Dune Rejuvenation Trials Overview Report

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Yn dilyn asesiadau o ofynion cenedlaethol Cymru a gafodd eu cynnal rhwng 2009 a 2012, cafodd mesurau ymyrryd prawf i adfer twyni eu rhoi ar waith yn Nhywyn Cynffig a Thywyn Merthyr Mawr yn ne Cymru, ac yn Niwbwrch ar Ynys Môn, yn ystod gaeafau 2011–12 i 2014–15. Yn 2013–14, ymgymerwyd â gwaith ym Merthyr Mawr yn unig. Mae'r adroddiad hwn yn darparu asesiad geomorffolegol o effeithiolrwydd y treialon hyn, a fydd yn llywio cynllunio ymyriadau yn y dyfodol. Mae'r adroddiad yn mesur y newidiadau mewn ardal tywod moel ym mhob safle, yn trafod dylanwad tywydd, cyflenwad gwaddodion, a ffactorau eraill ar wahaniaethau rhwng ac o fewn safleoedd, ac yn rhoi sylwadau ar fanteision cymharol gwahanol ddulliau monitro. Caiff cynigion hefyd eu gwneud ar gyfer gwaith ymyrryd pellach ym mhob un o'r safleoedd.

Yng Nghynffig, roedd cyfanswm yr ardal o dywod noeth yn gynnar ym mis Mawrth 2016 yn cynrychioli oddeutu 94% o'r ardal (10.3 hectar) ar adeg yr arolwg cychwynnol. Roedd ardaloedd blaen twyni Cam 2 (gorllewinol) a Cham 3 yn dangos cynnydd yn y maint o dywod moel, ond dim ond 38% o'r maint cychwynnol oedd maint y tywod moel yn ardal Cam 1 (dwyreiniol) (twyni mewndirol) ym mis Mawrth 2016 o ganlyniad i lystyfiant yn aildyfu. Ym Merthyr Mawr, roedd cyfanswm yr ardal tywod moel ddiwedd Chwefror 2016 yn cynrychioli tua 104% o'r ardal ar adeg yr arolwg cychwynnol, ac nid oedd yr un o'r ardaloedd adfywio wedi profi achosion sylweddol o lystyfiant yn aildyfu. Yn Niwbwrch, roedd cyfanswm yr ardal tywod moel ddiwedd Ionawr 2016 yn cynrychioli 108% o'r ardal ar adeg yr arolwg cychwynnol, a chofnodwyd cynnydd sylweddol yn ardaloedd Cam 2 (gorllewinol), Cam 2 (dwyreiniol) a Cham 3. Dangosodd ardaloedd prawf twyni mewndirol Cam 1 y ganran isaf sy'n weddill o dywod moel. Ac eithrio ardaloedd Cam 1 a Cam 2 (dwyreiniol) yng Nghynffig, ac ardal Cam 1 yn Niwbwrch, mae'r treialon hyd yn hyn wedi bod yn llwyddiannus wrth gynyddu maint y tywod moel, y mae llawer ohono yn symudol. Gellir priodoli lefel is o lwyddiant yn ardaloedd twyni mewndirol i ynni gwynt annigonol, diffyg cyflenwad tywod newydd o'r twyni blaen, ac amodau tywydd gwlyb, sydd wedi ffafrio amodau lle mae llystyfiant yn aildyfu’n gyflym. Er bod cyfnodau o wyntoedd cymharol gryf, sy'n gysylltiedig ag amlder uwch na'r cyfartaledd o ddiwasgeddau dwfn yn croesi Ynysoedd Prydain yn ystod y cyfnod 2012 – 2016, wedi ffafrio symudiad tywod mewn rhannau agored o'r twyni blaen, yn enwedig o fewn chwythbantiau naturiol a rhiciau artiffisial, nid ydynt wedi bod yn ddigonol i achosi symudiad o dwyni mewndirol sefydlog neu i atal llystyfiant rhag aildyfu mewn rhannau lle mae’r tywyrch wedi cael eu stripio.

Mae cyllideb waddod y traeth a'r twyni blaen wedi cael dylanwad pwysig ar raddfa symudedd tywod sydd wedi digwydd yn yr ardaloedd prawf. Yng Ngham 1 Cynffig a Cham 3 Niwbwrch, mae lefelau traeth yn isel ac nid oes ond cyflenwad bach o dywod posibl ar gyfer trafnidiaeth aeolaidd o'r traeth tuag at y twyni. Yng Ngham 3 Cynffig, Cam 2 Niwbwrch (gorllewinol) a Cham 2 Niwbwrch (dwyreiniol), mae lefelau'r traeth ychydig yn uwch ac mae cyflenwad cymedrol posib o dywod i'r twyni. Mae'r lefelau traeth uwch uchaf a'r cyflenwad posibl mwyaf o dywod traeth yn digwydd yn Nhywyn Merthyr Mawr, lle mae system cyn-dwyni fawr wedi datblygu o fewn yr 20 - 30 mlynedd ddiwethaf. Mae'n debygol y bydd llwyddiant o ran sefydlu trosglwyddiad tywod cynaliadwy o'r traeth, trwy dwyni blaen i ardaloedd twyni ôl, yn fwyaf mewn ardaloedd â chyllideb gwaddod cadarnhaol.

Er mwyn cael y data monitro gorau posibl yn ymwneud â newid morffolegol yn y dyfodol, argymhellir y dylid cynnal arolygon LIDAR o’r awyr cyn unrhyw waith ymyrryd pellach ac ar gyfnodau o bob dwy flwyddyn wedi hynny. Dylai arolygon GPS RTK wedi'u targedu hefyd gael eu cynnal o fewn pythefnos i bob arolwg LIDAR. Gallai arolygon UAV fod yn ddefnyddiol wrth fesur maint y tywod moel a’r dwysedd llystyfiant mewn ardaloedd bach, ond maent yn anaddas at ddibenion datblygu modelau golwg digidol cywir y gellir eu defnyddio i fesur newidiadau mewn cyfaint gwaddod ar draws ardaloedd mawr.

Yng Nghynffig, cynigir y dylai gwaith ymyrryd yn y dyfodol gynnwys cloddio dau ricyn newydd drwy'r twyni blaen a lefelu'r tir yn yr ardal Cam 1 bresennol i'r gorllewin o’r ffordd gludiant, gan osod y tywod wedi'i gloddio ar bob ochr o’r ffordd gludiant i godi lefel y ddaear a darparu llwybr di-dor ar gyfer symudiad tywod tuag at y twyn parabolig mawr ar ben dwyreiniol y cam. Cynigir hefyd fod toriad yn cael ei wneud ar grib y twyn hwn i gyflymu gwyntoedd lleol a chaniatáu symudiad tywod tuag at y tir.

Ym Merthyr Mawr, cynigir y dylid cloddio pedwar rhicyn ychwanegol yn y twyni blaen i'r gogledd o'r rhicynnau Cam 3 er mwyn annog llif tywod o'r traeth i'r ardal twyni ôl. Cynigir gwaith stripio tywyrch hefyd ar lethr atwynt a chrib twyn parabolig mawr ('Twyn B') i'r dwyrain o'r rhicynnau newydd, ac wedyn mewn coridor sy'n cysylltu â'r twyni blaen. Cynigir bod rhicyn arall yn cael ei greu trwy ganol twyn artiffisial a grëwyd yng Ngham 2 er mwyn hwyluso mwy o drafnidiaeth tywod tuag at y tir.

Yn Nhywyn Niwbwrch, cynigir y dylid ymgymryd â gwaith stripio tywyrch ychwanegol a gwneud rhiciau yn nhwyni blaen i'r de-ddwyrain o waith Cam 3. Dylid cloddio tri rhicyn yn y twyni blaen, lle bo'n bosib yn manteisio ar chwythbantiau naturiol presennol. Cynigir y dylid ehangu coridor presennol trwy ‘drwyn’ twyn parabolig mawr tuag at y tir, a chynnal gwaith stripio tywyrch a chloddio tywod ar raddfa lai ar rannau uwch o wal ddwyreiniol twyn parabolig mawr cyfagos.

Yn Nhraeth Penrhos, ar ochr orllewinol Coedwig Niwbwrch, cynigir y dylid ymgymryd â gwaith ychwanegol i gwympo coed a thynnu bonion yn yr ardal y tu ôl i grib y twyni blaen, i'r gogledd o ardal orllewinol Cam 2. Dylid torri dau ricyn ychwanegol trwy'r twyn blaen i gysylltu'r traeth â'r ardal y tu ôl i’r twyn, a gliriwyd yn ddiweddar, a thorri coed fesul cam ar hyd cyfan y prif lac twyni a llethr twyni atfor ar ei ochr tua’r tir, er mwyn creu gofod i grib y twyn blaen ymfudo tua’r tir mewn ymateb i gynnydd yn lefel y môr yn y dyfodol ac erydiad arfordirol.

Fel amcan cyffredinol, dylid lleihau'r newidiadau i'r nodweddion topograffig naturiol presennol a datblygu dulliau o amlhau’r buddiannau cadwraeth trwy’r dyluniad gorau posibl ar gyfer ymyriadau geomorffolegol ar raddfa fach, a thrwy reoli’r gyllideb gwaddod. Dylai'r treialon ychwanegol arfaethedig ymchwilio ymhellach i effaith amrywio dyluniad a lleoliad rhicynnau ar symudedd tywod, gan ategu gwaith arbrofol sy'n cael ei wneud mewn rhannau eraill o Ewrop.

Executive Summary

Following assessments of national Welsh requirements undertaken between 2009 and 2012, trial dune rejuvenation interventions measures were undertaken at Kenfig Burrows and Merthyr Mawr Burrows in South Wales, and at Newborough on Anglesey, during the winters of 2011-12 to 2014-15. In 2013-14 work was undertaken only at Merthyr Mawr. This report provides a geomorphological assessment of the effectiveness of these trials which will inform the planning of future interventions. The report quantifies the changes in bare sand area at each site, discusses the influence of weather, sediment supply, and other factors on differences between and within sites, and provides comment on the relative merits of different monitoring methods. Proposals are also made for further intervention works at each of the sites.

At Kenfig, the total area of bare sand in early March 2016 represented approximately 94% of the area (10.3 ha) at time of initial survey. The Phase 2 West and Phase 3 frontal dunes areas showed an increase in bare sand extent, but the bare sand extent within the Phase 1 area East (inland dune) in March 2016 was only 38% of the initial extent due to regrowth of vegetation. At Merthyr Mawr the total bare sand area in late February 2016 represented approximately 104% of the area at time of initial survey, and none of the rejuvenation areas had experienced significant re-vegetation. At Newborough, the total bare sand area in late January 2016 represented 108% of the area at time of initial survey, significant increases being recorded in the Phase 2 West, Phase 2 East and Phase 3 areas. The Phase 1 inland dune trial areas showed the lowest remaining percentage of bare sand. With the exception of the Phase 1 and eastern Phase 2 areas at Kenfig, and the Phase 1 area at Newborough, the trials have so far been successful in increasing the extent of bare sand, much of which is mobile. The lower level of success in the inland dune areas can be attributed to insufficient wind energy, lack of new sand supply from the frontal dunes, and wet weather conditions which have favoured rapid vegetation regrowth. Although periods of relatively strong winds associated with a higher than average frequency of deep depressions which crossed the British Isles during the period 2012 – 2016 have favoured sand movement in exposed parts of the frontal dunes, particularly within natural blowouts and artificial notches, they have not been sufficient to cause mobilization of stabilised inland dunes or prevent partial revegetation of turf-stripped areas.

The sediment budget of the beach and frontal dunes has had an important influence on the scale of sand mobility which has taken place within the trial areas. At Kenfig Phase 1 and Newborough Phase 3 beach levels are low and there is only a small potential supply of sand for aeolian transport from the beach towards the dunes. At Kenfig Phase 3, Newborough Phase 2 West and Newborough Phase 2 East the beach levels are slightly higher and there is a moderate potential supply of sand to the dunes. The highest upper beach levels and largest potential supply of beach sand occurs at Merthyr Mawr Warren where a large foredune system has developed within the past 20 – 30 years. Success in terms of establishing sustainable transfer of sand from the beach, through frontal dunes to hind dune areas is likely to be greatest in areas with a positive sediment budget.

