumed after 1965 and has continued to the present day.

At profile P21 the progradation trend continued until about 1982, after which time the dune toe position remained stable until the stormy winter of 2013-14, since when there has been slow erosion. At profile P10, however, net progradation has continued to the present, albeit with periods of erosion during stormy winters followed by periods of recovery.

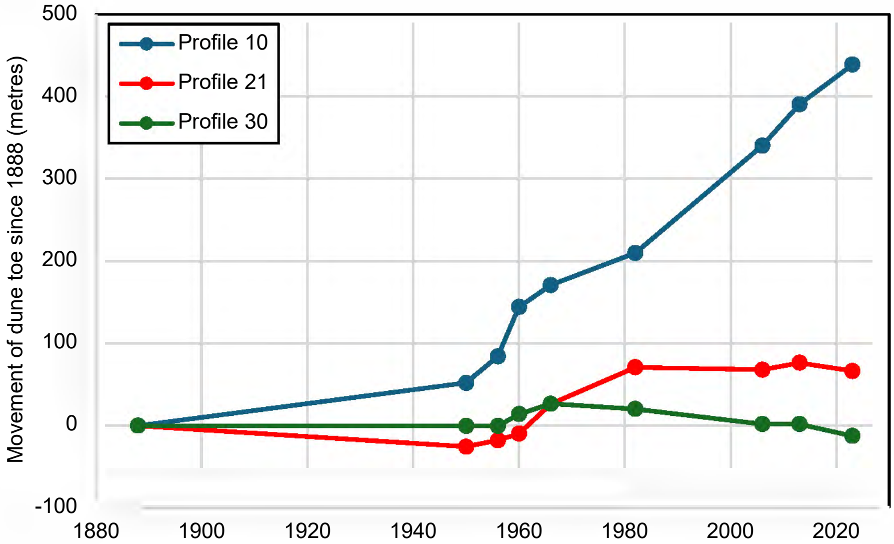

Figure 15. Cumulative movement of the dune toe (positive directed offshore) at profiles 10, 21 and 30 based on Ordnance Survey maps surveyed in 1888, and aerial photographs in 1950, 1956, 1960, 1966, 1982, 2006, 2013 and 2023

2.5 Relationship between frontal dune morphology and sediment budget

The morphological continuum in dune morphology and habitat types which is seen along Twyni Penrhos needs to be understood in terms of the longshore differences in beach and frontal dune sediment budget which exists (cf. Figure 16). At the southern end, where a dissected, narrow single foredune ridge is migrating landward, losing height and width as it does so, both the beach sediment budget and the foredune sediment budget are negative. The area around profile P21 corresponds with an area where the ‘foredune’ sediment budget is positive due to strong onshore wind energy but the beach sediment budget is becoming increasingly negative. At the northern end of the frontage near profile P10 both the net beach sediment budget and the foredune sediment budget have been strongly positive in the last 80 years. Foredune height in this area has been limited by the relatively rapid rate of coastal progradation and new embryo dune and foredune ridge development.

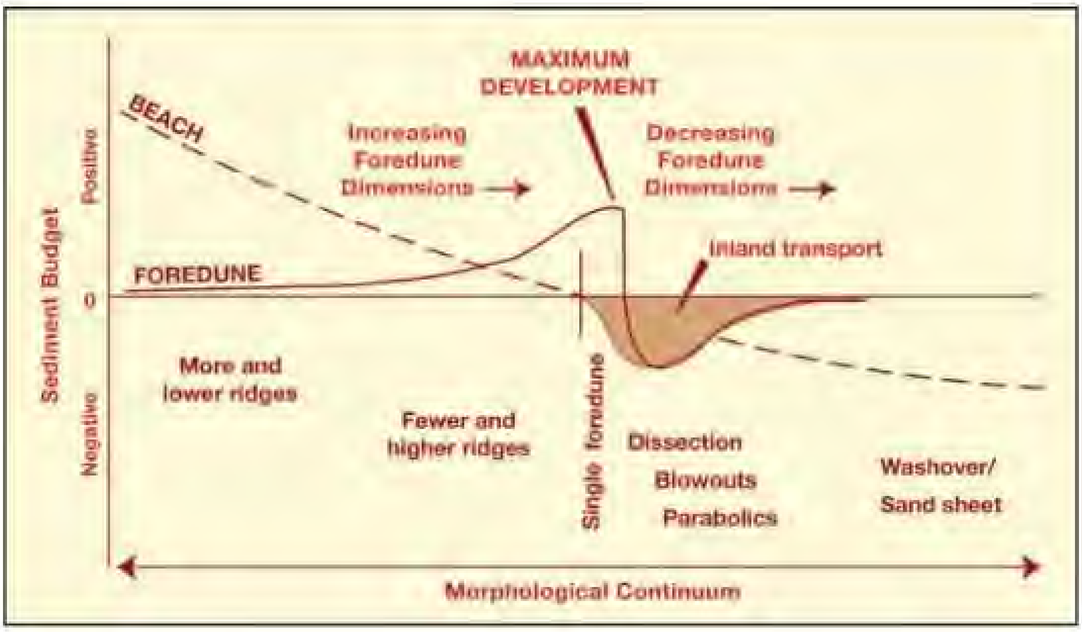

Figure 16. Conceptual relationship between the sediment budget of the beach, foredune and dune morphology. On shores with a marked sediment transport / supply gradient the morphological continuum is often reflected in an alongshore sequency of different frontal dune morphological types (after Psuty & Silveira, 2004)

2.6. Concepts of coastal vegetation zonation and succession

The concept of a spatial morpho-phytological transition, or zonation, between the sea and inland coastal dune areas (e.g. Figure 17) has a long history, as does the suggestion that the spatial zonation can be interpreted through ergodic reasoning as also representing temporal succession. These basic ideas were in use at least by the late 19th century during ecological studies of the Great Lakes sand dunes (e.g. Cowles, 1899).

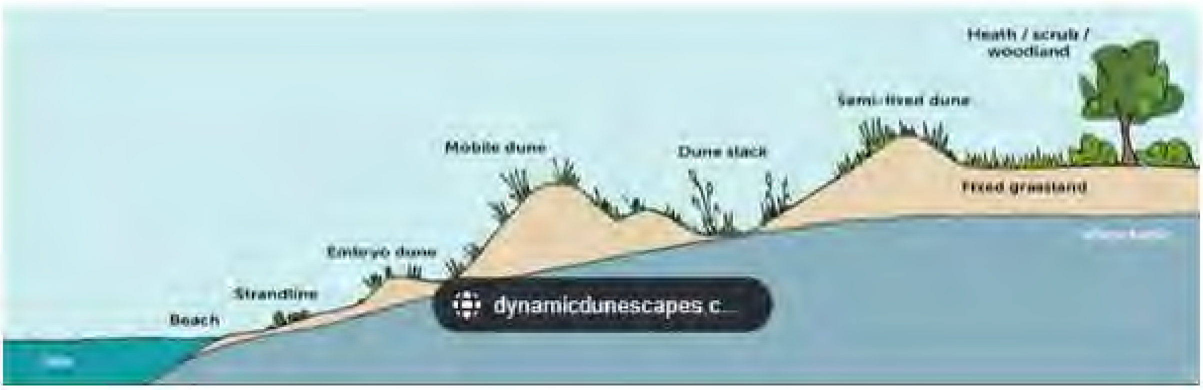

Figure 17. Schematic diagram showing the spatial zonation of dune morphology and habitats between the beach and inland areas (source: Dynamic Dunescapes https://dynamicdunescapes.co.uk/about-sand-dunes)

Tansley (1911) described the typical vegetation zonation between strandline and inland dunes commonly seen in the UK, describing the more seaward mobile sands as “white dunes”. By contrast Salisbury (1925, 1952) referred to the younger dunes closest to the sea, including “embryo dunes” and “semi-fixed dunes”, as “yellow dunes”, and differentiated them from “fixed dunes”, “medium-aged dunes” and “old dunes” further inland. The term “grey dunes” was not widely used by British ecologists until the later 20th century (e.g. the term is not specifically used by Salisbury, 1952 or Ranwell, 1972), but subsequent use of the term has referred to fixed dunes which have a greyish surface appearance due either or both to the build-up of humus in the surface soil layers or to the presence of significant areas with lichen communities. Some authors have restricted the term “grey dune” to dunes rich in lichen-rich communities, and have differentiated it from “fixed dune” grassland and dune heath” (e.g. Rhind et al., 2006). European authors have made more use of the term grey dunes and in some instances have defined it as an intermediate zone between more geomorphologically active yellow dunes to seaward and highly disturbed, often cultivated, dune sands to landward which have been referred to as “brown dunes” (e.g. Ellenberg, 1978; Jungerius & Van der Meulen, 1988; Isermann, 2005). However, the use of colour as a zonal, habitat or community descriptor is fraught with difficulties since surface dune sands in different regions show widely varying colours reflecting geological source differences and the effects of different soil development processes in different climates. It is now widely recognized that there are significant difficulties in applying the traditional concepts of dune zonation and succession in many areas, including the Great Lakes area where they were first developed, since they do not take account of spatial variations in coastal processes, shoreline evolution, substrate variation and human interventions (e.g. Miyanishi & Johnson, 2007). While examples of classical zonation can be found they are typically limited to areas of high net coastal sediment supply and shoreline progradation. On eroding coasts which have a net negative sediment budget a truncated zonation pattern without embryo dunes or semi-mobile foredunes may be found, or, more commonly, a complex three-dimensional mosaic of blowouts, hummocky dunes and mobile sand sheets or parabolic dunes. Where accommodation space allows, these mosaics may include mobile parabolic dunes, dune slacks and ephemeral pools, in which early-successional stage species and communities may be found.

2.7. Distribution of vegetation communities at Twyni Penrhos

The distribution of dune vegetation community types within Twyni Penrhos, as determined by a survey by JBA Consulting in early 2023, shows a close relationship with the spatial variation in dune morphology and coastal evolution (Figure 18 and Table 3).

An almost complete vegetation zonation between strandline (NVC code SD2), through mobile dune (SD5 and SD6) and semi-mobile (SD7) communities to fixed dune grassland (SD8) communities, corresponding to priority habitat codes H2110, H2120 and H2130), is present at the northern end of the system, but SD2 and SD5 are not present along most of the frontage and the width of the SD6 and SD7 zones become compressed in a southerly direction. Bare sand is shown as limited to the recently cleared areas around Pant Gwylan although there are also patches within the ‘undifferentiated mosaic’ area behind the notches at the southern end of the system.

The spatial relationship between the mapped NVC communities and topographic features along profiles P10, P21 and P30 are shown in Figure 19.

Figure 18. NVC habitat classification map of the Twyni Penrhos area based on field surveys by JBA Consulting in 2023 (Source: JBA Consulting 2024)

Table 3. NVC classification codes and community names identified by JBA Consulting as being present at Twyni Penrhos in 2023 (Source: JBA Consulting (2024) draft NRW Evidence Report) together with the priority habitats primarily associated with that community (source: JNCC)

code	**community name**	**sub-community name**	**Approximate equivalent primary priority habitat**
SD2	*Honkenya peploides-Cakile maritima* strandline community	none	Annual vegetation of drift lines (H2110)
SD4	*Elymus farctus* ssp. *boreali-atlanticus* foredune community	none	Embryonic shifting dunes (H2110)
SD5b	*Leymus arenarius* mobile dune community	*Elymus farctus* sub-community	Embryonic shifting dunes (H2110)
SD5c	*Leymus arenarius* mobile dune community	*Festuca rubra* sub-community	Shifting dunes along the shoreline (H2120)
SD6a	*Ammophila arenaria* mobile dune community	*Elymus farctus* sub-community	Shifting dunes along the shoreline (H2120)
SD6b	*Ammophila arenaria* mobile dune community	*Elymus farctus-Leymus arenarius* sub-community	Shifting dunes along the shoreline (H2120)
SD6c	*Ammophila arenaria* mobile dune community	*Leymus arenarius* sub-community	Shifting dunes along the shoreline (H2120)
SD6d	Ammophila arenaria mobile dune community	*Ammophila arenaria* sub-community	Shifting dunes along the shoreline (H2120)
SD6e	*Ammophila arenaria* mobile dune community	*Festuca rubra* sub-community	Shifting dunes along the shoreline (H2120)
SD6f	*Ammophila arenaria* mobile dune community	*Poa pratensis* sub-community	Shifting dunes along the shoreline (H2120)
SD6g	*Ammophila arenaria* mobile dune community	Carex arenaria sub-community	Shifting dunes along the shoreline (H2120)
SD7a	*Ammophila arenaria-Festuca rubra* semi-fixed dune community	typical sub-community	Fixed coastal dunes (H2130)
SD7b	*Ammophila arenaria-Festuca rubra* semi-fixed dune community	*Hypnum cupressiforme* sub-community	Fixed coastal dunes (H2130)
SD7c	*Ammophila arenaria-Festuca rubra* semi-fixed dune community	*Ononis repens* sub-community	Fixed coastal dunes (H2130)
SD8a	*Festuca rubra-Galium verum* fixed dune grassland	typical sub-community	Fixed coastal dunes (H2130)
SD8c	*Festuca rubra-Galium verum* fixed dune grassland	*Tortula ruralis* ssp. *ruraliformis* sub-community	Fixed coastal dunes (H2130)
SD8c	*Festuca rubra-Galium verum* fixed dune grassland	mixed	Fixed coastal dunes (H2130)
SD16a	*Salix repens-Holcus lanatus* dune-slack community	*Ononis repens* sub-community	Humid dune slacks (H2190)
SD16b	*Salix repens-Holcus lanatus* dune-slack community	*Rubus caesius* sub-community	Humid dune slacks (H2190)
SD16c	*Salix repens-Holcus lanatus* dune-slack community	*Prunella vulgaris-Equisetum variegatum* sub-community	Humid dune slacks (H2190)
SD17c	*Potentilla anserina-Carex nigra* dune-slack community	*Caltha palustris* sub-community	Humid dune slacks (H2190)
MC1a	*Crithmum maritimum-Spergularia rupicola* maritime rock-crevice community	typical sub-community	Vegetated sea cliffs of the Atlantic and Baltic coasts (H1230)
MC5b	*Armeria maritima-Cerastium diffusum* ssp. *diffusum maritime* therophyte community	*Anthyllis vulneraria* sub-community	Vegetated sea cliffs of the Atlantic and Baltic coasts (H1230)
OV27d	*Epilobium angustifolium* community	*Acer pseudoplatanus-Sambucus nigra* sub-community	Fixed coastal dunes (H2130)
OV27e	*Epilobium angustifolium* community	*Ammophila arenaria* sub-community	Fixed coastal dunes H(2130)