In order to obtain the best possible monitoring data relating to future morphological change it is recommended that airborne LIDAR surveys should be undertaken before

any further intervention works and at two yearly intervals thereafter. Targeted RTK GPS surveys should also be undertaken within two weeks of each LIDAR survey. UAV surveys could be useful in quantifying the extent of bare sand and vegetation density within small areas but are unsuitable for the purpose of developing accurate digital elevation models which can be used to quantify changes in sediment volume across large areas.

At Kenfig it is proposed that future intervention work should include excavation of two new notches through the frontal dune and to level the ground in the existing Phase 1 area west of the haul road, with placement of the excavated sand on either side of the haul road to raise the ground level and provide an uninterrupted pathway for sand movement towards the large parabolic dune at the eastern end of Phase 1. It is also proposed that a breach be cut in the crest of this dune to produce local wind acceleration and allow landward sand movement.

At Merthyr Mawr it is proposed that four additional notches should be excavated in the frontal dunes to the north of the Phase 3 notches to encourage sand flow from the beach into the hind-dune area. Turf stripping is also proposed on the windward slope and crest of a large parabolic dune ('Dune B') to the east of the new notches, and subsequently in a corridor linking with the frontal dunes. A further notch is proposed through the middle of an artificial dune created in Phase 2 to facilitate greater landward sand transport.

At Newborough Warren it is proposed that additional turf stripping and frontal dune notching should be undertaken to the southeast of the Phase 3 works. Three notches should be excavated in the frontal dune, where possible exploiting existing natural blowouts. It is proposed that an existing corridor through the 'nose' of a large parabolic dune to landward should be enlarged, and smaller scale turf stripping and sand excavation undertaken on higher parts of the eastern wall of an adjacent large parabolic dune.

At Traeth Penrhos, on the western side of Newborough Forest, it is proposed that additional tree-felling and de-stumping should be undertaken in the area behind the frontal dune ridge, north of the Phase 2 West area. Two additional notches should be cut through the frontal dune to link the beach with the newly cleared hind-dune area and tree felling undertaken in stages along the entire length of the primary dune slack and seaward facing dune slope on its landward side to create space from the frontal dune ridge to migrate landwards in response to future sea level rise and coastal erosion.

A general objective should be minimise changes to the existing natural topographic features and to develop means of maximising conservation benefits through the optimal design of small-scale-geomorphological interventions, and by sediment budget management. The proposed additional trials should investigate further the effect of varying notch design and positioning on sand mobility, complementing experimental work being undertaken in other parts of Europe.

1. Introduction

The Natural Resources Wales (NRW) Dune Rejuvenation Project aims to restore more dynamic conditions to several of the major Welsh dune systems, thereby increasing the representation of pioneer habitats and the specialist plants and invertebrates they support and restoring to favourable condition habitats and species of national and international importance. The rejuvenation management works are underpinned by detailed geomorphological studies of the dune systems which provide a historic and contemporary overview of dune processes, the options to restore dynamic conditions to best and most self-sustaining effect, and precise information as to the positioning, depth, orientation and size of the excavations (Pye & Blott, 2011a,b; 2012a).

Trial dune rejuvenation works have been undertaken at Kenfig, Merthyr Mawr and Newborough (Figure 1) during the winters of 2011-12 to 2014-15, with a hiatus in 2013-14 when work was undertaken only at Merthyr Mawr Warren. The purpose of this report is to provide a geomorphological assessment of the effectiveness of these rejuvenation works which will inform the planning of further works. The report provides a summary of changes in the extent of bare sand and mobile dunes at each site, discusses the factors which have resulted in differences in the impact between and within sites, and comments on the relative merits of the methods which have been used to monitor geomorphological change. Proposals are also made for further intervention works at each of the sites.

2. Methods

This assessment is based on an analysis of the following:

- Pre-works targets and objectives
- Initial accomplishments in terms of bare sand area created by the works
- Post-works RTK-GPS topographic survey data
- Pre-works and post-works LiDAR survey data
- Pre-works and post-works conventional aerial photographs
- Post-works UAV survey photography and photogrammetric data
- Pre-and post-works ground photographs taken during survey visits
- Wind, rainfall and temperature data for nearby weather stations.

2.1. Topographic survey data

In order to monitor changes in dune morphological features at the rejuvenation trial sites RTK-GPS ground surveys were conducted by KPAL using a ‘base and rover’ surveying technique. The dates of the ground RTK-GPS surveys and periods of rejuvenation works are shown in Table 1. Surveys in 2012 and 2013 were carried out using a Leica Viva GPS SmartRover GS15 Receiver mounted on a 2 m pole and a Leica Viva CS15 GNSS Field Controller. Later surveys in 2014 and 2015 used a Leica RX1250 SmartRover with ATX 1230GG Smart Antenna, GFU24 Siemens MC75 mobile phone and RX1250XC controller mounted on top of a 2m pole. The system was set to SmartRover RTK mode, using GPRS corrections from the Leica SmartNet network. Survey accuracy was generally better than 10 mm and precision on average better than 7 mm. The x, y, z coordinates of 1100 to 1500 points were determined in each survey. The survey strategy was primarily to define features of interest, including the extent of bare sand and standing water, and to quantify changes in elevation along specified transect lines. In the case of the 2012 and 2013 surveys additional points were taken across the entire area of the rejuvenation works in order to allow three-dimensional comparison with digital elevation models (DEMs) derived from LiDAR data. All data were processed using routines in the Golden Software Surfer program and specially written macros in Microsoft Excel. All spatial data outputs required for archiving have been converted into Arc format (ESRI shape files).

2.2. LiDAR survey data

The most recent available pre-works LiDAR survey data for each trial area were used to characterise the 'baseline' pre-works conditions. Available post-works LiDAR survey data have also been analysed to quantify change in surface levels and sand volumes since the works were undertaken. In the case of Kenfig, LiDAR data were available for surveys on 26th February 2006 and 31st March 2014. For Merthyr Mawr, LiDAR data were available for surveys on 16-29th October 2008 and 5th February 2015. In the case of Newborough, LiDAR data were available for surveys on 12th May 2009 (Newborough Warren only) and 9th April 2014 (covering both Newborough Warren and Newborough Forest). In most cases both filtered and unfiltered LiDAR data were analysed. However, for the 2009 survey of Newborough Warren only filtered data were available. The data used are freely available under Open Government licence. All of the data processing was undertaken using Surfer, with conversion to ESRI files where required.

2.3. Conventional aerial photography

Several epochs of conventional vertical photography are available for the three dune systems and provide useful evidence of changes in bare sand area and vegetation density. The results of analysis of selected photograph epochs was previously reported previously by Pye & Blott (2011, 2012a, 2012b and 2015a). For the purposes of the present assessment, the most recent available pre-works and post-works orthorectified aerial photographs were examined. In the case of Kenfig, these are flights on 12th October 2009 (provided by NRW) and 18th April 2015 (available from Google Earth). For Merthyr Mawr aerial photography was available for flights on 13th September 2009 (NRW) and 18th April 2015 (Google Earth). For Newborough, aerial photography was available for flights on 11th May 2009 (NRW) and April 2012 (Google Earth).

2.4. UAV photography and photogrammetric data

Unmanned aerial vehicle (UAV) surveys of the trial rejuvenation areas were commissioned by NRW in early 2016. A survey of the four rejuvenation areas at Newborough was undertaken by DTM Technologies in January 2016. Surveys of the Kenfig and Merthyr Mawr rejuvenation areas were undertaken by Resource Unmanned Aviation Services (UAS) on 2nd March 2016 and 29th February 2016, respectively. These data were made available by NRW for the present assessment. An additional UAV survey of the of the Phase 1 and proposed Phase 2 West trial areas at Newborough was undertaken by ExeGesis Ltd in June 2013 and these data were also re-examined as part of the present assessment.

The Newborough data were accompanied by four brief data processing reports (DTM, 2016a, b, c, d) containing the following information:

Phase 1 areas 1, 2, 3: Survey dates - January 2016; HERO4 Black camera, 140 images, flying altitude 45.4 m, 10 ground control points

Phase 1 area 4: Survey date January 2016; HERO4 Black camera, 91 images, flying altitude 48.4 m, 7 ground control points

Phase 2 West: Survey date January 2016; HERO4 Black camera, 118 images, flying altitude 54.2 m, 9 ground control points

Phase 2 East and Phase 3: Survey date January 2016; HERO4 Black camera, 369 images, flying altitude 47.3 m, 25 ground control and check points.

Maps are presented in each of the data processing reports showing the distribution of ground control points and associated RTK GPS data for each point are presented in tabular form, although no information is provided about ground survey methods.

No data processing reports were provided for the Kenfig and Merthyr Mawr surveys. However, subsequent enquiries to the contractor indicated that an Ascending Technologies Falcon 8 Trinity UAV was used, operating at flight heights of 70 - 120 m above ground level, and using a Sony Alpha 7R camera with 35 mm lens. No information was provided about the number or distribution of ground control points, and indeed whether any RTK GPS ground control measurements were undertaken.

Colour mosaic images were provided to KPAL in compressed .ECW image format, having a typical resolution of 2 cm per pixel. Digital terrain models (DTM) mosaics were also provided for Newborough and Merthyr Mawr, stored in Arc ASCII Grid .asc format (typical resolution 6 cm per pixel). Raw x, y, z data files were also provided. Initial checks revealed significant errors in the geo-referencing previously undertaken and so the raw x, y, z data were re-gridded at KPAL using a 50 cm grid and a kriging algorithm in Surfer.

The elevation (z) data provided for Kenfig and Merthyr Mawr elevation had not been referenced to Ordnance Datum Newlyn (ODN), and the elevation data supplied therefore had to be converted to elevations in metres above ODN using a conversion factor estimated by plotting the UAV elevation values against ODN values for the same grid points extracted from the 2014 and 2015 LiDAR DEMs. The data for the southern part of the Kenfig survey contained major errors. Attempts were made to reduce these by adjusting the x, y and z values for the areas most affected. Comparison of the LiDAR elevation values with RTK GPS survey elevations on hard, flat surfaces indicated that the average vertical accuracy of the 2014 and 2015 LiDAR is better than 100 mm. Previous error analyses have indicated average vertical errors of better than 10 mm for the RTK GPS survey data. The apparent elevations of the hard surface parts of the haul road taken from the 2014 LiDAR are therefore assumed to be accurate to within +/- 110 mm. Corrections were made to the UAV data using the LiDAR and RTK GPS elevation data and improved, but did not eliminate, the errors associated with the former, and the adjusted UAV data remain unreliable, especially for the southwestern part of the Kenfig survey area.

The UAV data for Merthyr Mawr were of better quality, with more accurate georeferencing, but the elevation values provided also required conversion to ODN. This was again achieved using a conversion factor obtained by comparing individual gridded UAV elevations (z values) with those extracted for the same grid points from the 2015 LiDAR DEM.

The UAV photographic image mosaics are composed of numerous individual images taken over periods of several hours during which there were substantial changes in sunlight / cloud conditions. Consequently, the photo mosaics display significant variations in surface brightness across. Moreover, under bright sunlight conditions the images suffer considerably from shadowing effects created by topographic variations and vegetation. The resolution of the processed image data is also spatially variable, with some parts of the Kenfig survey area in particular containing significant areas of poor resolution. For these reasons it was found to be impractical to apply automated image processing routines to quantify the extent of bare sand on a pixel by pixel basis. Consequently, the limits of major areas of bare sand were digitised manually for each area and the results compared with marginal limits mapped from previous air photographs and ground surveys. The values given for the extent of bare sand / mobile dunes are therefore maximum values since pockets of vegetation within the defined areas are included.

2.5. Ground photography

During each ground topographic survey and intervening ground walkover surveys, photographs were taken from known points taken using a digital camera to provide a visual record of changes in the vegetation cover and surface character. Ten site visits were made by KPAL personnel to Newborough between July 2011 and February 2016. Fifteen visits were made to Kenfig between July 2011 and July 2016, and nine visits made to Merthyr Mawr between April 2012 and July 2016. The photographic record was inspected as part of this assessment to assist interpretation of the aerial photographs, LiDAR and ground survey data.

3. Results

3.1. Kenfig Burrows

The dune rejuvenation trial sites at Kenfig Burrows are located within the Kenfig National Nature Reserve (NNR) which forms parts of the Kenfig Dunes Site of Special Scientific Interest (SSSI) and the Kenfig / Cynffig Special Area of Conservation (SAC) (Figure 2).

Prior to the 19th century, dunes fringed almost the entire northern and eastern shores of Swansea Bay, but during the past 150 years, large areas have been lost due to industrial and urban development (Howe *et al*., 2012). There has also been a marked reduction in the extent of bare sand and mobile dunes within the remaining dune areas. In 1941 bare sand covered approximately 154 ha at Kenfig (17.4% of the site), but by 2009 this figure had declined to only 4 ha, representing 0.5% of the total area (Figure 3). The decline in pioneer dune and dune slack habitats has had a significant negative impact on the conservation status of the European site (Howe *et al.*, 2012).

3.1.1. Phase 1

Following an initial study to evaluate options for dune rejuvenation (Pye & Blott, 2011a), plans were refined and works started on a Phase 1 trial area of approximately 5 ha in early February 2012 (Figure 4). The work was undertaken using a JCB excavator and two articulated Volvo dump trucks (Figure 5; Table 2). The work included stripping of turf from within the former deflation corridor of a large stabilised parabolic dune which is bisected by a former haul road built in the mid-1960s to transport of limestone from local quarries to Port Talbot Outer Harbour. The parabolic dune was partially active in the 1960s and 70s but became progressively stabilised during the 1980s. The Phase 1 work also involved lowering a system of younger and mostly vegetated hummock dunes which lay between the haul road and the sea which were acting as an obstacle to the flow of wind and sand towards the crest of the parabolic dune. The dune frontage on this part of the shore had been experiencing slow erosion for several years and consisted of a 3 - 4 m high cliff. This was graded to a lower angle as part of the Phase 1 work. A principal objective of the Phase 1 trial was to establish if the parabolic dune could be remobilised by increasing the wind speed and bare sand exposure within the deflation corridor, and by encouraging the flow of wind (and possibly sand) from the beach into the dune system. It was recognised that the supply of new sand from the beach into the dunes would be likely to be very limited in this area since beach levels are relatively low and much of the intertidal area remains wet at low tide.

Only a relatively thin (20 - 30 cm) layer of turf was stripped and, in many places, roots were left exposed on the stripped surface (Figure 5). The turf blocks were placed in pre-selected positions, notably to create a seaward extension to the southern ‘arm’ of the parabolic dune on either side of the haul road in order to encourage greater wind funnelling towards the dune crest. Some turf was also placed at the base of the windward slope leading to the dune crest in order to create a more gently concave windward slope. The turf blocks were mostly left uncovered although some were with sand buried to shallow depth.

Post-works RTK-GPS topographic monitoring surveys were carried out in July and October 2012 (Pye & Blott, 2012a, b) and in March 2013 (Pye & Blott, 2013a). An overview report was produced in July 2013 (Pye & Blott, 2013b) and further topographic surveys conducted in May 2014 (Pye & Blott, 2014a) and 2015 (Pye & Blott, 2015a).

3.1.2. Phase 2

Following an initial assessment to develop design proposals (Pye & Blott, 2012d), Phase 2 works were undertaken in January - February 2013 and involved further vegetation stripping on both sides of the haul road within an area of approximately 6.5 ha adjacent to the north side of the Phase 1 (Figure 4). The stripped turf from the area east of the haul road was placed adjacent to a dune ridge which forms the northern limit of the Phase 2 stripped area in order to enhance the morphology of an existing subdued parabolic dune form. Small quantities of turf stripped from the western side of the haul road, including the dune surface above the notches, was placed on the back side of the frontal due ridge and buried with sand excavated from the notches. Four notches were excavated in the frontal dune ridge in order to funnel the flow of wind and sand from the beach. Analysis of historical photographs and beach survey data had shown that the position of the dune toe at the southern end of the Phase 2 area was relatively stable, due to a neutral beach sediment budget, with a tendency for slight progradation towards the northern end of the Phase 2 area where the beach sediment budget becomes slightly positive. The excavated notches were approximately 6 m deep, had a crest to crest width of approximately 20 m in the central section, and were almost flat-bottomed with an elevation just above extreme tide level (Table 2). The orientation of the notches was deliberately varied to test the effect of varying exposure to south-westerly, westerly and north-westerly winds (Figure 4). The work was undertaken using 14 tonne and 20 tonne excavators, equipped with digging buckets and grading buckets, and two large dump trucks (Table 2). Due to high rainfall in the late winter of 2013 parts of the site became submerged and the full area could not be worked.

During 2014 some slipped turf blocks and wave-washed debris were removed from the notches by the site warden using a tractor.

A post-works topographic monitoring survey of the Phase 2 area was undertaken in May 2013 (Pye & Blott, 2013c), and two further surveys carried out in March 2014 and March 2015 (Pye & Blott 2014b, 2015a).

3.1.3. Phase 3

Further works carried out in November and December 2014 (Phase 3) included additional turf stripping and sand removal in parts of the planned Phase 2 area which could not be worked in 2013 due to flooding, together with the creation of four more notches through the frontal dunes to the north of those created during Phase 2 (Table 2). The dunes along this section of the shore are higher than those further south due to a more positive beach and frontal dune sediment budget. The dunes are locally dissected by small blowouts but along the seaward edge a low foredune platform has developed through sand accretion in recent decades. The Phase 3 notch excavation work therefore sought to take advantage of the natural topography, with the notches located at natural low and/ or narrow points in the dunes. The notches created were of similar width (c. 20 - 25 m at the top) and cut depth (c. 6 - 7 m) to those created in Phase 2 but, owing to the greater average height of dunes in this area and the closer proximity of the haul road, the notches had a more steeply sloping base and greater maximum elevation relative to ODN (Table 3). One notch which was started had to be abandoned when a World War II concrete pillbox was encountered, and the notch was moved further north. The work was undertaken by the same contractors as in Phase 2 using two large dump trucks, one 14 tonne excavator and two 20 tonne excavators. A bulldozer was also used in the final week to assist profiling, and to clear accumulated sand, shingle and wave-rafted debris washed into the seaward ends of the Phase 2 notches during storms in December 2013, January and February 2014.

A post-works RTK GPS topographic survey was undertaken in March 2015 (Pye & Blott, 2015a) and a UAV survey undertaken on 2nd March 2016. The combined extent of bare sand shortly after completion of Phase 3 is shown by conventional air photography flown on 18th April 2016 (Figure 6).

Photographs 7a to 7e illustrate changes in the relative extent of bare sand and vegetation in the seaward part of the Phase I area between March 2012 and July 2016. In March 2012 much of the frontal dune area was bare (Figure 7a), but by mid July 2012 significant plant regrowth had occurred, principally of *Rubus caesius* (Dewberry) and *Ammophila arenaria* (Marram) (Figure 7b). Regrowth was facilitated by a failure of the turf stripping operation to completely remove or kill the plant roots, by a cool, wet spring and summer of 2012 which favoured plant recovery, and by a very small sand supply of fresh sand blown from the beach which on this part of the Kenfig shore is relatively low and often wet.

Areas showing significant vegetation re-growth were treated with herbicide in the autumn / winter of 2012-13, and by the time of the March 2013 survey the density of vegetation cover in this area showed a marked reduction compared with the earlier survey (Figure 7c). Vegetation regrowth was also inhibited in this period by the unofficial use of trail bikes in the area. However, since the autumn of 2013 there has been progressive vegetation regrowth in this area, principally of Marram (Figures 7d, e, f)

Regrowth of vegetation from buried turf blocks was evident within the eastern part of deflation corridor east of the haul road in the later summer of 2012 (Figure 8a). Some of these turf blocks were physically removed during the winter of 2012-13 and placed on the margins of the site. Largely as a result of this intervention, vegetation cover within the deflation corridor and on the dune windward slope was thin and patchy at the time of site visits in February and March 2013 (Figure 8b), despite heavy rains which created a large area of standing water in the deeper parts of the deflation trough (Figure 8d). However, since late 2013 there has been a pronounced increase in vegetation cover within this area (Figure 8e, f, g). Those parts of the Phase 1, 2 and 3 trial areas are grazed by cattle throughout the year, although at relatively low stocking density. Movement of stock onto the frontal dunes is prevented by a fence along the landward side of the haul road.

The Phase 2 turf stripped area on the landward side of the haul road became flooded in the spring of 2014 (Figure 9a). It dried out after late April (Figure 9b) and some patch regrowth of vegetation occurred during the summer and autumn, particularly on the better drained marginal slopes and hummocks where roots had not been completely removed. Parts of the area were scraped to a greater depth as part of the Phase 3 work in the winter of 2014-15, and at the time of survey in May 2015 only limited vegetation regrowth was apparent (Figure 9c). However, vegetation significant recovery taken place during and since the summer of 2015 (Figure 9d). This reflects the relatively low wind speeds in this area and the limited quantity of fresh sand being blown across the haul road in this area from the Phase 2 frontal dune notches.

The Phase 2 area on the seaward side of the haul road has, however, experienced very significant accumulation of sand eroded from, and funnelled through, the four notches cut through the frontal dune ridge in January - February 2013. A significant depression, which formed a shallow pool in March 2013, has been infilled with sand and by July 2016 supported a dense stand of Creeping willow (*Salix repens*). The sand lobes immediately behind the notches have remained bare but more distal areas of sand accumulation have experienced significant colonization by species such as Sea holly (*Eryngium maritimum*) and Marram (*Ammophila arenaria*) (Figures 10a-d).

Following creation of the four northern notches in November-December significant sand movement occurred within the Phase 3 area. In part this reflected redistribution of sand deposited mechanically behind the notches but also was the result of wind erosion of the sides and floor of the higher, landward parts of the notches. Some new sand has also been blown from the beach, across the accretionary foredune platform which is present along this part of the shore, and through the notches. By March 2015 significant widening and partial deepening of the notches had occurred, resulting in slumping of turf blocks down the sides of the notches, and a significant quantity of blown sand had crossed the haul road into the dunes on its landward side (Figure 11a-d).

Figure 12 shows the extent of bare sand revealed by the UAV survey on 2nd March 2016. By this time blown sand has extended across the haul road behind the four northern notches (5,6,7 & 8) created in Phase 3, and part of the boundary fence had to be raised due to the increase in land levels on the eastern side. Blown sand also crossed the haul road behind notches 1 and 2 created in Phase 2, but most of the sand extending landward behind the southernmost notches (3 and 4) was trapped in a depression on the seaward side of the haul road (Figure 10).

The positions of selected RTK GPS survey transects used to monitor topographic changes associated with the notches are shown superimposed on the pre-works and post-works LiDAR DEMs in Figures 13 & 14, respectively. Elevation data for the same transects were also extracted from the February 2006 and March 2014 LiDAR survey DEMs, and from the February 2016 UAV survey DEM.

As noted in Section 2.4 of the report, the UAV data supplied to KPAL were found to contain significant geo-referencing and other errors which were particularly large for the southern part of the survey area (Figure 15). In an attempt to correct the data as far as possible, the raw data were re-gridded, and the x. y positions adjusted to match the existing LiDAR DEM grids. The UAV elevation values for each grid point were then compared with the 2014 LiDAR survey elevations, producing the relationship shown in Figure 16. An average trend line determined using linear regression was then used to adjust the UAV elevation data to ODN values. Comparison of the adjusted UAV elevation values with LiDAR elevation value for points along the haul road (Figure 17) showed that between chainage 450 and 700 the two data sets showed reasonable agreement, but between change 0 and 450, and south of chainage 700, the UAV adjusted data are 1.5 to 2 m ‘too high’. As a further stage of data correction, the observed height differences for each point along the haul road were extrapolated in an east-west direction and the UAV DEM data ‘warped’ in Surfer. The resulting adjusted UAV DEM (Figure 18) is an improvement on that produced using the raw data but still contains significant errors, especially in the southwest part of the survey area.

Figure 19 shows the difference in elevation between the 2006 and 2014 aerial LiDAR surveys. The areas of sand excavation (red) and deposition (green) clearly seen. Also evident are small areas of natural wind erosion and deposition in the northern part of the trial area (Phase 3 works had not been undertaken at the time of the 2014 LiDAR survey) and a significant area of apparent frontal dune erosion in front of the Phase 1 area. In part this reflects the process of artificially reducing the height of the dune cliff to form a gentler ramp at the start of the Phase 1 works (largely by pushing sand onto the upper beach), but also reflects the effects of wave erosion during the stormy winter of 2013-14. Much of the sand lost from this area was moved northwards by longshore drift and some appears to have been blown through the Phase 2 notches after their creation.