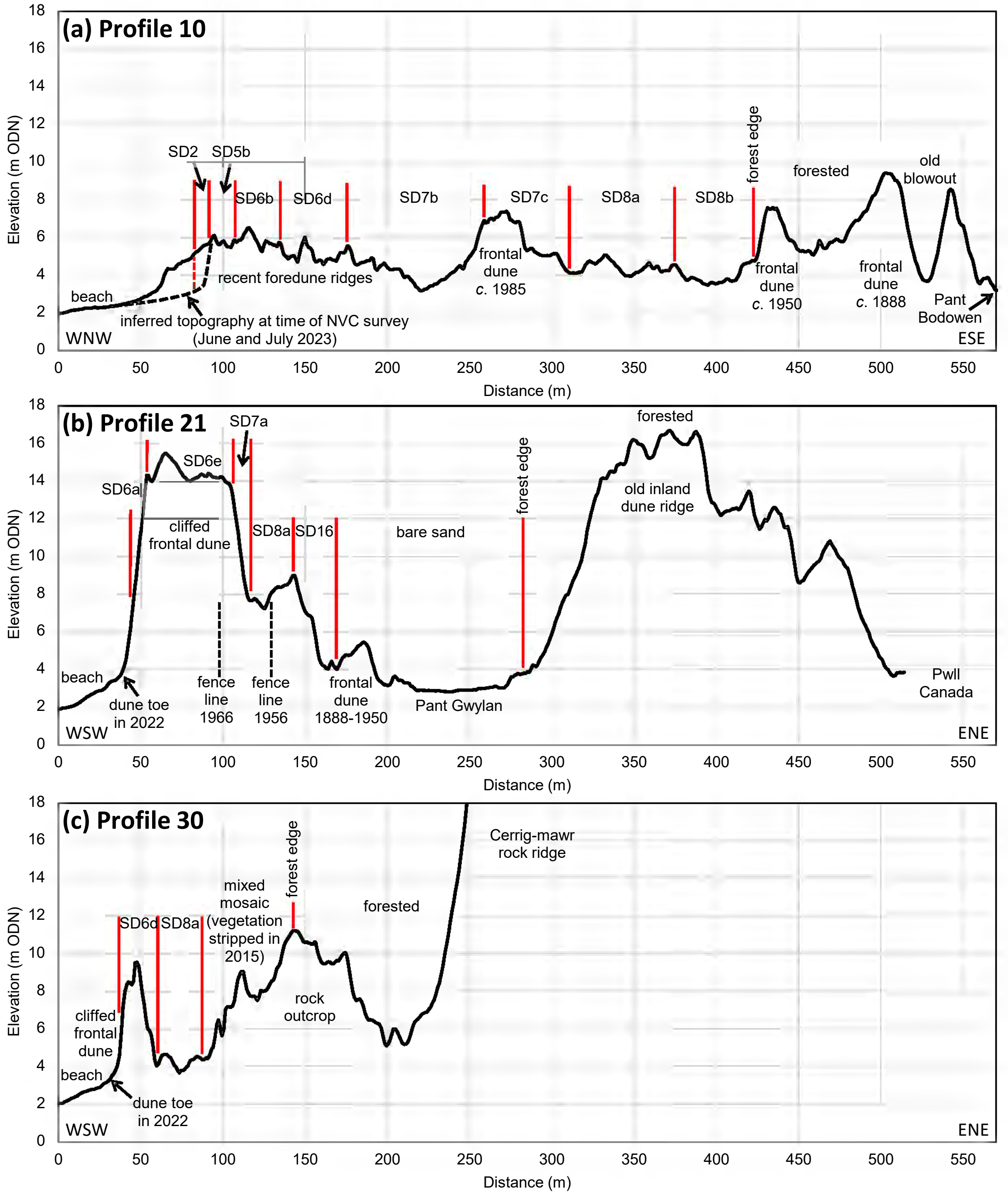

Figure 19. Profiles 10, 21 and 30 of the upper beach and dunes, taken from the 2022 LiDAR DTM, overlaid with the NVC classification (surveyed June and July 2023)

3. Nature conservation objectives

Twyni Penrhos forms part of the Tywyn Niwbwrch– Ynys Llanddwyn Site of Special Scientific Interest (SSSI) and the Y Twyni o Abermenai i Aberffraw Special Area of Conservation (SAC) (Figure 20). Part of Tywyn Niwbwrch (Newborough Warren) was notified as a SSSI in 1955 and the area extended to include Coedwig Niwbwrch (Newborough Forest) and Gwningaer Fawr/Twyni Penrhos in 1957. The SAC was first proposed in 1995-96 and designated in December 2004. Tywyn Niwbwrch, Ynys Llanddwyn and the Malltraeth / Cefni Estuary are also included within the Tywyn Niwbwrch a Ynys Llanddwyn National Nature Reserve (NNR), declared in 1955, but Coedwig Niwbwrch and Twyni Penrhos are excluded.

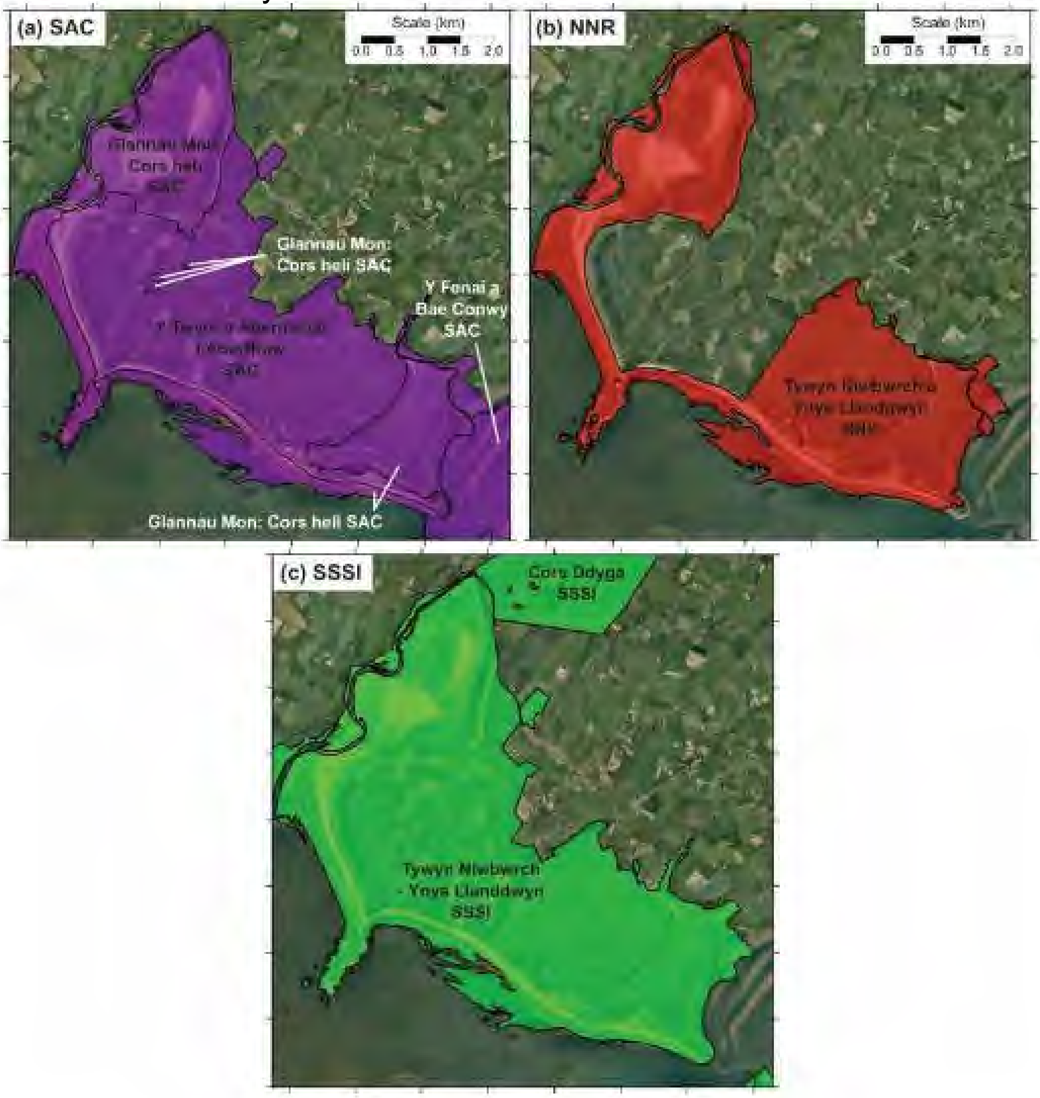

Figure 20. The extent of (a) SAC, (b) NNR and (c) SSSI designated areas at Niwbwrch

The Annex I habitats that are a primary reason for selection of the Y Twyni o Abermenai i Aberffraw SAC (https:/sac.jncc.gov.uk/site/UK0020021) are:

1330 Atlantic salt meadows (*Glauco-Puccinllietallia maritimae*),

2110 Embryonic shifting dunes,
2120 Shifting dunes along the shoreline with *Ammophila arenaria* ("White Dunes"),
2130 Fixed coastal dunes with herbaceous vegetation ("Grey Dunes"),
2170 Dunes with *Salix repens* ssp. argentea,
2190 Humid dune slacks,
3150 Natural eutrophic lakes with *Magnoptamio*n or Hydrocharition type vegetation.

All five of the SAC dune habitat types were judged 'Unfavourable' in the last condition assessment. The habitats of principal concern in this report are Embryonic shifting dunes (EU habitat code H2110), Shifting dunes along the shoreline (H2120) and Fixed coastal dunes with herbaceous vegetation (H2130).

Conservation objectives for the Y Twyni o Abermenai i Aberffraw SAC were first published as part of a Core Management Plan developed by the Countryside Council for Wales (CCW) in 2008. Some changes have been made since that time but the major conservation objectives remain the same. The most recent version of the Plan (NRW, 2022) states that (key geomorphological points in bold):

"Abermenai to Aberffraw dunes and Glannau Môn saltmarshes, with Glan-traeth together form a complex coastal sedimentary geo-system. **These coastal landforms should demonstrate the natural processes of sediment transfer, erosion and deposition within the local coastal system**. These geomorphological processes (which move shingle, sand and mud to create beaches, dunes, slacks, estuarine flats and shingle ridges) also create the physical template upon which biological features develop. The sequence of coastal habitat zones is an important aspect to the integrity of these sites. The sites should exhibit typical rocky shore, shingle, dune and estuarine communities, normally including mudflats and sandy foreshore, strandline, foredunes, mobile and fixed dunes, dune heath, humid dune slacks and saltmarsh. **These will vary in their relative proportion and location in response to naturally changing landforms but should not diminish in total (aggregate) extent**. Sandbanks occur offshore, controlled by cycles of currents, tides and waves in Caernarfon Bay and the Menai Strait, while mudflats accumulate in sheltered estuaries. **There should normally be a strandline with embryonic dunes on the windward shore each summer, areas of mobile dune, "blowout" and areas of newly formed wet slack** to provide early successional phases of these habitats. Dune grassland should be herb rich with short grasses, including early sand grass and a rich invertebrate fauna. Native dune woodland and scrub, composed of locally native species, may develop on inland parts of the fixed dunes where organic rich soils have naturally formed. Dune heath should be maintained wherever it occurs and encouraged on appropriate areas where leaching and acidification of dune soils has occurred".

"Newborough forest forms part of the coastal ecosystem in the SAC. **The maturing mixed pine forest has had and continues to impact on the conservation status of the sand dune** and species features and to **deprive the soft coastal frontage of the capability to react to storms and changing climatic events. This reduces the dune system's ability for natural recovery.** Future management should seek to reduce impacts, restore remnant dune vegetation and allow both the habitats and the forest to adapt to climate change and sea level rise."

Conservation Objective for Feature 1: Embryonic shifting dunes (EU Ref: H2110)

"**Extent should be stable in the long term, or where appropriate increasing**. There shall be no decrease in the total (aggregate) area of dune habitats for which this site was designated (i.e., **the sum total of 675 ha of dune habitat should not diminish**). **The extent and location of embryonic shifting dune features may be subject to periodic and seasonal variation. Embryonic shifting dunes should be evident along the beach in late summer wherever sediment accretion and organic strandline material permits**. Quality (including in terms of ecological structure and function) should be being maintained, or where appropriate improving. **The typical dune zonation, from beach (through embryonic shifting dunes, white dunes, dune slacks) to fixed dune, shall be intact along 95% of the soft coastal frontage. There should be active erosion and deposition of the embryonic shifting dunes with at least 50% bare sand on these foredunes**. Populations of the habitat's typical species must be being maintained or where appropriate increasing. The strandline and embryonic dune vegetation should be made up of the typical species listed below. *Cakile maritima*, *Honkenya peploides*, *Salsola kali*, *Atriplex* spp., *Beta vulgaris*, *Matricaria matricoides*, *Elytrigia juncea* (*Elymus farctus*), *Leymus arenarius*, *Festuca rubra*, *Sonchus asper*. Factors affecting the extent and quality of the habitat and its typical species (and thus affecting the habitat's future prospects) should be under appropriate control. **This feature requires a supply of sediment, opportunity for aeolian transport and naturally occurring organic strandline material. Sediment supply and mobility shall be maintained**. Man-made obstructions shall be absent. A regular deposit of strandline organic material is required to initiate development. All factors affecting the achievement of these conditions are under control."