The difference in elevation between the 2014 aerial LiDAR DEM and the 2016 adjusted UAV DEM is shown in Figure 20. The effect of major errors in the UAV data for the western part of the Phase 1 area, southern part of the Phase 2 area, and the adjoining beach are clearly evident. However, the difference map does display with reasonable reliability the patterns of sand excavation and deposition associated with the Phase 3 notches and the notches 1 and created in Phase 2.

Figure 21 presents a comparison of topographic long profiles for the Phase 2 notches, while cross-profiles for the mid part of each notch are compared in Figure 22. It should be noted that the profiles extracted from the 2016 UAV DEM are unreliable. All of the notches showed significant deepening of their seaward and mid sections between May 2013 and March 2014, although accumulation of sand and wave-washed debris during the stormy winter of 2013-14 led to the formation of low ridges at the mouths of the notches. These were later cleared in late 2014 by bull-dozing the material onto the beach. Between March 2014 and March 2015 notches 1 and 2 showed a reduction in depth in their mid-sections but there was little change in depth of notches 3 and 4. In all cases there was significant accumulation of sand in the areas behind the notches. All of the notches showed a slight increase in width in the mid-section, particularly affecting the upper parts of the side slopes. Undercutting of the turf at the top of the slopes caused collapse and sliding of turf blocks which progressively break up as they dry out and the vegetation dies.

Notches 5 to 8 initially had a shallow form and steeper landward slope than notches 1 to 4, partly due the closer proximity of the haul road to the shore (Figure 23). Although the long- and cross profiles and cross-sections extracted from the 2016 UAV survey DEM are prone to significant error, they show a rise in ground level along the mid and inner parts of the trough, in the areas on either side of the haul road, and at the seaward ends of the troughs which is consistent with visual observations. At the time of the RTK GPS ground survey in March 2015 some widening on the notches was evident, notably on the northern side. However, consideration of the approximate relative volumes involved suggests that the quantity of sand released from widening of the notches is insufficient to account for the magnitude of sand which has accumulated within the floor of the troughs and in the areas to landward; input of new sand from the beach and frontal dune platform is highly likely as on this section of the shore, both the beach and frontal dune sand budget are positive. However, observations made during the site inspection in mid July 2016 indicated that vegetation is becoming re-established on the foredune platform and within the mouths of the notches, with the consequence that transport of sand through the notches is now less than previously.

3.1.4. Overall assessment

Table 3 summarises the changes in bare sand extent in each of the Kenfig phases between time of first survey and the beginning of March 2016. The Phase 1 area west of the haul road showed a reduction in bare sand area of 62.2% due to vegetation regrowth, whereas Phase 2 area west of the haul road and the Phase 3 area showed increases in bare sand area of 2.2% and 26.6%, respectively (Table 4).

The following conclusions can be drawn regarding the Kenfig trials:

- The greatest sand mobility has occurred within the Phase 3 area; the main reason for this is greater sand availability with sand supplied both from the beach and from widening of the notches themselves, but the steeper nature of the notches has assisted by encouraging greater wind speed up and sand transport capacity.

- Those parts of the Phase 1 and Phase 2 areas to the east of haul road have seen only limited sand mobility and increasing encroachment of vegetation; this reflects relatively low exposure to strong winds and a very limited input of new sand from the west.

- The part of the Phase 1 area to the west of the haul road initially saw a significant increase in sand mobility, especially on the seaward side and immediately landward of the dune ridge which remained after crest lowering, but there has been an progressive tendency towards re-vegetation owing to (a) no notches were created to funnel the wind and (b) there is little or no supply of new sand from the beach in this area.

- The part of the Phase 2 area west of the haul road has seen a significant and sustained increase in sand mobility immediately behind the four notches; sand has extended eastwards towards the haul road but not crossed it, infilling a former depression where vegetation growth has now been stimulated; the relative success in this area is partly attributable to funnelling and acceleration of the wind which has led to widening of the notches and to the fact that there has been some input of sand from the beach, largely eroded from the up-drift frontal dunes during the stormy winter of 2013-14.

- The application of herbicide to vegetation regrowth in the Phase 1 area had a beneficial effect which lasted for approximately 2 years.

- Cattle grazing and trampling on the eastern side of the haul road has helped to slow vegetation regrowth within the Phase 1 and Phase 2 areas, and to maintain localised areas of bare sand around trackways, but has not been able to prevent it, with Dewberry (*Rubus caesius*), Ragwort (*Senecio jacobaea*) and Rosebay willowherb (*Chamaenerion angustifolium*) dominant on areas with low sand supply and Marram or other grasses in areas of greater sand availability.

3.2. Merthyr Mawr Warren

The Merthyr Mawr dunefield lies on the south-eastern side of Swansea Bay, just east of Porthcawl (Figure 25). Much of the area of blown sand falls within the Merthyr Mawr NNR and Merthyr Mawr SSSI. It also forms part of the Kenfig / Cynffig SAC. The dunes closest to the sea can be classified as being of bay-fringing type but further inland transgressive climbing dunes have advanced inland and climbed the Candleston Castle escarpment to reach an elevation of >80 m above ODN. The lower part of the dunefield is mostly underlain by deposits of marine shingle and sand, with areas of bedrock at shallow depth and exposed on the foreshore towards Newton

Burrows in the west (Pye & Blott, 2011). The total blown sand area is approximately 559 ha, of which approximately 39% consisted of bare sand and mobile dunes in the 1940s (Figure 26; Pye *et al.*, 2015a). By 2009 the percentage cover of bare sand had dropped to approximately 3.5%, mostly concentrated in areas of the frontal dunes, one large parabolic dune in the southeast corner of the site, and areas close to the Candleston Castle car park, which are subject to high visitor pressure (Figure 27).

Most of Merthyr Mawr Warren has traditionally been grazed at moderate to low density but since the construction of new fencing in 2013 stock are prevented from accessing the dune rejuvenation areas. However, pony-trekking is permitted within the rejuvenation area and, together with trampling by foot visitors, plays a role in creating and maintaining bare sand areas along trackways.

3.2.1. Phase 1

Outline proposals for dune rejuvenation works were proposed by Pye and Blott (2011b) and subsequently refined by local area NRW staff. Phase 1 works undertaken in December 2012 involved turf stripping and sand movement within an approximate 4 ha area on the seaward side of a large parabolic dune (Dune A) in the south-eastern part of the dunefield (Figure 28). A major objective of the work was to recreate more natural dune topography in an area which had been severely disrupted by gravel extraction during the late 1960s and early 1970s. The work consisted of the following elements (Ludlow, 2012; Table 4):

- turf stripping with the deflation corridor and on the inward facing slopes of Dune A.
- removal of a hummocky dune ridge at the base of the windward ramp of Dune A.
- deepening of the deflation corridor to create a wet slack area.
- excavation of sand from a sand ridge on the western side of the deflation corridor.
- placement of excavated sand to create / enhance the arms of Dune A.

Topographic monitoring surveys were undertaken in March 2013 (KPAL, 2013d), March 2014 (KPAL, 2014c) and March 2015 (KPAL 2015c).

3.2.2. Phase 2

In winter 2013-14 a small area of Phase 2 works was undertaken, consisting of further sand excavation from the western side of the artificial slack created in Phase 1 and deposition of the excavated sand to create an artificial dune adjacent to the south-eastern corner of the Phase 1 works where an existing dune had been removed / destroyed during gravel extraction works in the early 1970s (Ludlow, 2013; Figure 28). The work was undertaken using one 20 tonne excavator, one 8 tonne excavator and three dump trucks. In the time available it was not possible to excavate all of the sand which was planned, and the sand placement site had to be relocated to avoid placing overburden above a sewage pipeline route. It was therefore not possible to make the eastern arm of the large parabolic dune ‘A’ as long and continuous as had originally been planned.

3.2.3. Phase 3

A large-scale programme of Phase 3 works was undertaken in November 2014 and consisted of the following elements (Ludlow, 2014; Figure 29):

- 6 notches cut in the frontal dunes (1 to 6 in Figure 29, re-numbered A to F for topographic monitoring purposes)
- 4 troughs excavated to remove dune ridge obstacles and link frontal dune notches with inland areas (7 to 10 in Figure 29)
- Turf stripping upwind to expose more bare sand of the Phase 1 area
- Excavation and re-profiling of one large parabolic dune (Dune E)
- Extension to the artificial dune (Dune F) created in Phase 2

The work was undertaken using two 20 tonne 360 excavators, two JCB articulated dump trucks and a small Komatsu 41P bulldozer (Table 5). The notches were cut to a relatively shallow depth due to concerns about the sea breaking through and posing a threat to the buried sewage pipeline. The minimum level of the notches was kept approximately 2 m above the highest water levels observed during the high surge tides of December 2013 and January 2014. A summary of the main morphological parameters of each notch is provided in Table 6.

A total of approximately 3.5ha of bare sand was created in this phase, additional to the 2 ha created in earlier phases (Table 7). Some regrowth of Marram (*Ammophila arenaria*) and Dewberry (*Rubus caesius*) in the Phase 1 area was removed by a combination of hand pulling, spraying with glyphosate herbicide and weeding with a flame gun.

Ground photographs illustrating various phases of the works and the ground conditions during selected post-works surveys are presented in Figures 30-36. An aerial photograph taken on 18th April 2015 (Figure 37) shows the total bare sand area created during the three phases.

Figure 38 is an aerial photograph mosaic based on the UAV survey on 29th February 2016 which shows contrast striping apparently due to changes in cloud cover during the survey. Owing to the presence of these major contrast differences, and associated serious topographic shadowing effects, automated pixel by pixel determination of bare sand extent was not possible, and the external limits had instead to be mapped manually.

Figures 39 and 40 show the positions of selected long profile and cross-profile lines used to quantify changes in the level and morphology of the notches and associated sand transport corridors, superimposed on the October 2008 pre-works LiDAR survey, and on the post-works February LiDAR survey, respectively.

The composite DEM based on the UAV survey of Merthyr Mawr (Figure 41) was of better quality than that supplied for Kenfig, being correctly georeferenced, but elevation levels still had to converted to ODN. This was again done by comparing elevation values for each grid point in the UAV survey DEM with elevation values for the same grid points in the 2014 LiDAR DEM. In this instance a better linear relationship was obtained (Figure 42) and consequently greater confidence can be placed in the correction used to convert the UAV data to ODN (Figure 43).

Figure 44 shows the elevation differences between the October 2008 and February 2015 LiDAR surveys. The biggest differences are due to the excavation and placement of sand. However, other changes are also evident including significant deposition of sand on the landward side of the crest of the large mobile parabolic dune (Dune A). General sediment accretion within the frontal dune system is also evident, indicating a significant supply of sand from the beach to the dune system (in contrast to the Phase 1 and southern Phase 2 areas at Kenfig Burrows).

Figure 45 shows the elevation difference between the February 2015 LiDAR DEM and the February 2016 UAV DEM. The main differences are (a) major landward movement of sand towards the back of the frontal dune system, associated with the notches and sand corridors, (b) significant advance of sand from the turf stripped area into the seaward end of the Phase 1 area, resulting in the infilling / burial of a small pond which formerly existed in that area, and (c) deflation on the upwind side and deposition on the downwind side of the re-profiled dune (Dune E), d) deflation from the crest and deposition on the downwind side of the artificial dune (Dune E), (e) deflation from the two enhanced ‘arm’ extension of Dune A, together with deflation of the windward ramp and crest and deposition on and beyond the slip face.

The long profiles of the notches and sand corridors surveyed in March 2015 using RTK GPS are compared with profiles extracted from the February 2016 UAV DEM in Figure 26. The mid-point cross-sectional profiles are compared in Figure 47. A very slight lowering of the surface levels along the length each notch is indicated, but with no significant change in width. In the case of notches, A, C, D and E there has been major accretion of sand on the landward side of the notch, and in the case of Notch F sand deposition had led to an increase in the maximum crest height. Notch B showed no significant change of level up to 22 m from the dune toe, but significant transport had also occurred through this sand corridor with deposition occurring further inland. Most of the sand transported through the notches and deposited behind has evidently been sourced from the beach.

3.2.4. Overall assessment

The changes in bare sand area at Merthyr Mawr between 2012 and end of February 2016 are summarised in Table 7. A relatively high proportion (92.9%) of the original bare sand area within Phase 1 has been retained, bare sand within Phase 2 has more than doubled its initial footprint area, and there has been only a very slight reduction in bare sand area (1.9%) within the Phase 3 area.