Conservation Objective for Feature 2: Shifting dunes along the shoreline with *Ammophila arenaria* ("white dunes") (EU Ref: H2120)

"Extent should be stable in the long term, or where appropriate increasing. There shall be no decrease in the total (aggregate) area of qualifying dune habitats for which this site was designated (i.e., **the sum total of 675 Ha of qualifying dune habitat should not diminish**). The extent and location of individual dune habitat features may be subject to periodic and seasonal variation. **Shifting dunes should ideally be 30% of the total dune habitat and not less than 15%.** The distribution of shifting dunes with *Ammophila arenaria* within the site may vary in response to dynamic processes and changes to other qualifying dune habitats for the site. Quality (including in terms of ecological structure and function) should be being maintained, or where appropriate improving. The typical dune zonation, including shifting dunes with *Ammophila arenaria*, from beach to fixed dune shall be intact along 95% of the soft coastal frontage**. Bare sand should be present over at**

least 20% of the shifting dune habitat. This should include at least "occasional" active blow-outs and mobile sands. Active mechanical intervention may be appropriate to mobilise sand. Invasive species, especially Sea Buckthorn (*Hippophae rhamnoides*) Traveller's joy (*Clematis vitalba*) and Japanese rose (*Rosa rugosa*) should be rare or absent. Populations of the habitat's typical species must be being maintained or where appropriate increasing. The shifting dunes should be vegetated by the typical species listed below: *Ammophila arenaria*, *Elytrigia juncea* (*Elymus farctus*), *Festuca rubra*, *Senecio jacobaea*, *Hypochoeris radicata, Carex arenaria*, *Eryngium maritimum*, *Euphorbia portlandica*, and *Calystegia soldanella*, *Euphorbia paralias*, *Phleum arenarium*. There should be regular occurrence of: *Hypocaccus rugiceps*, *Broscus cephalotes*, *Hypocaccus rugiceps*, *Hydnobius punctatus*, *Aegialia arenaria* and *Xanthomus pallidus*. Viable population of sandhill rustic moth *Luperina nickerlii* should be present at Newborough Warren. Factors affecting the extent and quality of the habitat and its typical species (and thus affecting the habitat's future prospects) should be under appropriate control. **Sand supply and mobility shall be maintained or restored.** Man-made obstructions should be absent. All factors affecting the achievement of these conditions are under control."

Conservation Objective for Feature 3: Fixed dunes with herbaceous vegetation (\`grey dunes\`) (Habitats Directive priority feature) (EU Ref: H2130)

"**Extent should be stable in the long term, or where appropriate increasing.** There shall be no decrease in the total (aggregate) area of qualifying dune habitats for which this site was designated (i.e., **the sum total of 675 Ha of qualifying dune habitat should not diminish**). The extent and location of individual dune habitat features may be subject to periodic variation in response to dynamic processes and changes to other qualifying dune habitats for the site. The extent of fixed dune grassland habitat feature should not fall below 40% of total dune area (circa 58% in 2021). Quality (including in terms of ecological structure and function) should be being maintained, or where appropriate improving. The fixed dunes element of the typical zonation from beach to fixed dune shall be intact along 95% of the soft coastal frontage. **Bare ground should be present over 5 - 15% of the fixed dune habitat comprising small blowouts and erosion scars**. All successional stages of fixed dune grassland should be present, from early semi-fixed dune grassland to scattered scrub (no more than 5% cover) and dune heath where conditions allow. Populations of the habitat's typical species must be being maintained or where appropriate increasing. The typical species of the fixed dune vegetation include *Aira praecox*, *Anacamptis pyramidalis*, *Carex arenaria, Carex flacca, Cerastium fontanum, Crepis capillaris, Cladonia spp., Erodium cicutarium*, *Euphrasia officinalis*, *Festuca rubra*, *Galium verum*, *Geranium molle*, *Hypnum cupressiforme*, *Hypochaeris radicata, Linum catharticum, Lotus corniculatus, Luzula campestris, Odontites verna, Ononis repens, Peltigera* spp., *Pilosella officinarum, Plantago lanceolata, Prunella vulgaris, Rhinanthus minor, Rhytidiadelphus squarrosus, R. triquetrus, Sedum acre, Syntrichia (Tortula) ruralis* spp. Ruraliformis, *Thymus polytrichus, Veronica chamaedrys, Viola canina, V. riviniana* and *V. tricolor*. Skylark *Alauda arvensis* should breed regularly in each main fixed dune grassland block. Viable populations of vernal bee *Colletes cunicularis* should be present on semi-fixed dunes at Newborough Warren and Tywyn Aberffraw. Factors affecting the extent and quality of the habitat and its typical species (and thus affecting the habitat's future prospects) should be under appropriate control. Appropriate levels of grazing by livestock and/or rabbits should be maintained. Water levels should be appropriate and generally >50cm below ground surface. Invasive species (e.g. *Hippophae rhamnoides* and *Rosa rugosa*) should be under appropriate control and should be rare or absent. Active mechanical intervention may be needed to create bare mobile sand."

It should be noted that these conservation objectives relate to the designated site as a whole and not specifically to Twyni Penrhos.

4. Morphological and environmental requirements for priority dune habitats in "Good" ecological condition

2110 Embryonic shifting dunes

The fundamental requirement for the existence of sustainable embryonic shifting dunes is a wide sandy beach with a significant width of backshore (defined here as the zone above mean high water spring tide level) and a wide foreshore (the area between mean high water spring tide and mean low water spring tide levels). A wide foreshore is required to dissipate wave energy and a wide backshore is required to provide sufficient accommodation space above the level of normal spring and summer wave run-up to allow strandline vegetation to establish and trap sand blown by the wind from areas of the backshore and upper foreshore. Embryo dunes may be partially or wholly eroded away by winter storms and then rebuilt during subsequent less -stormy periods. Rebuilding of the upper beach, widening of the backshore and re-establishment of pioneer vegetation requires 'constructive' low steepness waves to move sediment from nearshore subtidal areas onto the upper beach. If this does not occur the sediment budget of the beach will become progressively negative and the average position of the high water mark will move landward; in such circumstances a sufficiently wide backshore cannot be maintained to allow formation of embryo dunes (sometimes referred to as 'incipient foredunes' (Hesp, 2002, 2008).

Where the annual net beach sediment budget is positive (i.e. there is a net gain of sand over time) embryo dunes can progressively grow in size and evolve into established foredunes, while a new belt of embryo dunes will periodically develop in front of the newly established foredune ridge. Areas of positive beach and foredune sediment budget occur where there is a large supply of sand either from offshore or alongshore by littoral drift. This is seen at the northern end of Traeth Penrhos where there is a wide sandy beach supplied with sand both from offshore and alongshore from the eroding section of dunes at the southern end.

Even on beaches with low rates of alongshore drift, longshore variations in the width of the backshore are often evident due to differences in the height and proximity of nearshore bars, often linked to local sediment circulation cells. Areas of wide backshore are often found behind prominent nearshore bars which reduce wave energy at the shoreline, and/or in areas of local sediment transport convergence. An example of recent embryo dune and foredune accretion on such an upper beach salient at Pendine is shown in Figure 21.

Figure 21. Satellite image of part of the central-eastern frontage of the Pendine dune system, Carmarthenshire, showing embryo dune and new foredune ridge development on a backshore salient (image dated 19 July 2021: Source Google Earth)

H2120 Shifting dunes along the shoreline

This habitat type can occur in several situations including:

- Areas of / intertidal supratidal sand accumulation and shoreline progradation where rates of sand transfer from the beach into the dune system are high; i.e. where both the beach sediment budget and frontal dune sediment budget are positive. This requires sustained supply of sediment to the upper beach by marine processes, exposure to relatively high onshore wind energy, and presence of a discontinuous cover of vegetation which may be natural or induced by visitor pressure. The capacity of species such as sea lyme (*Leymus arenarius*) and marram (*Ammophila arenaria*) to grow rapidly through accreting windblown sand allows the development of foredune ridges which may be almost continuous or, in areas of stronger winds and/or significant trampling pressure, dissected with more hummocky topography. There are relatively few examples of this in Wales since areas with high rates of sand supply to the upper shore are few and, where they do occur, usually at the distal end of longshore sediment transport cells, the newly accreted windblown sand is rapidly vegetated unless subject to heavy visitor pressure. However, an example from the Welsh coast near Burry Port is shown in Figure 22.

Figure 22. The eastern part of the Pembrey – Burry Port dune system, Carmarthenshire, showing development of shifting dunes along the shoreline (H2120) and fixed dunes (H2130) behind (Google Earth satellite imagery dated June 2023)

- Areas of shoreline recession where the beach sediment budget is negative but the frontal dune sediment budget is strongly positive, allowing aeolian sand in the form of mobile dunes or sand sheets to move inland, usually through gaps in the frontal dune ridges. There are many examples of this situation in the United Kingdom, including Morfa Dyffryn (Figure 23). Most of the Morfa Dyffryn frontage is backed by a relatively high foredune ridge which is gradually moving landwards in response to beach erosion and recession of the high water mark, but at the northern end near Mochras (Shell Island) where there is very high visitor pressure several significant gaps in the ridge have developed. These have funnelled the flow of wind and sand into the dune interior, leading to the creation of large mobile dunes.

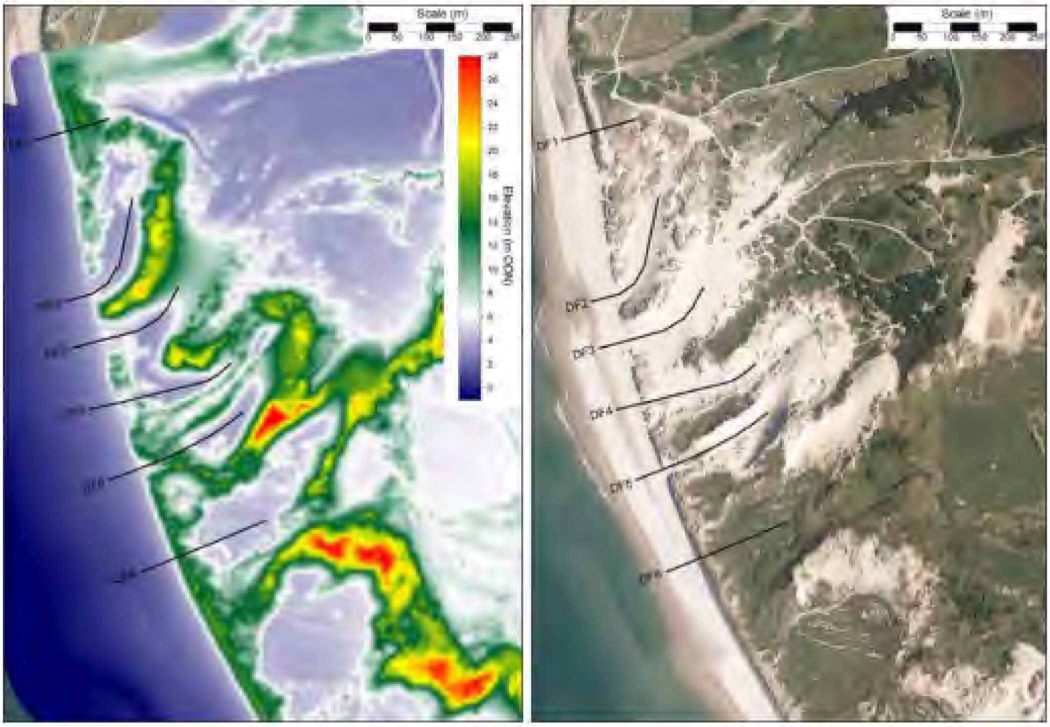

Figure 23. LiDAR DTM of the northern part of Morfa Dyffryn flown 06/01/2020 (left, source: SoLIFE project data) and (right) aerial photography of the northern part of Morfa Dyffryn, flown 2014 (source: NRW). Profile lines refer to KPAL coastal monitoring locations)

2130 Fixed coastal dunes with herbaceous vegetation ("Grey Dunes")

This habitat type is most commonly found in the more inland parts of dune systems and represents older dune morphological units which have been stabilised by vegetation for several decades or centuries but where natural plant succession towards scrubland and woodland have been halted by land-use practices such as grazing or the presence of large rabbit populations. In recent decades where rabbit populations have been decimated by disease (myxomatosis and Rabbit Haemorrhagic Disease (RHD)), or where there has been a reduction or cessation of grazing there has often been a tendency for the development of rank grassland and scrub, associated with a loss of floristic and faunal diversity. Without extensive rabbit grazing or human intervention this habitat type would be restricted to a relatively narrow zone behind the frontal dunes and would be mostly transient. On stable or prograding shores fixed dune grassland at a given location is naturally replaced by mixed native scrubland and native broadleaved woodland communities, while new fixed dune grassland may develop on areas of mobile and semi-mobile frontal dune as the shore moves seawards (e.g. Figure 23). As the distance from the shore increases the input of windblown sand 'rain' and associated marine source nutrients is reduced. Soil forming processes also result in progressive leaching of nutrients and calcium carbonate, lowering the pH (Maun, 2009). Under these conditions shore-related species such as marram (*Ammophila arenaria*) lose their vigour and may be replaced by other grass species and / or algal / bryophyte 'crusts'.

On eroding shores the more seaward areas of fixed dune grassland (and sometimes dune heath) may be replaced by semi-mobile H2120 communities if sufficient wind and sand is available. If little new sand is available from the beach but there is sufficient wind, blowouts and deflation corridors may develop in the H2130 communities closer to the shore, and mobile parabolic dunes may develop and progressively move inland, ‘rejuvenating’ both the morphology and the vegetation communities. Potentially, other forms of disturbance (fire, vegetation disease, digging by animals) may lead to the development of blowouts at some distance from the shore. The survival time of such features will depend on a number of factors including weather variations on annual to decadal timescales, position within the landscape (especially in relation to wind exposure), and whether the initial causes of disturbance are maintained).