The following overall conclusions can be drawn from the trials at Merthyr Mawr:

- the notches in the frontal dune ridge have been very successful in encouraging transfer of sand from the beach into the hind dune area

- the sand corridor extensions to some of the notches, and the wider stripping of turf, have been successful in encouraging the sand to spread further inland towards the deflation trough of Dune A which was deepened and widened in Phase 1

- most of the sand reaching this point has been trapped by the wet ground / seasonal standing water within the deepened slack

- deflation of the windward slope and crest of Dune A has continued, leading to continued deposition on the slip face and forward movement of the dune (to some extent enhanced by people climbing / sliding on the dune)

- the excavated sediment placed on the arm of extension of Dune A in Phase 1, and used to form Dune E in Phase 2, contained a significant amount of gravel which, as deflation has proceeded, has formed an armoured lag surface; this is likely to stop and even stop further sand deflation unless removed / disturbed

- the movement of sand at the trial sites is favoured by a positive beach and foredune sediment budget

- the convex long profile form of the notches has encouraged wind speed up and sand transport into the dunes

- some of the sediment excavated from within the Phase 1 area contained a significant proportion of gravel and selective wind erosion has caused this to form an armoured lag on the surface of some of the deposited sand, limiting its further movement; this could be addressed in the short term by raking of the surface and in the medium term by grading of some of the worst affected deposits, with the collected gravel being placed on the upper beach which is already characterised by a well-developed gravel berm.

3.3. Newborough

The Newborough dune system is located between the Menai Strait and the Cefni estuary in SW Anglesey. The dune system is divided into two parts by a SW-NE orientated rocky ridge (Craig Gwladus) which has a detached extension at Llanddwyn Island. To the south of this ridge Traeth Llanddwyn extends in a south-easterly direction towards Abermenai Point. The main dunes forming the main part of the system behind Traeth Llanddwyn (Newborough Warren) overlie glacial till at shallow depth. An extension to these dunes extends south-eastwards along Abermenai spit, a gravel and sand barrier which separates the extensive sandy flats of Traeth Melynog from the sea. North of Llanddwyn Island, Traeth Penrhos extends north-westwards towards the Cefni estuary. Frontal dunes form a narrow barrier ridge to the north of the Craig Gwladus, but transgressive climbing dunes, now stabilised by the conifer plantations of Newborough Forest, which extend up to 3 km inland. At the north-western corner of the system, a series of shore-parallel dune-capped sand ridges form a prograding spit system.

The majority of the trial dune rejuvenation works lie within the Newborough Warren NNR, but parts lie within the boundaries of Newborough Forest (Figure 48). Newborough Warren and Newborough Forest form parts of the Newborough Warren and Llanddwyn Island SSSI and the Abermenai to Aberffraw Dunes SAC. In the 1940s and 1960s more than 50% of the Newborough system consisted of bare sand and mobile dunes, but by 2009, the figure had been reduced to only 2.8% (Figure 49; Pye & Blott 2012a; Pye *et al*., 2015).

3.3.1. Phase 1

The requirements and options for dune rejuvenation trials at Newborough Warren were identified by Pye & Blott (2012a). An area for Phase 1 works, carried out in January - February 2013, was identified in an inland area of Newborough Warren approximately 500 m - 800 m east of the Newborough Forest boundary. This contained three adjacent stabilised parabolic dunes, which were identified as Areas 1, 2 and 3, respectively. A decision was made to use Area 1 as a control where no intervention works would be undertaken, while turf stripping and some sand excavation were undertaken in Area 2 and Area 3 (Figure 50). The main objective of the trials in Areas 1 and 2 was to test whether forward movement of the dunes could be restarted by clearance of vegetation from the windward slopes and most landwards parts of the deflation corridors, and by placing piles of 'sacrificial' bare sand at the base of the windward slope. The stripped turf was placed behind the dunes and at locations to raise low points on the 'arms' and crest of the dunes (Table 8). A separate area of low ground within one of the large dune deflation corridors (Area 4 shown on Figure 50) was also selected for turf stripping, primarily with the purpose of creating new pond / wet slack habitat. Turf stripped from the floor of the existing depression was used to from an artificial mound on the western side of the works area. The total area of bare sand initially created in the three areas was approximately 3.6 ha (Table 6).

A baseline topographic monitoring survey was carried out in January 2013 (KPAL, 2013e) as a cross-check on a 2009 LiDAR survey available for research purposes from the NERC website. Post-works monitoring surveys were undertaken in May 2013 (KPAL, 2013f), March 2014 (KPAL, 2014d) and March 2015 (KPAL 2015c). UAV aerial photography surveys were carried out by ExeGesis Ltd in June 2013 and by DTM Technologies Ltd in January 2016. A LiDAR survey of the area was undertaken by the Environment Agency on behalf of NRW in October 2014.

The aerial photograph mosaic based on the June 2013 UAV survey (Figure 51) shows the extent of bare sand at that time. Bare areas behind the dune crest and dune arms largely represent locations where excavated turf and sand was placed. The equivalent situation at the time of the January 2016 UAV survey is shown in Figure 52. Unfortunately, the 2016 image quality is inferior to that in 2013, shadowing being a particular problem for Area 4, and the entire area of interest for Areas 1 and 2 has not been captured by the 2016 survey. Nevertheless, a reduction in bare sand extent is qualitatively indicated.

The topography of the Phase 1 area revealed by the 2009 and 2014 LiDAR survey is shown in Figures 53 and 54, respectively, and the difference between the two shown in Figure 55. The largest differences are explained by the turf stripping and placement, although the results of the RTK GPS monitoring in 2013 and 2014 showed that significant smaller scale changes had also occurred due to wind deflation and deposition. This particularly affected parts of the windward slopes and crests of the dunes, and also the 'sacrificial' sand mounds placed around the base of the windward slopes.

The topographic data for the 2016 UAV survey (Figure 56) were found to be correctly georeferenced (in terms of x and y positions) but the elevation (z) data showed distortion across the survey area, reflecting the number and distribution of ground control points used to correct the survey, and with the vertical errors being the greatest beyond the areas of the works. This is evident from areas of apparent major increase or decrease in surface levels towards the margins of the UAV survey area, which are apparent when the UAV DEM data are compared with the 2014 aerial LiDAR data (Figure 57). However, areas of apparent slight surface lowering within the turf-stripped parts of the dune deflation corridors and windward slopes, and areas of slight deposition downwind of the dune crests, are consistent with the results of the RTK GPS surveys and observations during site walkover inspections. A series of sequential ground photographs taken from the dune crest of Area 2, looking upwind across the partially stripped deflation corridor, is shown in Figure 58. Similar sequences of photographs for Areas 3 and 4 are shown in Figures 59 and 60, respectively. A ground inspection carried out by KPAL personnel in early August 2016 indicated significant growth of vegetation since the DTM Technologies survey in January 2016. Area 4, in particular, had become largely vegetated. However, significant areas of mobile sand remained around the dune crests in Area 1 and Area 2, especially adjacent to tracks and other areas of disturbance used by ponies which graze the area.

3.3.2. Phase 2 West

Following an assessment of requirements and options for intervention (KPAL, 2013h), Phase 2 works commenced in November 2013 within an area identified in the Newborough Forest Management Plan 2015-2020 as Zone 1 West (Figure 61). The works were located in an area which was artificially enclosed and stabilized by the Forestry Commission in the 1950s and 1960s by the erection of fences to trap sand and subsequent planting with Marram and conifers. Two sub-parallel dune ridges were created which merged into a single ridge towards the southern end of Traeth Penrhos. Erosion during the 1970s resulted in narrowing and partial breaching of the southern part of the ridge which was repaired using sand excavated from an area behind the frontal dune.

A baseline UAV aerial photography survey was undertaken by ExeGesis Ltd in June 2013 (Figure 62) and a baseline ground topographic survey was carried out by KPAL in July 2013. An attempt was made to create a DEM based on the June 2013 UAV survey using photogrammetric methods (Figure 63) but comparison with the results of the July 2013 ground RTK GPS survey revealed major errors in the UAV DEM (KPAL, 2013h).

Four notches were created in the artificial frontal dune ridge in November 2013 by enlarging existing blowouts and areas of low ground around access paths to the beach. Tree removal and de-stumping on the landward side of the frontal dune ridge in November - December 2013. The dimensions of the notches were similar to those previously created at Kenfig (Table 8). Further tree felling and de-stumping within the primary dune slack and on the seaward side of higher ground to the east was undertaken in the period November 2014 - February 2015. Inferior quality timber was chipped on site and most of the brash and surface litter taken off site (Table 9). A combined bare sand area of approximately 3.88 ha was initially created (Table 10). Selected ground photographs taken before and after the works are shown in Figure 64.

An airborne LiDAR survey of the whole of Newborough Forest and Newborough Warren undertaken in April 2014 shows the locations of the four notches and surface topography after tree felling and de-stumping (Figure 65). A post-works ground RTK-GPS topographic survey was carried out by KPAL in March 2015 (KPAL, 2015d) and a partial survey undertaken in February 2016. A further UAV survey was undertaken by DTM Technologies Ltd in January 2016.

Figure 66 shows the extent of bare sand revealed by the January 2016 UAV survey compared with that mapped using RTK GPS in March 2015. Over the intervening period bare sand has extended into the surrounding forested areas and northwards along the trough behind the frontal dune. Vegetation cover on the frontal dunes between the notches was also very thin in January 2016.

The DEM produced from the January 2016 UAV survey data using photogrammetric methods is shown in Figure 67. A comparison of this DEM with the 2014 LiDAR DEM (Figure 68) showed reasonably close agreement around the landward end of profile 4 but increasingly large differences towards the margins of the survey areas, furthest away from the ground calibration points (shown as black dots on Figures 67 & 68). Further comparisons of line profiles along and across the notches extracted from the UAV DEM with those from the 2014 LiDAR and 2015 and 2016 RTK GPS surveys showed major errors (of > 1 m in the vertical) in the UAV DEM towards the margins of the survey area (Figures 69 & 70). Close examination also showed that the UAV DEM and imagery lack high resolution detail within the notches, apparently due to problems in obtaining adequate triangulation within these steep-sided features. Comparison of the March 2015 RTK GPS survey with the April 2014 LiDAR data indicated significant widening, not deepening of Notch A, but only minor changes in the cross-sectional profiles of Notches B, C and D (Figure 70). Depositional sand lobes had formed behind notches A, B and C, and sand had spread as a thin layer (< 50 cm) over a wide area behind all four notches (Figure 69).

3.3.3. Phase 2 East

During the period December 2014 to January 2015 tree-felling and de-stumping was undertaken within an area identified within the Newborough Forest Management Plan 2010-2015 as Zone II East, located on the frontal dunes to the south-east of the Traeth Llanddwyn car park (Figure 71). After tree felling and de-stumping of parts of the area, all surface debris including soil litter layer was removed from the area (Table 8). In the winter of 2014-15 three slot-like notches (A, B, C in Figure 72) were also excavated in the frontal dunes, the dimensions of which were similar to those in the Phase 1 West area (Table 9). A post-works RTK GPS survey of the site was undertaken shortly after completion of the notches in March 2015 (KPAL, 2015e). Approximately 3.5 ha of bare ground was initially created (Table 10). Selected photographs of the area before and after the works are presented in Figure 73.

Pre-works LiDAR surveys of the area were undertaken on 12th May 2009 (Figure 74) and 9th April 2014 (Figure 75). An elevation difference map of the two (Figure 76) shows limited area of sand erosion and deposition associated with small bare sand areas in the frontal dunes which are subject to relatively heavy visitor pressure, and also a large area of sand loss where the frontal dune platform was entirely eroded away, principally during the stormy winter of 2013-14.

A DEM of the area created from the January 2016 UAV survey data is shown in Figure 77. Comparison of this DEM with the 2014 LiDAR DEM clearly shows the effect of excavation at notches A, B and C and sand erosion close to the eastern end of the track running along the forest edge. A general lowering of sand levels is also indicated in the areas closest to the car park where pedestrian pressure is high. These areas are close to ground control points and the trends in surface level are therefore likely to be generally reliable. However, comparison with RTK GPS profile data surveyed by KPAL in February 2016 indicated that there are again significant errors in the UAV DEM data away from the ground control points (Figure 78). Comparison of line profiles along and across the notches indicated that the UAV data are up to 1 m ‘too high’ towards the western and eastern limits of the survey area, compared with elevations indicated by the RTK GPS survey undertaken only a few days later (Figures 79 & 80). The UAV DEM data show better agreement with the February 2016 RTK GPS data in the central part of the DEM close to the ground control points.

Comparison of the March 2015 and February 2016 RTK GPS survey data showed that all three notches had deepened by more than a metre over the intervening period, and it is highly likely that this has provided the major source of sand transported through the notches and hind dune area towards the forest margin.

A ground walkover survey by KPAL personnel in early August 2016 confirmed that active sand movement is taking place through the notches, fed by wind erosion of the floor, and to a lesser extent the sides, of the notches themselves and also by deflation from a relatively narrow backshore in front of the dunes. Beach levels have shown some recovery since the stormy winter of 2013-14 but the dry backshore remains narrow. In the areas between the notches, little sand movement has taken place and the surface has become partially vegetated by Dewberry (*Rubus caesius*), Ragwort (*Senecio jacobaea*) and other species.

3.3.4. Phase 3

Between January and March 2015 relatively large-scale turf stripping and sand excavation works were undertaken in the Phase 3 area at the north-west corner of Newborough Warren (Figure 71). The work involved excavation of six notches through the frontal dunes, all but one of which (Notch I) were linked to larger turf-stripped and partially excavated areas extending up to a maximum of 500 m inland (Figure 72). Stripped turf blocks and piles of excavated sand were placed mainly at the back of the worked area. The work was undertaken using two 14 tonne excavators, two 35 tonne dumper trucks and one bulldozer (Table 8).

The notches D to I were designed to have varying lengths and depths of cut, bed slopes and orientations relative to the prevailing wind, but the maximum elevation of the base of troughs (relative to ODN) was similar in all cases (Table 9). Photographs of selected notches at different times after completion are illustrated in Figure 73.

The area of bare sand at the time of first survey in late March 2015 was 6.69 ha. At the time of the UAV survey in late January 2016 6.39 ha of bare sand remained within the original area and sand had spread to cover an additional 2.61 ha, an overall increase in bare sand area of 34.5% (Table 10).

Pre-works LiDAR DEMs of the area are shown in Figures 74 and 75 and a post-works DEM based on the 2016 UAV survey is shown in Figure 77. A difference map between the 2014 and 2016 DEMs (Figure 78) shows that the UAV DEM is again unreliable beyond the limits of the ground control points, and there is a marked ‘step’ in elevation running SW – NE through the Phase 3 area which is possibly caused by differences in datum assigned to different flight lines.

Profiles along and across the notches surveyed by RTK GPS in late March 2015 (KPAL, 2015f) and early February 2016 are compared with profiles extracted from the January 2016 UAV DEM in Figures 82 & 83. The UAV DEM again shows systematic errors towards the western and eastern limits of the survey area, furthest away from the ground control points. The UAV survey also displays anomalously high elevations for standing water areas.

Comparison of the March 2015 and February 2016 RK GPS profiles indicates that all of the notches had undergone deepening of their seaward slopes to varying degrees, with eroded sand moved landwards to form a depositional lobe at the landward end of the notch (Figure 82). Given the relatively low, wet and stony nature of the beach fronting the notches during this period, it is unlikely that any significant quantity of sand was supplied from the beach to the hind dune area. A site walkover survey in early August 2016 indicated that some deepening, and limited widening, of the notches is still taking place, but this cannot continue indefinitely, and the supply of cannibalized sand supplied from the notches to the hind dune area is likely to decline over time.

During the August walkover survey, it was observed that the largest increase in bare sand area had occurred at the landward side of the works area where conical piles of sand, deposited in February – March 2015 beyond the landward limit of the excavations, had broken down and spread as a sloping sand lobe across the vegetated area behind. This implies that the creation of large piles of bare sand, left exposed to the wind, is an effective and simple means of creating bare sand sheets and low mobile dunes.

3.3.5. Overview of Newborough works

The changes in bare sand area at Newborough between March 2012 and January 2016 are summarised in Table 10. Considering Phase 1, 2 and 3 together, the total bare sand area in January 2016 was approximately 8% larger than at the time of first survey shortly after the works were completed. Only the phase 1 areas on the inland dunes have shown in reduction in bare sand area of time. The following general conclusions can be drawn:

- Wind velocities in the inland Phase 1 areas are too low to allow sustained wind erosion, and sand mobility is now restricted to disturbed areas near the crest of the higher dune (area 2); the lack of supply of sand from upwind is a further factor encouraging a trend towards re-vegetation.

- The aim of the Phase 1 trial area 4 was primarily to create additional pond / wet slack habitat, and so far, this objective has been met.

- The notches in the frontal dune ridge within Phases 2 West, 2 East and 3 have so far been very successful in locally accelerating the wind and encouraging sand transfer into the hind-dune area.

- At Phase 2 West there has also been significant transport of sand from the beach through the notches into the hind-dune area; it is estimated that the amount of sand entering the Phase 2 West hind dune area is two to three times greater than would have been the case with an intact foredune.

- At Phase 2 East it is estimated that approximately two thirds of the sand blown into the hind dune area has originated from deepening and widening of the notches, with one third representing new sand derived from the beach.

- In the case of the Phase 3 notches very little new sand has so far been transported from the beach on account of the very low, stony nature of the beach following the stormy winter of 2013-14.

- Deepening and some widening of the Phase 3 notches has released sand for transfer into the hind-dune area, and some sand eroded by the wind from the dune cliffs has been blown along the cliff toe and then inland through the notches.

- The sand corridor extensions to some of the Phase 2 East and Phase 3 notches, and the wider stripping of turf, have been successful in encouraging sand to spread further inland.

- The initial convex long profile form of many of the Phase 2 and Phase 3 the notches has encouraged wind speed up and sand transport into the dunes.

- Had the Phase 2 and Phase 3 notches not existed, the supply of sand to the hind dune area would have been much smaller (perhaps only 10-15%).

- The long-term sustainability of bare sand areas within Phase 2 east and Phase 3 is hampered by a lack of new sand supply from the beach under present conditions; they are unlikely to change in the short term since much of the sand eroded during the 2013-14 and 2014-15 winters has been transported southwards towards Abermenai rather than offshore, but in the medium term, positive beach sediment budget conditions may return.

- Tree felling on the margin of the Newborough Forest has resulted in an important gain of sand dune habitat and has freed the coastal strip to respond to natural processes; wind velocities and sand movement within the Phase 1 West and Phase 2 East areas have been greatly increased and created space within which the frontal dunes can respond to future changes, including rollover in response to sea level rise or increased storminess.

4. Discussion, conclusions and recommendations

4.1. Overview of changes in bare sand area

Tables 5, 7 and 10 summarise the changes in bare sand area over time within the different rejuvenation trial areas at Kenfig, Merthyr Mawr and Newborough, respectively. At Kenfig, the area of bare sand in March 2016 represented approximately 94% of the area (10.3 ha) at time of initial survey. The Phase 2 West area and the Phase 3 area showed an increase in bare sand area, while in the Phase

1 area East (inland dune) the bare sand area in March 2016 was only approximately 38% of the original area. At Merthyr Mawr the total bare sand area in late February 2016 represented approximately 104% of the area at the time of the initial survey, and none of the rejuvenation areas had experienced significant re-vegetation. At Newborough, the total bare sand area in late January 2016 represented 108% of the area at the time of the initial survey, significant increases in area being recorded at Phase 2 West, Phase 2 East and Phase 3. The Phase 1 inland trial areas showed the lowest remaining percentage of bare sand, the lowest value (12.4%) being recorded in area 4, where the primary design objective was to create a wet slack rather than mobile dunes.

With the exception of the Phase 1 and eastern Phase 2 areas at Kenfig, and the Phase 1 area at Newborough, the trials can be considered to have been so far successful in terms of increasing the extent of bare sand, much of which is mobile.

To date, follow-up intervention measures have been limited to movement of a few turf blocks from the sides and clearance of sand / shingle / driftwood from the Phase 2 notches at Kenfig, limited spraying of Dewberry (*Rubus caesius*) within the Kenfig Phase 1 area in later 2012, hand pulling of Marram regrowth and some spraying at Merthyr Mawr in 2014 and 2015.

4.2. Factors influencing the relative success of the intervention trials

Several factors have influenced the relative success of the trial interventions both between and within areas, including weather conditions beach sediment budget and sand supply to the dunes, variation in local wind conditions, and differences in pressure on vegetation from grazing and visitors.

4.2.1. Weather conditions

The scale and timing of post-intervention sand movement at all three trial sites has been influenced by variations in weather conditions. Aeolian sand transport is influenced strongly by wind speed and duration, and to a moderate degree by precipitation, temperature and humidity. Rainfall suppresses aeolian sand movement but surface sand can dry out within as little as thirty minutes if evaporation rates, which are affected by wind, temperature and humidity, are sufficiently high (Pye & Tsoar, 2009). Longer term sand mobility is strongly influenced by rates of vegetation spread and vertical growth. These in turn, are strongly dependent on precipitation and temperature and to a lesser extent on wind speed, sand deposition rate and factors such as nutrient availability and salt spray deposition (Ranwell, 1972; Maun, 2009). Medium to long term dune mobility reflects a balance between these two factors and also disturbance factors which include grazing by livestock and rabbits, pedestrian and vehicular visitor pressure, fires and dune management measures (fencing, vegetation planting / cutting etc.).

Figure 84 shows the temporal variation in aeolian sand drift potential between 2000 and 2015 based on wind records for the closest Met Office meteorological station to Kenfig and Merthyr Mawr (Mumbles Head in Southwest Swansea Bay, Figure 1), and to Newborough (Valley in northwest Anglesey). Values of sand drift potential (DP) were calculated from the raw 15-minute wind data using a modified version of the method proposed by Fryberger and Dean (1979). Average wind roses for the full period of available digital record are shown in Figure 85. In both cases the average resultant sand drift direction (RDD) is towards the northeast, reflecting the dominance of southwesterly winds at both stations. Owing mainly to the nature of the surrounding coastal morphology and topography, Valley has greater exposure to winds from the south and south-southwest than Mumbles. At Kenfig, and to a lesser extent at Merthyr Mawr, on the eastern side of Swansea Bay, there is greater exposure to northwesterly winds than at Mumbles, and the resultant drift direction is slightly more easterly. At Newborough, the dunes behind Traeth Llanddwyn, and to a lesser extent behind Traeth Penrhos, are also sheltered from northwesterly winds by high ground inland, and the average resultant drift direction is not very different from that at Valley (Pye & Blott, 2012a). The Mumbles recording station is located at a higher elevation above sea level than the Valley station and consequently the measured wind speeds and calculated drift potential values are relatively higher. In order to evaluate the impact of wind speeds and potential sand drift on dune mobility it is more useful to consider three and six-monthly periods rather than individual monthly values, which show considerable variability. A high frequency of moderate and strong winds must be sustained over at least a three-month period to have any significant effect on dune growth and mobility. In general, the autumn and winter months (October to March) are characterised by high wind speeds than the spring and summer months (April to September), and in the winter period shows greater year to year variability than the summer period (Figure 84e and f). With regard to the period of the dune rejuvenation trials, the period prior to October 2013 was one of relatively low windiness and sand drift potential at Mumbles, but the winter period of 2013-14 was very windy. The anemometer was out of operation for part of the 2014 summer, but conditions during the winter of 2014-15 and summer of 2015 were 'average', followed by another windy winter in 2015-16. A broadly similar pattern is shown by the Valley record.

Figure 86 presents cumulative potential aeolian sand transport vector plots calculated for the two stations and the period 2000-2015. At Valley a period of more easterly transport potential is indicated between 2004 and 2011, after which time the resultant transport direction returned towards the longer term average trend as southwesterly and southerly winds became more influential (Figure 86a). At Mumbles, a similar period with more easterly potential transport occurred between 2007 and 2013, after which time there was a return to the longer-term trend with greater southwesterly and southerly influence (Figure 86b).

Figure 87 shows the temporal variation in three monthly and six-monthly rainfall recorded at Mumbles and Valley over the same time period. A general pattern of winter – summer variation is again apparent, although the differences are smaller than for wind and there is greater inter-annual variation. At Mumbles the winters of 2012-13 and 2013-14 had the highest winter (October to March) rainfall totals in the period of record (since 2000), and the winters of 2014-15 and 2015-16 were also relatively wet. At Valley, the winter of 2015-16 was the second wettest recorded since 2000, followed by the winters of 2013-14 and 2012-13. Rainfall during the summer periods of 2013, 2014 and 2015 at both Mumbles and Valley can be considered as 'average' relative to the period since 2000.