Input of nutrients associated with sand deposited from suspension (‘sand rain’) requires winds of sufficient strength and frequency and a source of fine sand which can either be from a high, wide dry sand beach or aeolian re-working of relatively young, un-leached dunes closer to the shore. Beaches with slightly positive or neutral beach sediment budget favour the former mode of nutrient input, while the second mode is favoured by a negative beach sediment budget and either positive or negative frontal dune sediment budget. The spatial extent over which airborne sand ‘rain’ and spray deposition occurs is dependent on wind strength and the morphology of the frontal dunes. Input of nutrients associated with input of ‘fresh’ sand can also occur through the processes of saltation, modified saltation and creep. Transfer inland by these mechanisms is favoured where gaps (natural or otherwise) exist in the frontal dune ridge and transgressive sand lobes are able to form in the area behind.

5. Length scales for full transition from supratidal beach to fixed dune

5.1 Embryonic shifting dunes (H2110)

The width of beach required to allow embryo dunes and established foredunes to form varies from location to location, depending on tidal range, wave energy at the shoreline and beach sediment size distribution (Saye et al., 2005). In general, beaches or sections of beach exposed to long-wavelength, low-steepness waves which break a considerable distance seaward of the high water mark (classified as dissipative beaches in the terminology of Short & Hesp, 1982) have a wide foreshore and a wide backshore composed of relatively fine sand which provides accommodation space for the formation of incipient foredunes. By contrast, sections of beach which experience a wave regime dominated by shorter wavelength, steeper waves tend to lose sediment and are both steeper and coarser grained, providing a narrower backshore which may not provide sufficient space for embryo dunes to develop (reflective beaches in the terminology of Short & Hesp).

As noted earlier in this report, on Traeth Penrhos at the present day there is an alongshore gradient in wave conditions with higher, steeper waves impacting the southern part of the shore following refraction around Ynys Llanddwyn, and a progressive more dissipative regime with longer period, less steep waves towards the Cefni estuary. Consequently, there is little or no potential to develop incipient foredunes along the southern two thirds of the beach. Even at the northern end, a succession of storms experienced since the 2013-14 winter have led to beach steepening and narrowing of the backshore and erosion of the incipient foredunes formed in the preceding two decades. **As a general rule, a supratidal (backshore) width of at least 50 m is required to allow the development of drift line communities and embryo dunes.**

5.2 Shifting dunes along the shoreline (H2120)

The width of a zone of shifting dunes along the shoreline depends upon a number of factors including the degree of wind energy, rate of sand supply to the frontal dune system, the density of vegetation and degree of disturbance due to trampling, grazing and other agencies. Numerous field and laboratory wind-tunnel investigations of wind flow and aeolian sand transport across foredunes have been undertaken (e.g. Arens, 1996; Arens et al., 2005; Hesp et al., 2005), and in the past two decades numerical and computational fluid dynamics (CFD) modelling has also been widely used to assess the relative effects of variations in foredune morphology, including human interventions (e.g. Hesp & Smyth, 202; Nguyen et al, 2021; Smyth et al., 2023).

When airflow approaches a foredune ridge with smooth, sinusoidal-like cross-sectional geometry, a slight reduction in near-surface wind speed is commonly observed at the dune foot, leading to sand deposition which forms a concave-upwards ramp. The wind is then accelerated up the windward slope with maximum 'speed-up' usually located just seaward of the crest where streamlines are forced closely together. On the lee side of the crest the streamlines diverge and there is generally a lowering of the near-surface wind velocity (e.g. Arens et al, 1995). The exact degree and pattern of wind speed variation is in part governed by the density and height of surface vegetation. However, on foredunes which have a steep (scarped) seaward face due to wave erosion and sand slumping, or which have a marked slip-face on their seaward side, flow separation usually occurs at or near the crest. This creates a 'dead zone' of very low wind velocity in the lee of the dune where a weak reverse eddy may also form. In extreme cases of very high wind speeds over bare-crested dune ridges a zone of very high winds speeds (a 'low-level jet') may form near the surface (Hesp & Smyth, 2021).

Finer sand blown over the crest of the dune loses contact with the surface and may be transported downwind in short-term suspension before it gradually falls to the surface as 'sand rain'. The coarser sand particles are deposited closer to the crest and/or on the top of the slip face if one is present. Deposition at the top of the slope eventually causes instability which initiates the formation of avalanche 'tongues' which may propagate to the base of the slip face. The distance over which sand rain is deposited is dependent on the height of the foredune crest, wind speed and degree of turbulence, sand size and the nature of the topography and vegetation behind the crest. In extreme cases with very high, bare dune crests significant amounts of sand may be deposited from short-term suspension over a kilometre landward of the crest, for example at Skagen in northern Denmark (Saye et al., 2006), but a few tens of metres to about 200 m is more typical in the UK. The rate of sand rain deposition declines exponentially with distance from the dune crest. In most situations the rate of sand deposition is only a few millimetres per year 10 m downwind of the crest and reduces to less than 1 mm/year at a distance of c.100 m. Most dune plant species are able to grow through sand deposited at such rates.

On eroding shores where the beach sediment budget is negative, as along the southern two thirds of Traeth Penrhos, foredunes tend to have a steep, scarped seaward slope which is periodically activated during high storm tides. Depending on the nature of the beach, including seasonal variation in the height and width of the backshore, and on the directional variability of the wind regime, foredunes in such situations can either roll back, sometimes gaining or losing height and volume as they do so (Pye, 1990). Field observations and modelling have shown that where the wind approaches the foredune front at an oblique angle the direction of wind and sand transport is deflected along the dune front and relatively less is transported up the stoss slope, over the crest and into the lee zone behind (e.g. Arens, 1996; Hesp et al., 2005; Hesp & Smyth, 2021).

At present shifting dunes along the shoreline (H2120) in England and Wales mainly occur on eroding sections of coast where sand from existing older dunes is being ‘cannibalised’ and moved inland by the wind. At Freshfield, north Merseyside, for example, the dune-backed shore has been eroding for over a century. Mobile dunes and sand sheets are moving inland as the coast erodes. Sand for the mobile dunes is derived both from the beach and from in situ reworking of older dunes (Pye & Blott, 2010). Inland movement of the dunes is impeded in places by coniferous woodland planted in the 1930s, by a caravan park which has previously been relocated inland from a site now lost to the sea, and by the approach track to it. The width of the mobile sand belt presently ranges up to 250 m with active sand lobes moving into the pine plantations behind (Figure 24).

In general, in the UK, a zone at least 50 m wide, and preferably over 100m is required to allow shifting dunes and mobile sand lobes to develop in an unimpeded manner.

Figure 24. Example of mobile dunes advancing up to 250 m inland into the pine forest north of Victoria Road, Freshfield. Base aerial imagery dated 22/04/2022 (source: Google Earth)

5.3 Fixed coastal dunes (H2130)

Virtually all significant Welsh and wider UK dune systems contain fixed dunes with herbaceous vegetation, although the extent and ecological 'quality' vary greatly depending on past and present land-use. The width of this habitat in a shoreward direction varies from a few tens of metres to more than 2 km, depending on location. **However, a minimum width of 400m to 500 m, as seen at Burry Port (Figure 22), should be regarded as the minimum required for favourable conservation status.**

6. Planting of conifers on fixed dunes

Planting of conifers (and less commonly deciduous tree species) has been undertaken for centuries in order to stabilise shifting sands and at the same time provide a useful timber resource. Early large-scale examples include the Landes area of Gascony starting with the work of the Dutch Engineer Nicholas-Theodore Bremontier in the late 1790s and early 1800s (Bremontier, 1833; Ford, 2023). In the 19th century several private landowners in the United Kingdom also used tree planting (mainly pines) to stabilise dunes on their estates, one of the best known being the Earl of Leicester at Holkham (Clarke & Rendell, 2005). The terms of reference of the Royal Commission on Coastal Erosion, established in 1906, were widened to include Afforestation in 1908. It was noted that Great Britain and Ireland had a much smaller proportion of forested land (c. 5%) than any other European country, but a major driver at that time was to explore opportunities for employment. The Second Report of the Commission (RCCEA, 1909) recommended that a body of Forestry

Commissioners should be established to investigate the opportunities and to manage a programme of land acquisition and forestry development. There was little immediate progress and it was not until the outbreak of the First World War, when it became apparent that Britain could not rely on timber imports to satisfy increased demand, that significant steps were taken. A Committee was set up by Prime Minister Herbert Asquith in July 1916, under Francis Acland MP, to examine ways of developing domestic forestry resources. The Committee's final report in 1918 recommended the creation of a "Forest Authority equipped with funds and powers to survey, purchase, lease and plant land and generally to administer the areas acquired, with compulsory powers to be exercised, when needed, after due enquiry and the award of fair compensation". An interim Forest Authority was set up in 1918 and followed by creation of the Forestry Commission in 1919 (Brown, 1919). At this time sand dune areas were widely regarded as unproductive 'wastes ripe for reclamation' by many engineers and ecologists (e.g. Carey & Oliver, 1918; Case, 1922). Extensive areas of sand dunes were purchased and planted from the early 1920s onwards at sites such as Culbin and Tentsmuir in Scotland. By 1929 about 284,000 ha of forest was under direct management, and more than 55,000 had been planted. A further 21,850 ha had been planted by private landowners aided by grants from the Forestry Commission. The Second World War brought further high demand for timber, and following the end of the War the Forestry Commission engaged in further land acquisition, including at Newborough.

6.1 Wind interaction with the forest edge

There has been considerable investigation of the general inter-relationships between wind and wooded areas, driven partly by requirements to design shelterbelts to protect crops and partly by the need to limit damage to commercial forestry plantations (e.g. Fons, 1940; Plate, 1971; Gross, 1992; Talkkari et al., 2000). However, very few studies relating specifically to wind flow and sand transport at the margins between coastal forestry plantations and sand dune systems have been published. Choi et al. (2013) reported that the presence of pine forest on dunes in Korea significantly reduced the wind velocity on dunes in front of the forest and that dune recovery following storms was slower than on unforested comparison sites. To date, however, no detailed similar studies have been conducted in the UK.

Figure 25 presents a schematic cross-section showing the relationship between the artificial (inner) and partly artificial (outer) ridges and the forest margin in the central area of Tywni Penrhos. Simple field observations with a hand-held anemometer have shown that wind speed-up occurs over the frontal dune ridge and that there is a zone of flow separation and low wind-velocity in the lee of the frontal ridge, consistent with more detailed investigations elsewhere. Near-surface wind speeds drop off rapidly inside the forest boundary and the presence of the trees prevents reattachment of the wind streamlines downwind of the dune, limiting the potential for surface sand entrainment in the tree-covered area.

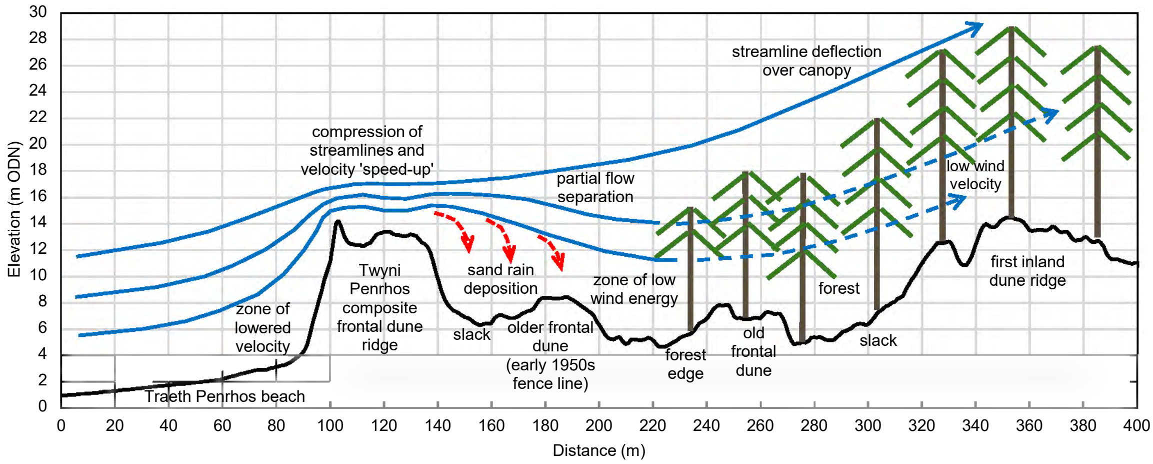

Figure 25. Schematic of wind streamlines over the Twyni Penrhos frontal dunes and forest

Tree-covered areas, like any form of surface roughness, increase the drag on the wind and cause a reduction in near-surface velocities. The nature and magnitude of the effect is dependent on a number of factors including the height and girth of individual trees, the density of trees and the spatial arrangement of their trunks, the thickness and density of the canopy, and the nature of the topography / slopes on which the trees are located.

6.2 Clearance of conifers on fixed dunes

Clear-felling of pine woodland plantations has been undertaken for nature conservation reasons at a number of UK sites since the 1990s. 1990s clear-felling at Ainsdale National Nature Reserve in Merseyside (>800 m, Figure 26), at Whiteford Burrows since the 1990s (200 – 390 m, Figure 27), and at Morfa Harlech since 2014 (570 – 600 m, Figure 28).