Following completion of the Phase 1 dune rejuvenation works at Kenfig in February 2012, wet, cool and non-windy conditions limited the scale of sand blowing and favoured plant regrowth, notably of *Rubus caesius* (Dewberry) where roots had not been completely removed during turf stripping. Intervention in the form of herbicide application was required in late summer - autumn 2012. In February - March 2013 a period of drier conditions associated with easterly winds returned, facilitating significant wind movement of sand at a time when plant growth was at a minimum. This was followed by significant sand under the influence of southwesterly winds and relatively dry conditions in April and May 2013. However, during the summer and autumn of 2013 regrowth of vegetation occurred in areas which had not been sprayed the previous year, including on piles of deposited turf which had not been buried by sand. Wet conditions during the winter of 2013 - 2014 led to flooding of lower lying areas and prevented the completion of the Phase 2 works. Virtually no aeolian sand movement occurred during this time. However, during the summer of 2014 lower rainfall and higher temperatures led to drying out of the slack areas and sufficient wind events occurred to allow significant movement of sand within the seaward part of the Phase 1 area and around the Phase 2 notches. Further inland, wind energy was insufficient to cause more than local scouring within the Phase 1 and Phase 2 areas landward of the haul road, and significant recovery of vegetation took place. A return to wetter conditions in the winter of 2014 -15, associated with only moderate wind energy, restricted aeolian transport to areas with greatest exposure and supplies of new sand (principally areas close to the notches). With the return of higher temperatures encouraged further vegetation growth in the late spring and summer of 2015. Some dieback occurred during the late summer and autumn but extensive sand movement in inland areas was not favoured by high precipitation during the 2015-16 winter and spring – early summer 2016. Sand movement during this period was again largely restricted to the areas within and behind the frontal dune notches.

Broadly similar patterns occurred at Merthyr Mawr and Newborough, and it can be concluded that the relatively wet conditions which have prevailed since 2012 have favoured vegetation growth and generally acted to suppress aeolian sand transport in inland areas. Periods of relatively strong winds associated with a higher than average frequency of deep depressions which have crossed the British Isles during this period have favoured sand movement in exposed parts of the frontal dunes, particularly within natural blowouts and artificial notches, but have not been sufficient to cause mobilization of stabilised inland dunes.

While variations in weather conditions are beyond management control, management practices can be adapted to respond to such variations, including employment of vegetation spraying, changing of levels of stock grazing pressure and mechanical scarification of the sand surface.

4.2.2. Beach sediment budget and coastal erosion / accretion

The sediment budget of the beach and frontal dunes has a profound influence on the scale of sand mobility which takes place, both under natural conditions and after the creation of artificial notches in frontal dune settings. The importance of this factor is illustrated by Figure 88 which compares beach profiles in front of the three rejuvenation phases at Kenfig and Phase 3 at Merthyr Mawr. The present beach sediment budget at Kenfig is negative along the southern two thirds of the shore, including the Phase 1 area, and frontal dunes along this section are prone to periodic erosion (Saye *et al*., 2005). In the area of the Phase 2 notches the beach sediment budget shows a transition from negative to weakly positive and becoming increasingly positive towards the Kenfig River. There is a corresponding increase in beach levels which increases the area of dry beach exposed at low tide from which sand deflated by wind and transported towards the dunes (Figure 88a). The potential sand supply through the notches into the hind dune area consequently increases from south to north, being highest for the northernmost Phase 3 notches. Accumulation of sand to form a foredune platform in front of the Phase 3 notches, and subsequent colonisation by Marram, is creating an increasingly effective barrier to sand entry into the notches, although this is a problem which could be managed by periodic clearance of the vegetation and levelling of the sand mounds.

Figure 88a also shows that the beach levels are higher at the Merthyr Mawr Phase 3 site than along the Kenfig trial frontage, reflecting an even more strongly positive beach sediment budget due to transport both from offshore and alongshore by southeasterly littoral drift. Consequently, there is greater potential for sand supply from the beach towards the notches and frontal dunes at Merthyr Mawr than at Kenfig. Although the upper beach and frontal dunes suffered at Merthyr Mawr a few metres of erosion during the stormy winter of 2013-14, upper beach levels have recovered and there has been no lasting impact on the rejuvenation trial areas.

At the Newborough Phase 2 West site at the southern end of Traeth Penrhos, the beach levels are relatively high (Figure 88b) and there is usually a significant area of dry sand beach at low tide from which sand can be deflated and transported towards the dunes. Traeth Penrhos is a dissipative, sediment-rich beach system, with waves breaking a long way from the shoreline to create a wide, gently sloping beach composed of fine sand. The upper beach width and elevation increase towards the Cefni estuary, increasing the area available for wind deflation and sand transport towards the dunes. During the stormy winter of 2013-14 the frontal dunes along the Phase 2 West trial area frontage suffered 2 to 3 m of erosion, but since that time, upper beach levels have recovered and a windblown sand ramp has formed along most of the eroded dune cliff. Significant quantities of sand have also been blown from the beach through the notches into the areas behind, particularly behind the two northern notches where more sand is available.

By contrast, the northern half of Traeth Llanddwyn, south of Llanddwyn Island, currently has a negative net sediment budget and low beach levels (Figure 88b). In the past 15 years sand has been moved southwards by waves and currents towards Abermenai spit, where significant beach and frontal dune accretion has taken place. Further severe erosion affected the frontal dunes along the Phase 2 East and Phase 3 frontages during the stormy winter of 2013-14 and beach levels fell to a low level, exposing cobble lag deposits and patches of glacial till. Since mid-2014 there has since been some upper beach recovery along the Phase 2 East frontage which now provides a potential source of windblown sand to the notches and frontal dunes. However, along much of the Phase 3 frontage the beach levels remain low, with extensive exposures of cobbles and gravel (Figure 90b). The potential source of sand available for transport into the dunes is therefore small and the dune cliffs behind the beach remain susceptible to further erosion during storms. The sand available for movement through the notches created in 2014 and 2015 is presently limited largely to that provided by slumping and wind erosion of the dune cliffs.

The supply of sand to and through the notches plays a key role in maintaining bare sand and mobile sand lobes in the hind-dune area. Sand movement scours the surfaces of the notches and sand corridors and, where deposition rates are high enough, leads to burial of vegetation. Where little or no sand is supplied from the beach, artificial notches are likely to deepen and widen to a point where no further deepening is possible, and/ or the cross-sectional area is so large that the speed up effect on the wind is reduced to a point where sand movement becomes infrequent. If the sand originating from a notch moves onto low-lying ground, local wind speeds are likely to be insufficiently high to sustain forward movement, as is the situation at Kenfig Phase 1 and Phase 2. Continued landward movement of the sand is much more likely where there is rising ground behind the notches and frontal dunes, since wind speeds are likely to accelerate over the higher ground. Many of the formerly active parabolic dunes at Newborough, Merthyr Mawr and inland parts of Kenfig maintained their forward movement in this way. However, the topographic wind acceleration effect is much reduced by the presence of dense tree cover, as within Newborough Forest.

At all of the trial sites, a relationship is evident between rates of sand deposition and the degree and type of vegetation development. In areas of very low new sand supply species such as Dewberry (*Rubus caesius*) and Ragwort (*Senecio jacobaea*) rapidly regrow. In areas of moderate sand supply species such as Sea holly (*Eryngium maritimum*), Creeping willow (*Salix repens*) and Sand couch (*Elymus farctus*) quickly become established. In areas of moderate to high sand deposition Marram (*Ammophila arenaria*) growth is favoured, but areas of very high sand deposition (>1 m / year), or those with a high transport rate but little accretion, remain bare.

On eroding dune shores, as presently found along the northern half of Traeth Llanddwyn, self-sustaining blowouts and mobile parabolic dunes often form naturally where wind velocities are locally high enough to scour the bare dune cliff face and move sand landwards through low areas in the dune crest line. There are a number of such small-scale natural blowouts to the south of Phase 3 frontage at Newborough Warren, and along the northern part of Abermenai spit. The growth and landward movement of such features is favoured where there is some supply of sand from the beach as well as from local erosion of existing dune deposits, since the additional sand helps to maintain high rates of sand deposition and bury vegetation on the margins of the blowout / parabolic dune.

Sediment budget management is therefore an important tool which can be used to create and sustain bare, mobile sand surfaces. Locally positive sediment budgets can be created by beach or dune nourishment, including use of marine dredged sand or sand taken from excavations inland. Options and potential multiple benefits of such operations in Wales were considered by Winnard *et al*. (2010). However, if the supply of sand to the beach from nearshore sources is too large, prograding vegetated foredune ridges, rather than transgressive sand dunes and sand sheets, are likely to form unless pioneer vegetation growth is impeded by very heavy visitor pressure or other disturbance.

4.2.3. Topography and local wind speeds

All of the notches at Kenfig, Merthyr Mawr and Newborough have been successful, to varying degrees, in creating areas where wind speeds are locally accelerated, due both to topographic focusing of wind streamlines and due to reduced surface roughness created by the absence of vegetation. The trials involving notches through the frontal dunes (e.g. Kenfig Phases 2 & 3, Merthyr Mawr Phase 3, Newborough Phases 2 & 3) have been more successful in creating sustainable areas of bare sand than those trials which have involved only stripping of turf and dune form enhancement inland, un-connected with the beach (e.g. Kenfig Phase 1, Newborough Phase 1). This is interpreted to be due mainly to the fact that local wind speeds at the inland sites have been insufficiently high to maintain large-scale sand movement.

The evidence suggests that those notches with a convex long profile or a steep linear seaward slope onto higher ground have been more effective in promoting sand transport than those with an almost flat floor just above beach level. This can be attributed to compression of wind streamlines and speed-up over rising ground.

Most of the notches created to date have had a rectangular plan form – i.e. almost constant width along their length. Based on the evidence from natural parabolic dunes, it is expected that notches which have a trapezoid plan form - i.e. wider at the mouth than at the back - would lead to greater acceleration of flow velocities in the landward direction and would therefore be potentially more effective in transporting sand landwards.

In areas with thick sand deposits, blowouts and mobile dunes are not only initiated at the shoreline but can also develop inland if the vegetation cover is disrupted and local wind speeds are sufficiently high. Exposure to strong regional winds by virtue of an elevated topographic position, or to locally accelerated winds associated with turbulence around small-scale and sharp topographic variations, are of critical importance for the creation and maintenance of inland dunes. There are presently a number of active and recently active inland dunes at Newborough Warren which have evolved from blowouts on the higher parts of older dunes, now unconnected with the sea and largely vegetated. An example is provided by Dune 'H' in the southeastern corner of Newborough Warren which has evolved from a small blowout formed on the higher part of the eastern arm of a large parabolic dune, well inland from the beach (Figure 89). The blowout is surrounded by dune grassland vegetation and has a sharp rim which is being undercut by the wind as the blowout continues to deepen and enlarge. Local wind scouring within the blowout is causing a net movement of sand towards the east, forming a steep conical dune mound with slip faces on the northern and eastern sides. Steep, deep features of this type generate local wind turbulence and locally high velocities which causes the feature to grow through positive feedback processes until the feature achieves a maximum equilibrium size or a threshold is exceeded, and local wind velocities drop sufficiently for vegetation to gain the upper hand. A number of stabilised and semi-stabilised dunes occur adjacent to Dune 'H', and there are other vegetated and semi-vegetated saucer blowout dunes on the northern end of Abermenai spit (Figure 90). These recently active dunes are clearly near the threshold for stabilization and offer opportunities for management intervention measures to reactivate them. The evidence provided from the Phase 1 trials at Newborough are that these dunes (Areas 2 and 3) are too far from the threshold to be sustainably reactivated under present local wind, precipitation and temperature conditions.