Figure 26. Distance between the dune toe and the edge of forest at present. Base satellite imagery flown 04/07/2023

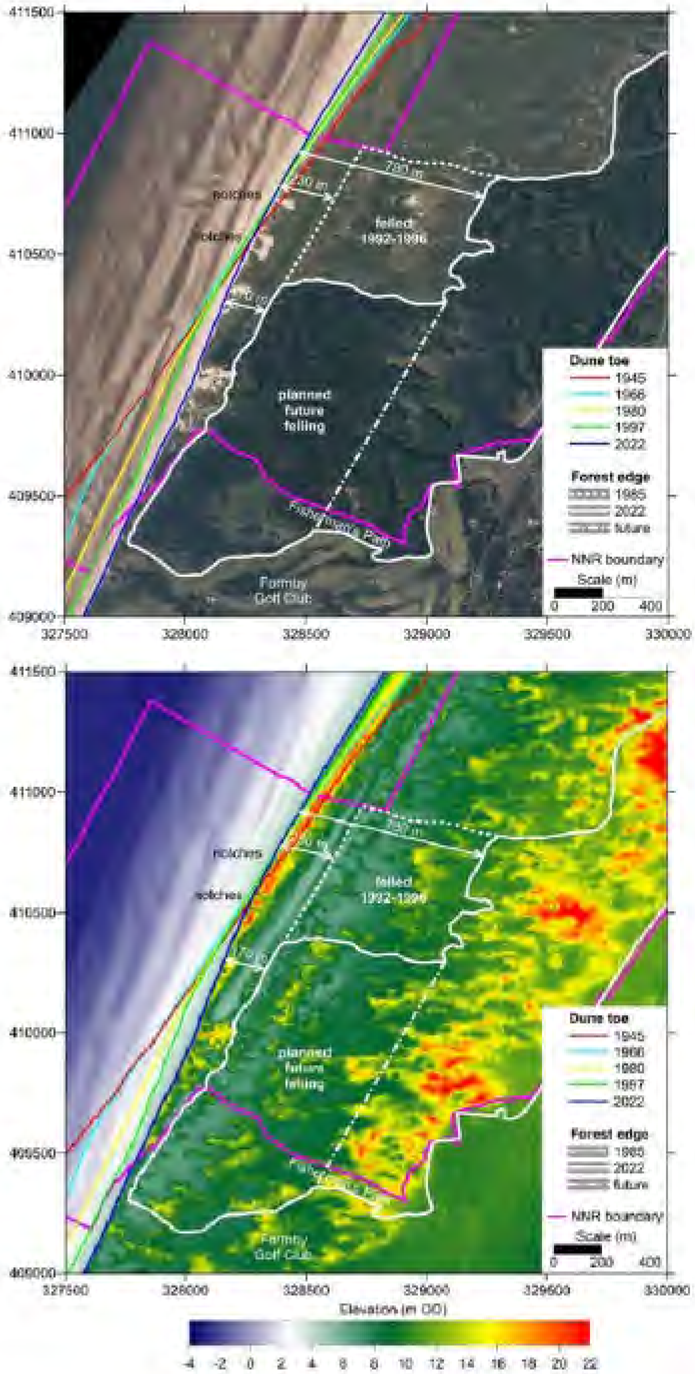

Figure 27. Google Earth satellite image dated 10/08/2022 (top) and airborne LiDAR DTM (bottom) of part of the Ainsdale Sand Dunes National Nature Reserve where clear felling of conifers was undertaken in the 1990s and where further felling is currently proposed. The frontal dune ridges in front of the clear-felled area were created using fencing on the upper beach during a period of coastal progradation in the early 20th century. The southern part of the frontage is eroding and the dunes between the sea and remaining conifer plantations are being squeezed

Figure 28. Google Earth satellite imagery of Whiteford Burrows dated 19/06/2023 showing changes in the position of the forest edge due to thinning and clear-felling in 2022 as part of the SoLIFE project

Prior to 2013 the seaward edge of the eastern part of Newborough Forest extended as far as the dune edge on both sides of the main Traeth Llanddwyn car park. A zone of foredunes up to 30 m wide had formed in front of the forest edge between the 1990s and c. 2007. These dunes were partly eroded between 2007 and 2013 and the remains completely removed in the stormy winter of 2013-14. Further erosion of the higher dune platform behind was caused by winter storms in the period 2014-2021. By 2013 the erosion had reached the forest edge and trees were falling into the sea. In a zone up to 180 m wide behind the dune edge trees were either dead or dying, some having been snapped or thrown from the roots by the wind. A report commissioned by Welsh Government (Pye & Blott, 2013) proposed that the area seaward of the coastal access track should be clear-felled and parts of the area de-stumped and cleared of litter. It was also proposed that three notches should be created in the frontal dunes within this area (denoted as Phase 2 East) in order to assist the movement of sand from the beach into the hind-dunes. Works were carried out in 2014 and 2015. Coincidentally, a series of severe storms in the winter of 2013-14 removed much of the sand from the fronting beach and cut back the dune cliff. Further dune cliff recession occurred as a result of further storms in the period winter 2014/15 to winter 2020/21, although since the summer of 2021 there has been some upper beach recovery. The combined effects of clear-felling, de-stumping, litter removal, stormy conditions and visitor trampling pressure have led to a significant increase in surface sand mobility and active sand lobes have now crossed the coastal access track and entered the remaining forest edge (where the outermost tress show evidence of wind and salt scalding, needle loss and branch snapping). The linear distance between the dune edge and the forest edge ranges between 35 m and 135 m (Figure 29). The degree of surface mobility and extent of sand incursion beyond the forest edge shows a clear association with the rejuvenation methods employed, greatest mobility and greatest inland sand movement being associated with felling, de-stumping and litter removal in areas behind and on either side of notches in the frontal dunes (Pye & Blott, 2020b). **Incursion of sand lobes into the forest, especially evident at the western end of this area since 2023, suggest that the zone of tree clearance is not yet sufficiently wide to allow a full sequence of semi-mobile and fixed (grassed) dunes to develop**.

Figure 29. Example of clear-felling and sand mobilisation east of the main Llanddwyn beach car park (Phase 2 East area), with indicative distances from the dune toe to the edge of the remaining forest. Three notches were artificially created in the eastern half of the frontal dunes in 2014, the central one having been used to provide vehicle access to the beach. Much of the felled area was de-stumped and the litter layer removed. Between 2014 and 2021 the dune frontage experienced significant marine erosion, especially at the western end, and several smaller notches formed spontaneously at points where paths reach the beach. Since 2014 mobile sand has extended into the edge of the remaining forest behind. Base satellite imagery flown 04/07/2023.

7. Significance of future climate change, Shoreline Management Plan policy and past interventions for future management options

7.1 Recent and projected future sea level rise

Any evaluation of management options to deliver sustainable transitional habitats needs to take into account potential future changes in shoreline position and driving factors such as climate and sea level change. Tide gauge records and satellite altimetry data provide clear evidence of an increase in the rate of mean sea level (MSL) rise around the UK coast since c.1990. For most of the 20th century the rate of MSL rise was 1 – 2 mm/ yr. Linear regression analysis of the Holyhead tide gauge record for the period 1964-2018 indicated an average rate of increase in MSL of 2.3 mm/yr (Pye & Blott, 2020a). However, satellite altimetry data suggest that MSL in the NE Atlantic region is now increasing at a rate of >3 mm /yr and further acceleration is projected further by UKCP modelling (Lowe et al., 2018; Figure 30). Increases in extreme water levels are also projected (Table 4), increasing the likelihood of coastal flooding and storm-induced erosion (Table 4).

An assessment of the likely implications of sea level rise by Pye & Saye (2005) and Saye & Pye (2007) concluded that, even if the rate of MSL rise continues at historical rates, the dunes along the southern part of Traeth Penrhos and the northern part of Traeth Llanddwyn would be likely to experience further beach and frontal dune erosion, while there would be further vertical accretion of dunes and some lateral progradation at the northern end of Traeth Penrhos and along Braich Abermenai. However, they noted that the nature of further shoreline change will be heavily dependent on possible variations in storminess and on the exchange of sediment between the offshore banks (the Malltraeth and Menai Straits ebb tidal deltas) and the shore. It was considered unlikely that sea level rise will have a significant impact before 2035 but will become increasingly important in driving shoreline erosion in the medium (20 - 50 years) and longer term (50 - 100 years). A simple landward displacement of the shoreline in this area, with transfer of eroded frontal dune sand to the nearshore sea bed as suggested by a simple Bruun-type model (Bruun, 1962), is highly unlikely given the relatively high wind exposure and importance of alongshore sediment transport along Traeth Penrhos. A more likely response to sea level rise is a combination of offshore, alongshore and onshore transfer of sand by aeolian processes as envisaged in the model proposed by Davidson-Arnott (2005). However, in the absence of intervention, with a fixed forest edge a short distance behind the landward moving frontal dune ridge the intervening area of semi-mobile and fixed dune grassland will gradually become narrower, a process referred to by Doody (2013) as “sand dune squeeze”.

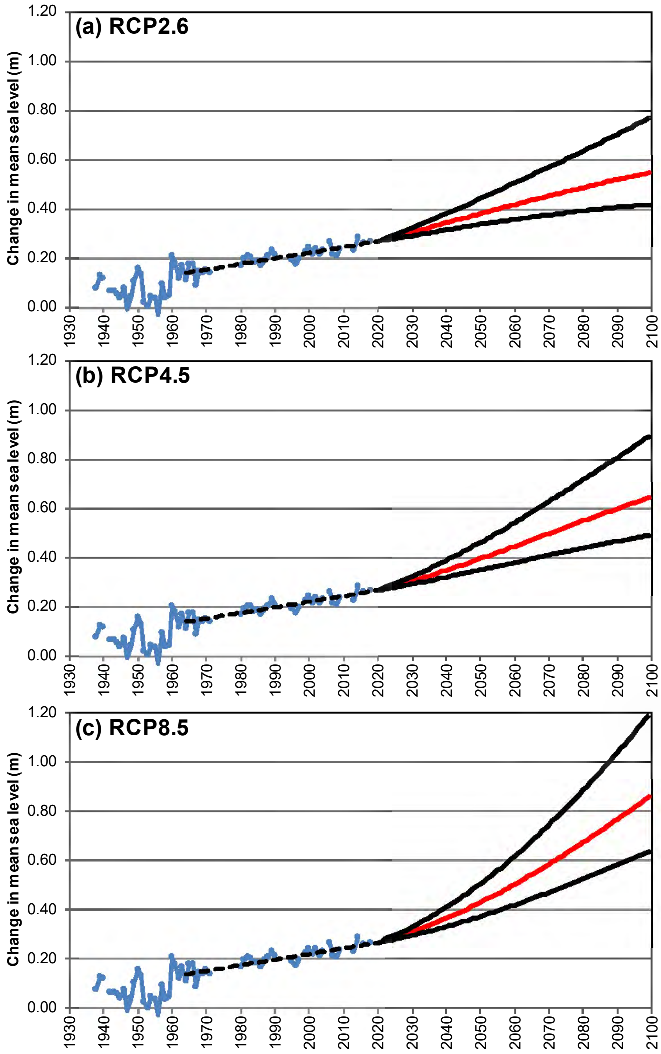

Figure 30. Projections of sea level rise by UKCP18, under three scenarios (RCP2.6, RCP4.5 and RPC8.5), showing the central estimate (50th percentile, red line) and the upper and lower estimates (5th and 95th percentiles of the model outputs, black lines). Also shown are the historical mean sea levels recorded at Holyhead during the period 1938-2018 (from PSMSL), and the 1964-2018 linear regression line (black dashed line, rising at 2.3 mm/year). Source: Pye & Blott, (2020a)

Table 4. The levels of Mean High Water Springs (MHWS), Highest Astronomical Tide (HAT) and extreme high water levels at Traeth Penrhos, taken from the Environment Agency Coastal Boundary Study 2018 Update (McMillan et al., 2019), using a base year of 2017. Also, projections of the same levels in the years 2050 and 2100 taken from the UKCP user interface, based on a 'medium' emissions (RCP4.5 50th percentile) and 'extreme' emissions (RCP8.5 95th percentile) scenarios

Level	2017	2050	2050	2100	2100
		RCP4.5 50%	RCP8.5 95%	RCP4.5 50%	RCP8.5 95%
MHWS	2.13	nd	nd	nd	nd
HAT	2.72	2.85	2.91	3.09	3.40
1 in 1 year extreme	2.84	2.98	3.04	3.23	3.55
1 in 50 year extreme	3.32	3.46	3.53	3.71	4.03
1 in 200 year extreme	3.50	3.64	3.71	3.89	4.21
1 in 10,000 year extreme	4.12	4.26	4.33	4.51	4.83

In addition to changes to mean sea level and extreme water levels, consideration also needs to be given to potential future changes in wave climate and storm frequency and magnitude. Current UKCP modelling projections regarding future wave climate are subject to a high degree of uncertainty, since much will depend on possible changes in storm tracks and the rate at which low pressure systems cross the UK. However, it is evident from meteorological records that significant changes in wind speed and wind direction have affected the Welsh Coast over the course of the past century, even before the impact of man-made climate change became apparent (e.g. Pye & Blott, 2017). The past 30 years has seen an increase in the frequency and duration of winds from the south-southwest and west at Newborough which is likely to have resulted in increased wave refraction and northward alongshore sediment drift on Traeth Penrhos. An increase in the frequency of significant storms has also resulted in a tendency for increased erosion and slower rates of post-storm beach recovery. If current climate warming trends continue, the tendency for more frequent and intense southwesterly winds and waves is likely to be enhanced, with a likelihood of accelerated and more extensive dune erosion along the Twyni Penrhos frontage.

7.2 Shoreline Management Plan policy

The West of Wales Shoreline Management Plan 2 (SMP2, Royal Haskoning, 2012), developed primarily from the perspective of coastal erosion and flood risk management, identified a preferred coastal management policy for the Newborough Forest (Traeth Penrhos) Policy Unit of *No Active Intervention* in all three SMP2 epochs (0 - 20, 20 - 50 and 50 -100 years, relative to 2010). The SMP2 advises that no actions should be taken which would interfere with natural processes, and that removal of forest should be undertaken to create width for natural coastal adjustment. It also recognises that other management interventions may be required for the purposes of nature conservation and tourism management.

7.3 Previous dune rejuvenation interventions at Twyni Penrhos

In late 2014 a programme of work was started at the southern end of Traeth Penrhos to remove some of the dead and dying forest timber in order to create additional accommodation space for dunes and mobile sand lobes to move landward as the high water mark advances. Four relatively small notches were cut in the frontal dune ridge to encourage wind and sand flow from the beach into the hind-dune area (Pye & Blott, 2013, 2016). In early 2023 one of the notches (D) was deepened and widened to enhance this process which a comparison of airborne LiDAR digital elevation models shows has been relatively successful (Pye & Blott, 2020b; Figure 31).

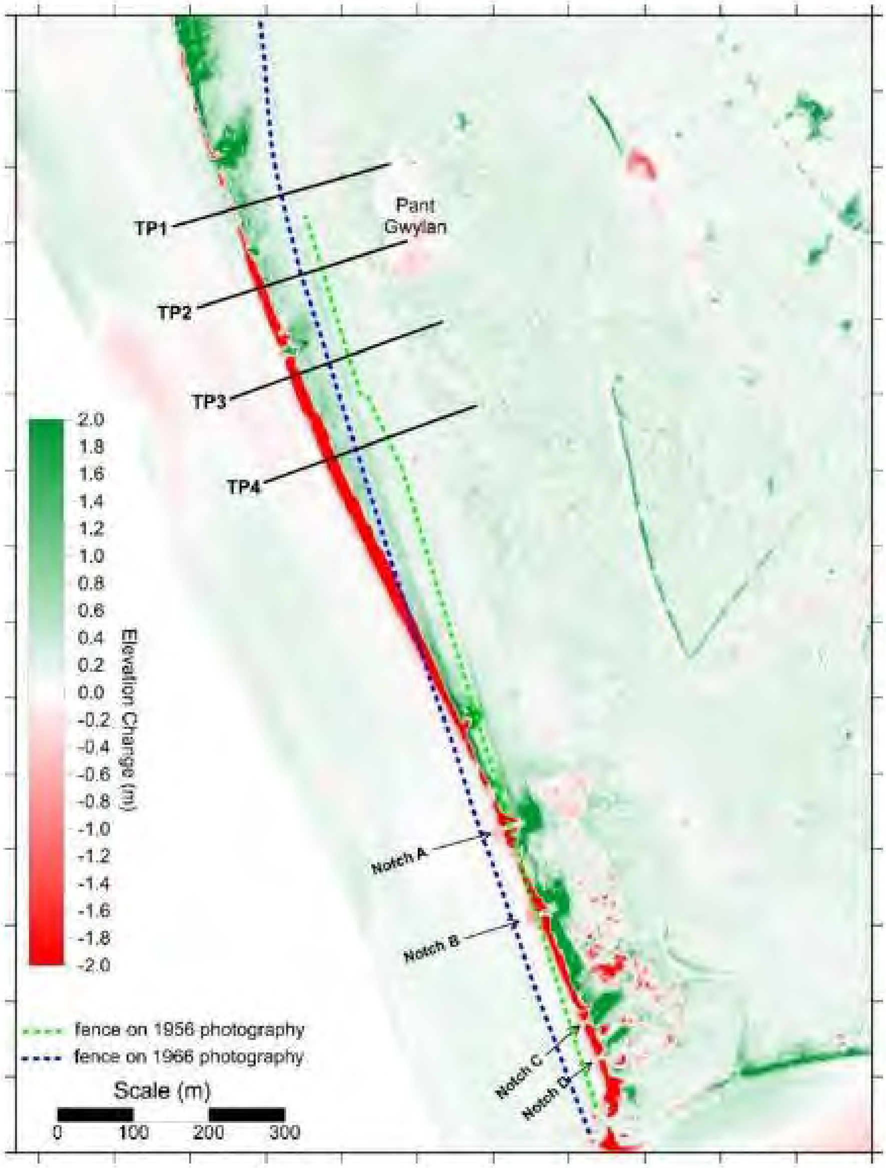

Figure 31. Change in elevation between LiDAR DTMs flown in 2014 and 2022. Source: Data Map Wales. Note the significant accretion of sand behind Notches A-D and behind the natural parabolic dunes near Pant Gwylan

In late summer and autumn of 2022 tree and scrub clearance work was extended northwards in the direction of Pant Gwylan as part of the Sands of LIFE project. The slack was cleared of vegetation and surrounding areas of bare sand created by localised tree felling, litter removal and turf stripping (Figure 32).

Figure 32. Photograph looking west across Pant Gwylan (photograph taken by K. Pye taken in mid-May 2024)

In 2023 further scrub removal and mowing was undertaken on the Twyni Penrhos composite ridge, and in the adjoining slack, to reduce the height of the vegetation and encourage sand rain deposition between the ridge and the forest edge. This has been successful in rejuvenating the dune grassland which contains a wide variety of annual flowering plants (Figure 33). However, the composite ridge still shows very limited surface sand mobility and acts to impede to inland movement of sand from the beach into the hind dune area.

Figure 33. Photograph looking north along Twyni Penrhos with Newborough Forest on the right and the eroding outer artificial ridge on the left (photograph taken by K. Pye taken in mid-May 2024)

The width of the zone between the dune toe and the forest edge, in which the development of semi-mobile dunes and bare sand lobes might take place, varies between c.100 m in the south and 160 m in the north (Figure 26).

8. Options for further management interventions to achieve a resilient set of transitional habitats at Twyni Penrhos

There are a number of future management options for Twyni Penrhos which would involve varying time and cost. Not all would deliver the identified conservation objectives for the whole site but selection of the most appropriate option needs to consider what is achievable given the nature of the operative physical processes, the likely pattern of future shoreline evolution, and the financial and labour resources which are likely to be available.

The principal intervention options can be summarised as follows:

Option A – No Active Intervention – Allow coastal erosion to continue along the central and southern part of the frontage, with erosion front continuing to move north over the medium and longer term; the outer dune ridge crest will continue to move backwards, gaining in height and increasing slightly its width landward, infilling the linear depression between the first and second ridges where such exists; eventually a combined ridge will over-run the slack area through which the Coastal Path passes, and ultimately the forest edge. The narrow zones of fixed dune grassland and semi-mobile dunes will be lost.

Option B - Deepen and/or widen existing blowouts and incipient parabolic dunes in the outer ridge crest. There are currently four minor blowouts / incipient parabolic dunes in the outer ridge around Pant Gwylan and a number of smaller ones to the north and south of this area; these could be enlarged by turf stripping of the margins and by shallow excavations of the crestal 'lips', the aim being to funnel and accelerate the wind and increase the extent of sand rain deposition. This would increase the extent of bare and mobile sand but would not address the issue of 'squeeze' affecting the semi-mobile and fixed dune grassland communities.

Option C – Create artificial notches similar to, or on a larger scale than, those created at the southern end of Twyni Penrhos. Over time this would be likely to create a mosaic of bare sand, semi-fixed and fixed dune habitats similar to that at the southern end of the system but would not create a 'classic' linear pattern of habitat zonation or address the issue of 'squeeze' of the fixed dune habitats.

Option D – Turf stripping and small-scale re-profiling of the crestal area along a large length of the frontal composite ridge (c. 1 km); this would accelerate the wind speed across the ridge crest, enhance flux of sand from the beach and dune stoss slope into the hind-dune area. This would increase the extent of bare sand and mobile / partly fixed dunes but would not address the issue of 'squeeze' affecting the fixed dune grassland habitats.

Option E – Large-scale beach nourishment to encourage a wide backshore suitable for the formation of an embryo dune buffer zone and to slow the rate of recession of the cliffed frontal dunes while at the same time encouraging higher rates of sand transport into the hind-dune area. This would be an expensive option and the most difficult to deliver since a cost-effective source of suitable sand would need to be found, and repeat nourishment would probably be required every 10 – 20 years depending on the scale of works undertaken.

Option F – Further felling of trees along the forest margin to increase the accommodation space available for the development of fixed dune grassland and semi-mobile dunes. In the short term further felling would need to be consistent with the 30 Year Vision of the draft Newborough Forest Resource Plan which identifies a series of zones within which different forest management approaches will be used. It is currently proposed that the outermost of these zones (A on Figure 31) will ultimately be managed as open habitat, with a phased programme of tree felling and clearance. Up to 10 ha of tree clearance is envisaged in the next 10 years, although exact areas, timescales and methods (clear-felling, mosaic felling, block and corridor felling and/ or thinning) have not yet been prescribed.

Option G – Further tree felling amounting to 10 ha undertaken as proposed in Option F, but with felling concentrated around Pant Gwylan in order to give a maximum accommodation space width for fixed and semi-mobile dune communities of up to 300 m. This would be combined with turf stripping and limited ridge crest reprofiling as proposed in Option D, and as shown in Figure 32.

Option H – Up to 10 ha of tree felling but with felling to a more restricted depth around Pant Gwylan but extending further south to include the area where ‘squeeze’ of SD7 and SD8 is most serious. This would again be combined with Option D, turf stripping and limited reprofiling of the outer dune ridge to increase sand flux into the hind-dune area (Figures 33, 34 & 35).

Option I – up to 52 ha of tree felling to create sufficient space for the full range of dune habitats (H2110, H2120 H2130 to develop and adapt by landward movement in response to climate change / sea level rise and associated shoreline response (Figures 36 & 37). Again, this would be combined with the turf stripping and crest re-profiling in Option D.

Figure 34. Forest management areas proposed in the draft Newborough Forest Resource Plan – the long-term (30 year) vision: A = open habitat management; B = successional woodland; C = native woodland management; D = standard forest management. Base satellite imagery flown 04/07/2023. Source: NRW https://ymgynghori.cyfoethnaturiol.cymru/forest-planning-cynllunio-coedwig/newborough-forest-resource-plan/

Figure 35. Option G: area of reprofiling (white solid line) and deposition (white dashed line) of sand along the frontal dune, with 10 ha of clear felling behind in the zone identified for "Open Habitat Management" (A) in the 30 year vision Forest Plan (dash-dot-dash white line). Other Forest Management 30 year vision areas are B (successional woodland) and C (native woodland management). Also shown are the lines of fences shown on historical aerial photographs: Fence Line 1 (green dashed line, shown on aerial photographs flown 02/02/1956); Fence Line 2 (blue dashed line, shown on aerial photographs flown 31/05/1960 and 07/06/1966). Base Google Earth satellite imagery flown 04/07/2023.

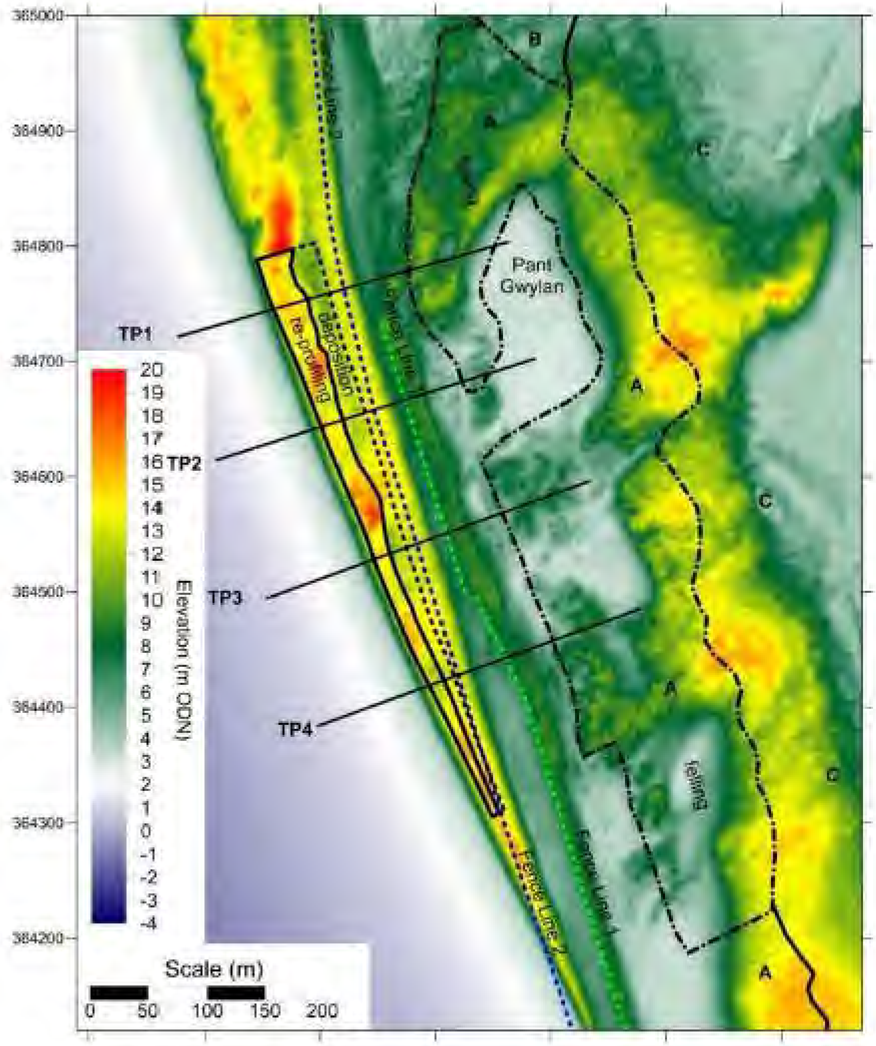

Figure 36. Option G: area of reprofiling (black solid line) and deposition (white dashed line) of sand along the frontal dune, with 10 ha of clear felling behind in the zone identified for "Open Habitat Management" (A) in the 30 year vision Forest Plan (dash-dot-dash white line). Other Forest Management 30 year vision areas are B (successional woodland) and C (native woodland management). Also shown are the lines of fences shown on historical aerial photographs: Fence Line 1 (green dashed line, shown on aerial photographs flown 02/02/1956); Fence Line 2 (blue dashed line, shown on aerial photographs flown 31/05/1960 and 07/06/1966). Base LiDAR DTM flown 2022 (source: Data Map Wales).

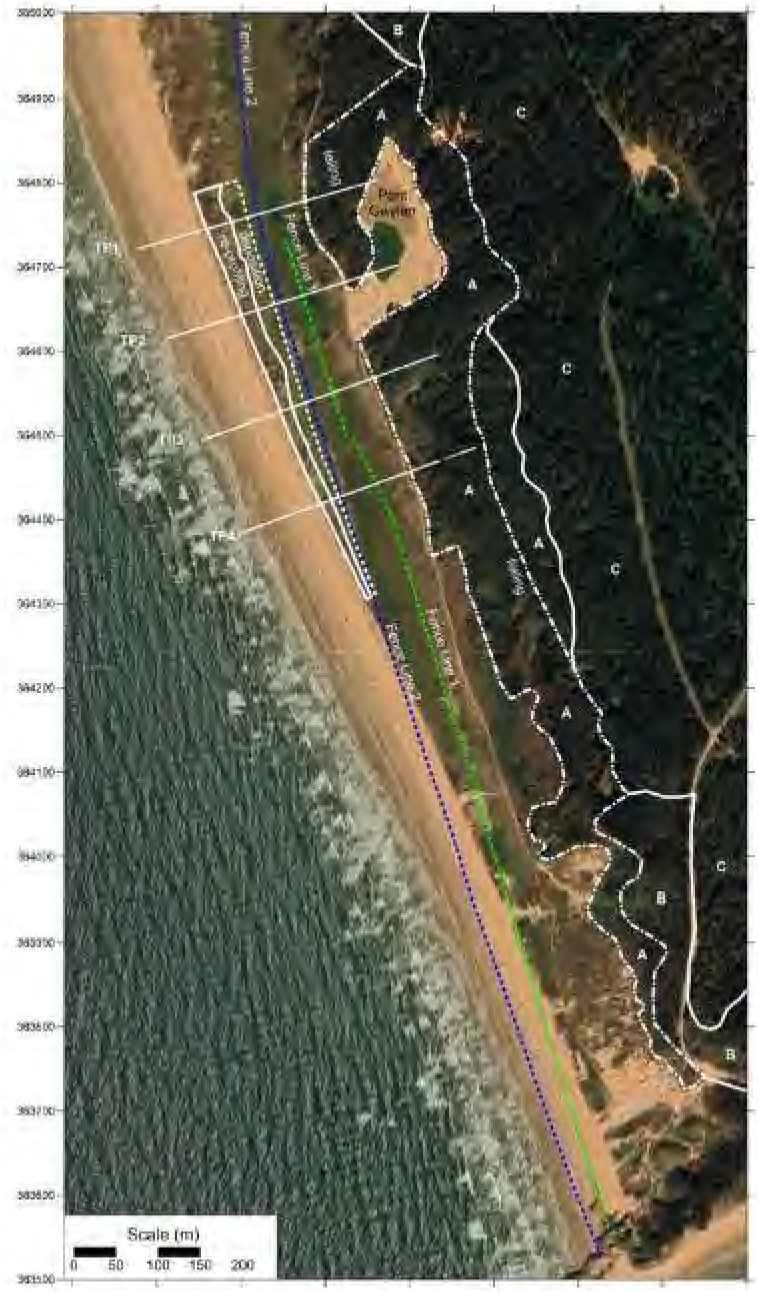

Figure 37. Option H, prioritising felling of a 10 ha area of the trees closest to the frontal dune to reduce "sand dune squeeze".

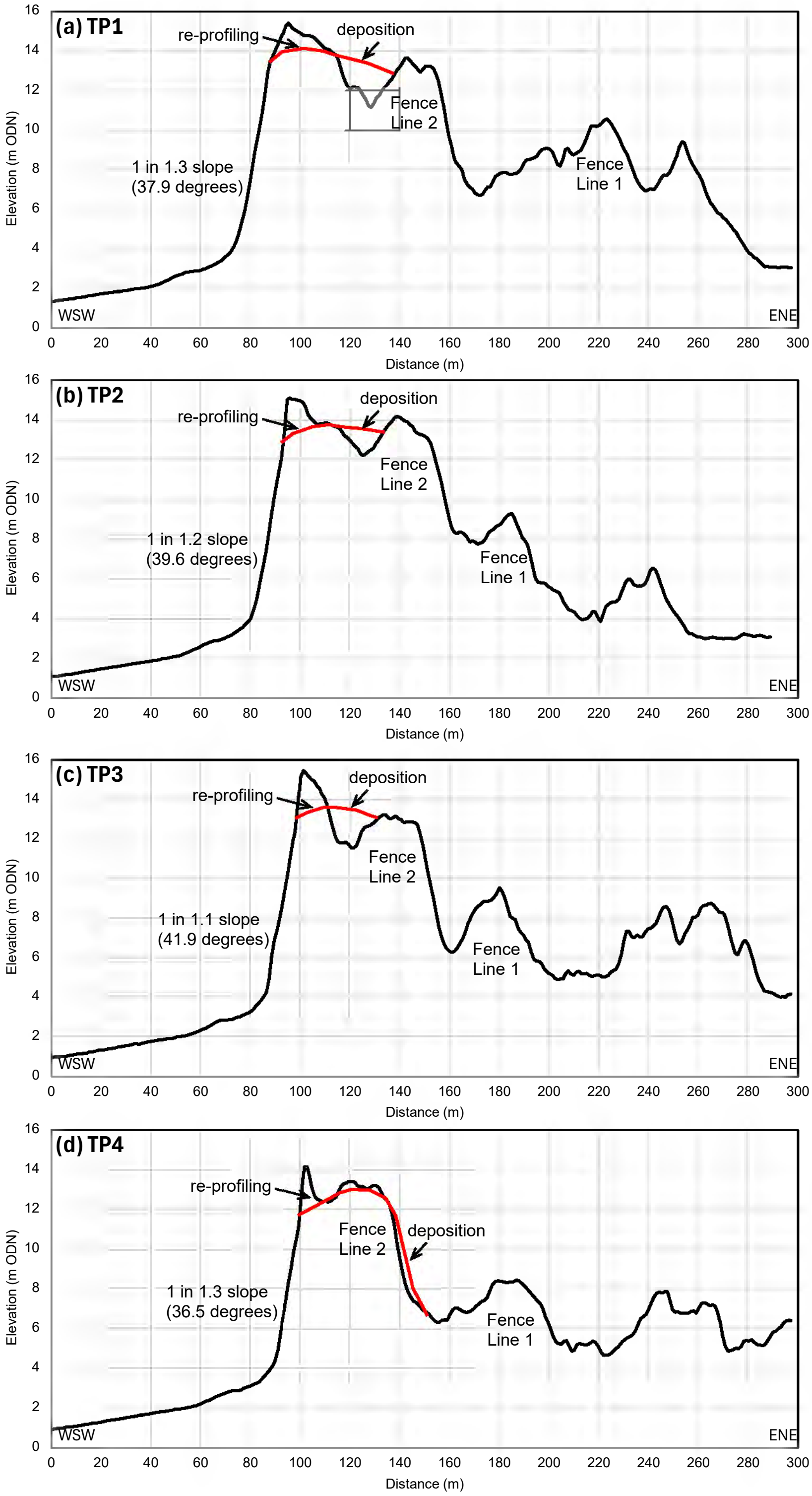

Figure 38. Profiles TP1 to TP4 showing suggested reprofiling option D which might be undertaken in association with further tree felling under Options G and H. Fence Line 1 relates to the position of the fence on aerial photographs flown 02/02/1956; Fence Line 2 relates to the position of the fence on aerial photographs flown 31/05/1960 and 07/06/1966. The red line indicates locations of suggested reprofiling and deposition of sand

Figure 39. Suggested area of tree felling as part of Option I (area outlined with white lines, total area of 52.9 ha). Base satellite imagery flown 04/07/2023. Source: NRW.

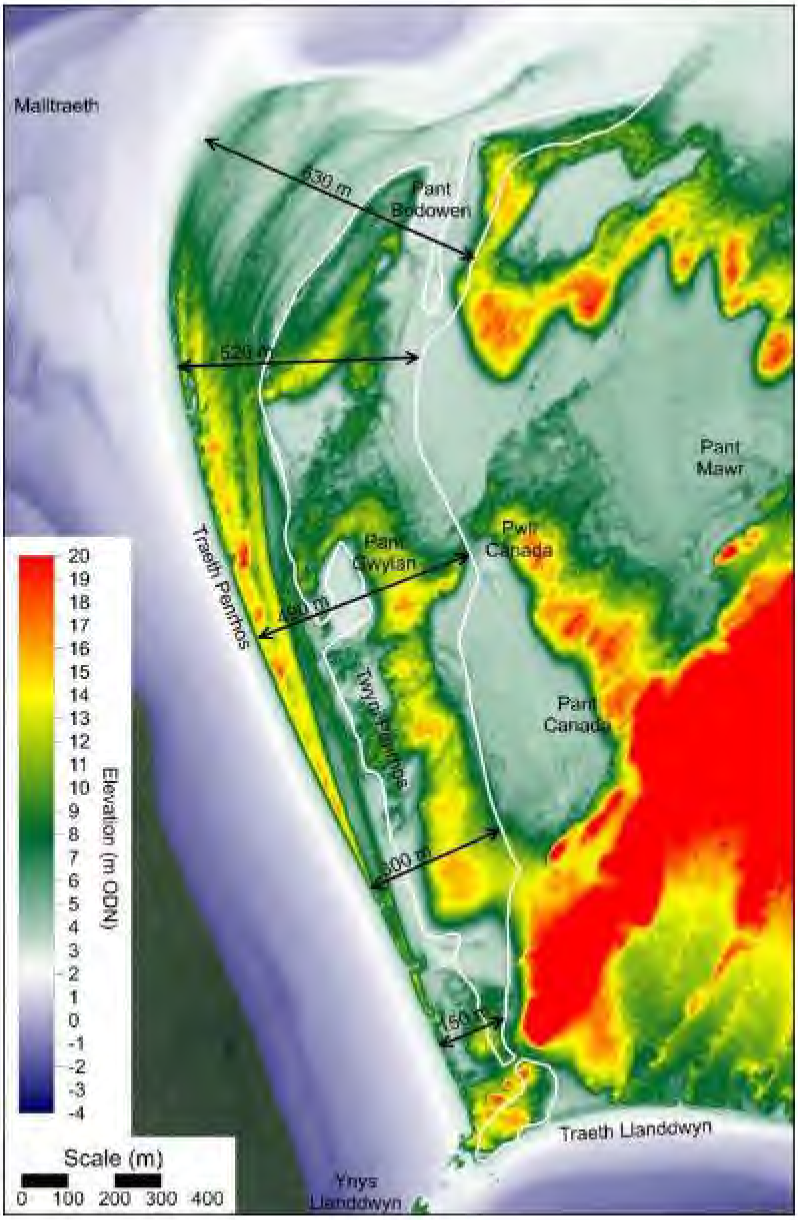

Figure 40. Suggested area of tree felling as part of Option I (area outlined with white lines, total area of 52.9 ha). Base LiDAR DTM flown 2022. Source: NRW.

Table 5 presents a tabulated summary showing how each of the identified future management options would or would not deliver the stated conservation objectives for each of the three priority dune habitats, together with the area of associated tree felling which would be required.

Table 5. Area of tree felling required to achieve each option, and the impact in terms of area gain or loss on the priority habitats: positive = +; slightly positive = (+); slightly negative = (-); negative = -

Option	Description	Area of tree felling required (ha)	Embryonic Shifting Dunes (H2110)	Shifting Dunes Along the Shoreline (H2120)	Fixed Coastal Dunes (H2130)
A	No active intervention	0.0	-	-	-
B	Deepen and widen existing blowouts	0.0	-	(+)	-
C	Creation of new artificial notches	0.0	-	(+)	-
D	Turf stripping and small-scale reprofiling	0.0	-	+	-
E	Beach nourishment	0.0	+	+	-
F	Tree felling	28.7	-	(+)	(+)
G	Tree felling and Option D	10.0	-	+	(+)
H	Tree felling and Option D	10.0	-	+	(+)
I	Large-scale tree felling and Option D	52.9	-	+	+

9. Conclusions

There is currently a clear conflict between the nature conservation objectives for the site and the presence of stands of poor quality non-native conifer woodland close to the shore at Tywni Penrhos. Along two thirds of this coastal frontage the priority H2120 and H2130 vegetation communities are being ‘squeezed’ between a retreating shore and a fixed forest plantation edge. The fixed dune H2130 communities in particular are limited to a very narrow zone and at risk of being eliminated as the mobile frontal dunes (with H2120 communities) moves landward in response to coastal erosion. Consequently, there is a requirement to create additional accommodation space to allow the zone of fixed dune grassland communities to move landwards. The issue of habitat ‘squeeze’ is likely to become worse in future years as the rate of sea level rise is projected to increase and the effect of winter storms will probably become greater, in part due to greater nearshore water depths and in part due to a possible increased frequency of severe storms.

At the southern (Ynys Llanddwyn) end of the system the beach has experienced a negative sediment budget since the 1960s and the frontal dune ridge in this area has been retreating landwards and decreasing in size for several decades; it is likely to continue to do so under conditions of sea level rise if there is no increase in sediment supply. Ephemeral strandline and transient embryo dunes (H2110 communities) may develop in this area during periods with few storms when the backshore is sufficiently wide but owing to the nature of the coastal processes regime these cannot evolve into established foredunes. A large-scale beach nourishment scheme would be required to change this situation. Frontal dune notching and other interventions (scrub clearance, localised tree felling, de-stumping and litter clearance) in this area since 2013 has created a mosaic of small-sale habitats which has biodiversity value, but which is unlikely to evolve into a classical habitat / vegetation community zonation pattern because owing to the limited accommodation space available (< 100 m) and the complexity of the topography and pattern of sediment movement within the area.

The central part of the Twyni Penrhos frontage is intermediate, in terms of sediment budget and morphological character, between the northern and southern ends of the system. The net beach sediment budget is neutral to slightly negative, and the dune toe erosion front is moving slowly northwards. The frontal dune sediment budget is currently slightly positive and the frontal dune ridge is growing slightly in height and width as sand is blown over the crest as ‘sand rain’. Areas of bare sand and semi-mobile dunes (H2120 communities) in this area are largely restricted to areas around blowouts in the dune crest. Areas of fixed dune grassland behind the frontal dune ridge in this area are being ‘squeezed’ between a landward extension of the frontal dune ridge and the forest edge.

Along the northern third of the Twyni Penrhos frontage both the upper beach and frontal dune sediment budgets remain net positive, allowing net coastal progradation and maintenance of a classical vegetation zonation pattern including strandline, embryo dunes, semi-mobile foredunes and fixed dunes to exist. In this area the forest edge lies (400 – 800 m) back from the shoreline and the nature conservation objectives are currently being met.

The most appropriate intervention methods to increase sand flux into the hind dune area along the central section of the system would be turf stripping and small-scale reprofiling of the frontal dune ridge crest. Increased sand flux into the system would increase the physical resilience of the landward migrating ridge and would enhance the development of mobile and semi-mobile dune vegetation communities. However, if undertaken in isolation it would also increase the ‘squeeze’ of fixed dune communities further landward. In the short term (up to 10 years) this pressure could be eased by further partial or complete removal of trees in a zone 150 – 250 m wide around Pant Gwylan. In order to avoid further squeeze on the narrow zone of fixed dune habitat (H2130), and to create sufficient accommodation space for natural coastal adjustment to future shoreline recession, the forest edge would need to be moved further back, to a position c.500m landward of the present dune toe (approximately to the line of the existing forest track at Pant Canada). This will be essential in order to maintain the existence of viable SD6, SD7 and SD8 (H2120 & H2130) communities and to meet the nature conservation objectives.

Based on the experienced gained from previous rejuvenation interventions at Niwbrwch/Newborough and elsewhere, further felling should aim to create a sinuous and tiered structure to the forest edge, for aesthetic, dune habitat and timber crop management reasons, and tree removal, where undertaken, should include de-stumping, removal of brash and chippings and clearance of the surface litter layer to expose the sand surface.

References

Arens SM 1996. Patterns of sand transport on vegetated foredunes. Geomorphology 17, 339-350.

Arens SM, van Kaam-Peters HME, van Boxel, JH 1995. Air flow over foredunes and implications for sand transport. Earth Surface Processes and Landforms 20, 315-332.

Birch TW 1936. The afforestation of Britain. Economic Geography 12, 1-26.

Bremontier N-T 1833. Mémoire sur les dunes. Annales des Ponts et Chaussés 1, 145-224

Brown T 2019. Forestry Act 119: 100 Years. House of Lords Library Briefing. Forestry Act 1919: 100 Years - House of Lords Library (Parliament.UK)

Bruun P 1962. Sea-level rise as a cause of shore erosion. Proceedings of the American Society of Civil Engineers, Journal of Waterways and Harbours Division 88: 117-130.

Carey AE, Oliver FW 1918. Tidal lands A Study of Shore Problems. Blackie and Son Limited, London.

Case GO 1914. Coast Sand Dunes Sand Spits and Sand Wastes. St Bride's Press, London.

Choi KH, Kim, Y, Jung PM 2013. Adverse effect of planting pine on coastal dunes, Korea. Journal of Coastal Research Special Issue 66, 909-914.

Clarke ML, Rendell HM 2005. 'This restless enemy of all fertility': exploring paradigms of coastal dune management in Western Europe over the last 700 years. Transactions of the Institute of British Geographers 40, 414-429.

Cowles HC 1899. The ecological relations of the vegetation of the sand dunes of Lake Michigan. Botanical Gazette 27, 95-117, 167-202, 281-308, 361-391.

Davidson-Arnott RGD 2005. Conceptual model of the effects of sea level rise on sandy coasts. Journal of Coastal Research 21, 1166–1172.

Doody JP 2013. Sand Dune Conservation, Management and Restoration. Springer, Dordrecht.

Duigan C, Rimington N, Howe M (eds) 2014. Welsh Coastal Storms, December 2013 & January 2014 – An Assessment of Environmental Change. NRW Evidence Report 33, July 2014, Natural Resources Wales, Bangor.

Ellenberg H 1978. Vegetation Mitteleuoropas mit den Alpen. Verlag Eugen, Stuttgart.

Fons WL 1940. Influence of forest cover on wind velocity. Journal of Forestry 38, 481-486.

Ford C 2023. The Environmental Transformation of “Empty Space”: From Desert to Forest in the Landes of Southwestern France. Comparative Studies in Society and History, 1–24, doi:10.1017/S0010417522000482

Gaberrou S, Le Cozannet G, Parteli E, Pederos R, Guerber E, Millescamps B, Mallet C. Oliveros E 2018. Modelling the retreat of a coastal dune under changing winds. Journal of Coastal Research Special Issue 85, 166-170.

Greenly E 1919. The Geology of Anglesey. Volumes I and II. Memoir of the Geological Survey, HMSO, London.

Gross G 1993. Numerical Simulation of Canopy Flows. Springer-Verlag, Berlin.

Hesp PA 2002. Foredunes and blowouts: initiation, geomorphology and dynamics. Geomorphology 48, 245 – 268.

Hesp PA, Smyth TAG 2016. Jet flow over foredunes. Earth Surface Processes and Landforms 41, 1727-1735.

Hesp PA, Smyth TAG 2021. CFD flow dynamics over model scarps and slopes. Physical Geography, 42(1), 1-24.

Hill MO, Wallace HL 1989. Vegetation and environment in afforested sand dunes at Newborough, Anglesey. Forestry 62, 249-267.

Isermann M 2005. Soil pH and species diversity in coastal dunes. Plant Ecology 178 111-120.

JBA Consulting 2024. National Vegetation Classification Survey of Newborough Forest 2023. NRW Evidence Report (Draft)

Jungerius PD, van der Meulen F 1988. Erosion processes in a dune landscape along the Dutch coast. Catena 15, 217-228.

Lowe JA, Bernie D, Bett, P. & 31 others. 2018. UKCP18 Science Overview Report Version 2.0. Exeter: The Met Office: pp73. Available at https://www.metoffice.gov.uk/pub/data/weather/uk/ukcp18/science-reports/UKCP18-Overview-report.pdf

Maun MA. 2009.The Biology of Coastal Sand Dunes. Oxford University Press, Oxford.

Mayhead GJ 1989. Newborough Forest Site of Special Scientific Interest: a management plan for commercial working. Quarterly Journal of Forestry 84, 247-256.

Mitchell SJ 2013. Wind as a natural disturbance agent in forest: a synthesis. Forestry 86, 147-157.

Miyanishi K, Johnson EA 2007. Coastal dune succession and the reality of dune processes. In: Johnson EA. & Miyanishi K (eds.) Plant Disturbance Ecology, Academic Press, Burlington, Maryland, 249-282.

Nguyen D, Hilton M, Wakes S 2021. Wind flow dynamics and sand deposition behind excavated foredune botches on developed coasts. Earth Surface Processes and Landforms 47, 1698-1719.

NRW 2019. Twyni Byw- Sands of LIFE Briefing Note, Version 3 July 2019. Natural Resources Wales (www.naturalresourceswales.gov.uk).

NRW 2022. Core Management Plan including Conservation Objectives for Abermenai to Aberffraw Dunes SAC / Anglesey Coast: Saltmarsh SAC / Glantraeth SAC incorporating Newborough Warren – Ynys Llanddwyn SSSI and Tywyn Aberffraw SSSI. Natural resources Wales, Bangor.

Plate EJ 1971. The aerodynamics of shelter belts. Agricultural Meteorology 8, 203-227.

Psuty NP, Silveira TM 2010. Global climate change: an opportunity for coastal dunes? Journal of Coastal Conservation 14, 153-160.

Pye K 1990. Physical and human influences on coastal dune development between the Ribble and Mersey estuaries, northwest England. In: Nordstrom, K.F., Psuty, N.P. and Carter, R.W.G. (Eds.) Coastal Dunes: Form and Process. John Wiley & Son Ltd., Chichester, pp. 339-359.

Pye K, Blott SJ 2010. Geomorphology of the Sefton Coast sand dunes. In: Worsley AT, Lymbery G, Holden VJC, Newton M (Eds.) *Sefton's Dynamic Coast*. Proceedings of the conference on coastal geomorphology, biogeography and management 2008. Coastal Defence: Sefton MBC Technical Services Department, Ainsdale-on-Sea, pp. 131-160.

Pye K, Blott SJ 2012. A Geomorphological Survey of Welsh Dune Systems to Determine Best Methods of Dune Rejuvenation, Appendix 3: Newborough Warren. CCW Science Report No. 1002.

Pye K, Blott SJ 2013. Newborough Forest – Proposed Methods for Dune Remobilisation and Rejuvenation. Report prepared for Welsh Government, August 2013. Report No. Ex 1258, Kenneth Pye Associates Ltd., Solihull.

Pye K, Blott SJ 2016. Dune Rejuvenation Trials Overview. NRW Evidence Report 296, Natural Resources Wales, Bangor.

Pye K, Blott SJ 2017. Evolution of a sediment-starved, over-stabilised dunefield: Kenfig Burrows, South Wales, UK. *Journal of Coastal Conservation* 21, 685-717.

Pye K, Blott SJ 2020a. Newborough Coastal Change Assessment. KPAL Report No. Ex. 090320, March 2020. Kenneth Pye Associates Ltd, Reading.

Pye K, Blott SJ 2020b. Dune Remobilisation Trials at Kenfig, Merthyr Mawr and Newborough: Development Update. Report No. Ex 080320 prepared on behalf of Natural Resources Wales, Kenneth Pye Associates Ltd., Reading.

Pye K, Blott SJ 2023. Freshwater West and Castlemartin Corse: Flood and Coastal Erosion Risk Assessment. KPAL Report No. Ex 070223 Prepared on behalf of The National Trust, 12 April 2023.

Pye K, Saye SE 2005. The Geomorphological Response of Welsh Sand Dunes to Sea Level Rise over the Next 100 Years and the Management Implications for SAC and SSSI Sites. CCW Science Report No. 670.

Pye K, Blott SJ, Howe MA 2014.Coastal dune stabilization in Wales and requirements for rejuvenation. Journal of Coastal Conservation 18, 27-54.

Ranwell DS 1955. Slack Vegetation, Dune Development and Cyclical Change at Newborough Warren, Anglesey. PhD Thesis, University of Wales, Bangor.

Ranwell DS 1958. Movement of vegetated sand dunes at Newborough Warren, Anglesey, Journal of Ecology, 46, 83-100.

Ranwell DS1959. Newborough Warren, Anglesey. I. The Dune System and Dune Slack Habitat. Journal of Ecology 47, 571-601.

Ranwell DS 1972.Ecology of Saltmarshes and Sand Dunes. Chapman & Hall, London.

Rhind PM, Blackstock TH, Hardy HS, Jones RE, Sandison W 2001. The evolution of the Newborough Warren dune system with particular reference to the past four decades. In: Houston JA, Edmondson SE, Rooney PJ. (eds.) Coastal Dune Management: Shared Experience of European Conservation Practice. Liverpool University Press, Liverpool, 345-379.

Rhind P, Stevens D, Sandison R 2006. A review and floristic analysis of lichen-rich grey dune vegetation in Britain. Biology and Environment: Proceedings of the Royal Academy, 106B (3) 301-310.

RCCEA 1909. Second Report (on Afforestation) of the Royal Commission appointed to inquire into and report on certain Questions affecting Coast Erosion and Afforestation in the United Kingdom. HMSO, London, Volume 2.

Royal Haskoning 2012. West of Wales Shoreline Management Plan 2 Cardigan Bay and Ynys Enlli to the Great Orme Coastal Group. Royal Haskoning, Peterborough.

Salisbury EJ 1952. Downs and Dunes. G Bell & Sons Ltd, London.

Saye SE, Pye K 2007. Implications of sea level rise for coastal dune habitat conservation in Wales, UK. Journal of Coastal Conservation 11, 31-52.

Saye SE, Pye K, Clemmensen LB 2006. Development of a cliff-top dune indicated by particle size and geochemical characteristics: Rubjerg Knude, Denmark. *Sedimentology* 53, 1-21.

Saye SE, van der Wal D, Pye K, Blott SJ 2005. Beach dune morphological relationships and erosion/accretion: an investigation at five sites in England and Wales using LIDAR data. Geomorphology 72, 128-155.

Short AD, Hesp PA 1982. Wave, beach and dune interactions in southeastern Australia. Marine Geology 48, 259 - 284.

Smyth TAG, Rooney P, Yates K 2023. Dune slope, not wind speed, best predicts bare sand in vegetated coastal dunes. Journal of Coastal Conservation 27: https://doi.org/10.1007/s11852-023-00957-9

Talkkari A, Peltola H, Kellomaki S, Strandman H 2000. Integration of component models from tree, stand and regional levels to assess the risk of wind damage at forest margins. Forest Ecology and Management 135, 303-313.

Tansley AG 1911. The sand dune formation. In: Tansley AG (ed.) Types of British Vegetation, Cambridge University Press, Cambridge, 339-352.

Wuyts K, Verhagen K, De Schriver A, Cornelis WM, Gabriels D 2008. The impact of forest edge structure on longitudinal patterns od deposition, wind speed and turbulence. Atmospheric Environment 42, 8651-8660.

Data Archive Appendix

No data outputs were produced as part of this project.

Further copies of this report are available from library@cyfoethnaturiolcymru.gov.uk