4.2.4. Grazing and visitor access

Grazing by cattle has been allowed on the landward side of the haul road within the Phase 1 and Phase 2 areas at Kenfig, and by ponies and cattle on the eastern side of a relocated fence line cutting through the Phase 3 area at Newborough. The grazing has helped to reduce vegetation regrowth and locally has aided sand mobility, notably along trackways, but has also led to eutrophication and promoted algal growth in some lower lying areas. Cattle grazing at Kenfig Phase 1 East and Phase 2 East, in particular, has been of net benefit in helping to control tall, coarse vegetation regrowth. Grazing by ponies and some cattle on the landward side of the repositioned Newborough Warren fence line (stocking rates approximately 0.3 – 0.4 LSU per ha) has had some effect in controlling vegetation regrowth, but has been more important in creating physical disturbance within the Phase 1 and inner part of the Phase 3 areas.

Visitor access, including horse riders, has continued to be permitted within all of the rejuvenation trial areas although it has had little influence at Kenfig and in the Newborough Phase 1 area. Elsewhere it has played a useful contributory role in helping to maintain sand mobility.

4.3. Advantages and disadvantages of different monitoring methods

4.3.1. RTK GPS surveys

The RTK GPS ground survey methodology used in the rejuvenation trial monitoring to date has been found to work reasonably well, especially when used with a base station. However, problems can be periodically encountered in areas where a clear view of the sky is impeded by dense trees or steep terrain (e.g. cliffs), and where only a poor satellite signal can be obtained. In the monitoring work undertaken for this project, this was only a significant problem for areas in and adjacent to Newborough Forest.

This methodology is best suited to surveys which are designed to map the limits of specified features (e.g. dune toe, vegetation, water bodies), and / or to compare changes in surface levels along specified profile lines. The greatest benefit of ground-based RTK GPS surveys arises from the relatively high degree of spatial and vertical survey accuracy (often better than +/- 10 mm. However, the main disadvantage is presented by the time taken to survey large areas and / or large numbers of profiles. Dense point clouds suitable for DEM construction can only practically be obtained from relatively small areas. Moreover, ground survey is inevitably invasive in the sense that disturbance is caused both to vegetation and surface features (e.g. the side slopes of notches when cross profiles are being surveyed).

4.3.2. UAV surveys

Experience has shown that UAV surveys are highly useful for acquisition of oblique aerial imagery, especially of features such as cliffs which are poorly resolved by vertical imagery and airborne LiDAR. Vertical imagery obtained by UAV surveys also provides a rapid method of mapping features of interest such as bare sand or specific vegetation, provided that the individual photographic images are stitched together and georeferenced properly. However, owing to the size limitation on the camera and GPS equipment which can be carried by lightweight UAVs the image quality is often not as good as that which can be obtained using conventional aircraft borne aerial photography. Since UAVs operate at relatively low altitude and have limited battery life, numerous overlapping individual images must be obtained from several flights and stitched together as an orthorectified mosaic. It may take many hours or even days to acquire imagery of a large site, during which time illumination and cloud conditions may change considerably. Shadowing from trees and topographic features can cause particular difficulties when attempting to map bare sand, water or similar features. In this assessment it was found impossible to apply automated pixel classification methods to the UAV imagery supplied in order to quantify bare sand area and distribution. Although conventional aerial photography is not immune to such problems, the variations in contrast across an area of interest are usually less pronounced since the images are acquired over a much shorter time period.

Ortho-rectification of UAV imagery requires known ground control points whose x and y positions are accurately known, usually from an RTK GPS survey. Production of a DEM from overlapping aerial photographic images using photogrammetric software also requires that the height of the known control points is also accurately determined. The evidence obtained in this and previous assessments is that in many UAV surveys an insufficient number of accurately surveyed ground control points is established, and vertical errors of the order of 1 to 2 m are common towards the margins of the survey area where inadequate ground control is available. Errors of this magnitude make the resulting DEMs of no practical use for quantification of changes in ground surface level or sediment volume.

4.3.3. Airborne LiDAR

Airborne LiDAR provides a rapid and increasingly cost-effective method of acquiring morphological data over wide areas. An entire dune system the size of Newborough or Kenfig can be surveyed at high resolution (25 cm to 1 m) within a period of hours. No other method can provide three-dimensional terrain data over moderate to large areas with the same degree of speed, accuracy and cost-efficiency, although for very large areas (e.g. oceans, large coastal bays or regional land masses) satellite altimetry provides a more viable method once the initial satellite observing system is in existence.

Over bare ground, and with accurate ground control information, raw point cloud LiDAR data can have spatial and vertical accuracy of the order of 0.1 – 0.15 m, depending on flight height, swath width and accuracy of in-flight GPS corrections. After processing, data are normally presented at degraded spatial resolution (0.25 cm to 2 m), with typical spatial accuracy for 1 m resolution data of +/- 0.6 to 0.8 m. Vertical accuracy is linked to spatial accuracy, but on a flat, bare surface is typically of the order of 0.1 to 0.15 m. On vegetated ground vertical errors are typically larger, ranging from +/- 0.15 to +/- 1 m depending on the height and density of vegetation. Filtering algorithms can in theory ‘remove’ vegetation to create a ‘bare earth’ terrain model, but the filtering process can introduce artifacts into the resulting DEM by removing small-scale topographic features and smoothing out natural variations. The value of LiDAR data is always enhanced where contemporaneous RTK GPS survey data are available for validation and, if necessary, vertical adjustment to the DEM. Added value is also provided if LiDAR data can be acquired simultaneously with colour aerial photography or multi-spectral scanner imagery.

The major disadvantage of LiDAR surveys is the relatively high mobilization cost associated with conventional aircraft flights. For this reason, it often impractical to use conventional airborne LiDAR to survey small geographic areas on a frequent basis. This problem may be overcome if surveys of several small areas, or entire stretches of coastline, are carried out as part of the same sortie for the benefit of multiple users.

4.3.4. Terrestrial Laser Scanning

Terrestrial Laser Scanning (TLS) surveys are becoming increasing popular for monitoring of specific morphological features, particularly cliffs or river banks where better information can be obtained from a side-on or oblique survey than from a vertical airborne survey. TLS surveys have been undertaken at a number of sand dune locations in the UK and elsewhere, including at Newborough by Bangor University. This method is particularly useful for quantifying in a high detail the small-scale changes which take place over a small geographical area, such as a single blowout or short length of dune cliff. However, the technique relies on line of sight to obtain data and is impractical to deploy in complex terrain or across large areas.

4.3.5. Recommendations for future monitoring of geomorphological change

The effectiveness of the rejuvenation interventions in contributing to conservation objectives can only be assessed by monitoring, and by comparing observed changes with initial targets.

Several different types of monitoring are required, addressing changes in geomorphology (including bare sand extent, dune morphology mobility), hydrology, soil properties, vegetation assemblages, invertebrates and other elements of the biota. This assessment is concerned only with geomorphological changes which underpin almost everything else. Traditional methods for the quantification of geomorphological changes include analysis of aerial photography, ground topographic survey data, and the deployment of posts to measure changes in position and/ or surface level accretion. In the past 20 years, the application of geographical information systems (GIS) methods to quantify changes in morphology and sediment volume in three dimensions by difference analysis of digital elevation models (DEMs) has become more common. However, as noted by Walker *et al.*, (2013), robust and repeatable methods that account for measurement and analytical uncertainty are required to distinguish between noise and changes which are statistically significant. DEM precision and accuracy are of critical importance and are dependent on the quality of survey point data, sampling strategy and point density, sampling strategy and temporal consistency.

In any monitoring programme, there has to be a trade-off between survey detail, data quality, frequency and cost. However, survey data of any type are of little use if the data quality is poor, even though the cost of acquisition may be low.
The UAV surveys of the rejuvenation trial areas undertaken in January – March 2016 were carried out at relatively low cost (approximately £1150 for Newborough and £3000 for Kenfig and Merthyr Mawr combined, excluding VAT), but the resulting terrain level data and imagery were of poor quality, particularly for Kenfig. In the case of the Newborough surveys, too few ground targets were used, and the resulting DEM contained significant distortion error, especially around the margins of the survey area. In the case of Merthyr Mawr and Kenfig it is unclear how many, or indeed if any, ground control points were surveyed as no survey / data processing reports were provided. Serious short-comings were also evident in the post-survey data processing, and the Kenfig DEM in particular contained large and unexplained errors.

The costs of UAV surveys vary greatly on the location and size of area to be surveyed, the accuracy requested, the equipment used and the nature of the organization carrying out the survey. However, realistic costs for surveys of areas such as the rejuvenation trial sites considered in this report, which provide the minimum necessary data quality and level of reporting, including adequate RTK ground survey of ground control points and data processing procedures, would be £3000 to £5000 per area. However, as noted previously, owing to the low-level nature of UAV flights and limitations on camera payload, it would take a considerable time to survey a large site and the image / elevation data quality are likely to be much more spatially variable than those obtained using conventional aerial photography and airborne LiDAR. For the foreseeable future, UAV surveys are likely to be most valuable when deployed to obtain qualitative oblique (birds eye) aerial imagery, and particularly where near-vertical features (e.g. cliffs) are of principal interest. Although some UAVs deployed in the UK can now carry small LiDAR instruments, the results obtained are most similar to those obtained using terrestrial laser scanning and are effectively applicable only to small areas.

Dedicated RTK GPS surveys and post-survey data processing generally cost in the region of £800 to £1000 per day, but economies of scale apply where several nearby sites are surveyed around the same time. The time required for surveys aimed at feature mapping (limits of bare sand, dune lengths and cross-profiles) depend on the size and complexity of the area to be surveyed. Large sites such as the combined Phase 1, 2 and 3 areas at Kenfig, Merthyr Mawr and Newborough would each now take several days to re-survey, at a cost of £4000 - £5000 (excluding VAT) for each area, including data processing and reporting time.

Individual commercial LiDAR surveys typically cost of the order of £10,000 (excluding VAT) for a survey of a single 1 x 1 km tile area, which is often sufficient for small sites. Much of this is associated with mobilization costs and data processing, and significant economies of scale apply for larger survey areas. Once an aircraft is airborne, several different areas or large individual areas can be surveyed within a single day. Data can therefore be obtained for an entire dunefield, and its surrounding area, and the data used for multiple purposes. For example, the entire coastal zone and intertidal area of Swansea Bay, extending from the River Ogmore (south of Merthyr Mawr) to Mumbles Head could be surveyed, and processed filtered and unfiltered data provided, for a total cost of £15,000 to £25,000 depending on data specification, timing of survey, and the service supplier involved.

In order to obtain the best possible quality of data relating to future morphological change it is recommended that airborne LiDAR surveys should be undertaken prior to the commencement of any further intervention works and at two yearly intervals thereafter. Targeted RTK GPS surveys should also be undertaken within two weeks of each LiDAR survey in order to ground truth the LiDAR information. This is particularly important where dense / tall vegetation is present, and in areas where high resolution spatial and vertical data are required (e.g. the 'exact' position of a dune toe or cliff edge, saltmarsh edge or saltmarsh surface level). This strategy would reduce the time required for RTK GPS ground surveys to a minimum. Ideally, a conventional aircraft colour photography survey should be undertaken at the same time as the LiDAR survey, or within a short time window around the time of LiDAR survey. This survey should cover the whole of the dunefield within which the rejuvenation works are undertaken, in order to provide regional context. In order to minimise the costs and maximise the multi-user benefits of such joint aerial surveys, close communication between interested parties is essential.

It is impractical to undertake dunefield-wide surveys using UAV methodology, but this method can be used to good effect where there is a requirement to monitor changes in bare sand area and/or vegetation density within smaller areas at frequent intervals. Any future UAV surveys should employ an adequate number of ground control points, including locations outside the area of interest, which are accurately surveyed by RTK GPS. All future UAV survey commissions should also be required to deliver a detailed survey and data processing report which contains adequate quality assurance information.

4.4. Comparison with other dune rejuvenation schemes

Experiments to restore dynamic conditions to sand dunes in The Netherlands began in the 1980s, arising from concerns about over-stabilization and loss of biodiversity. Initial experiments were generally small-scale and in locations where they could have no adverse effect on the sea defence value of the dunes, but later experiments were more ambitious and larger in scale. Monitoring over periods of 15 to 20 years showed that in most cases a temporary increase in mobility of inland dunes was generally short-lived unless continuous maintenance measures were employed, including regular removal of exposed roots and treatment of any regrowth. Greatest success in creating sustainable mobility on inland dunes was achieved by stripping of vegetation from the crests of larger, higher parabolic dunes where wind velocities are sufficiently strong to maintain wind erosion of the sand surface and bury vegetation on the leeward side of the crest with new sand. Experiments in foredune settings have indicated that it is much easier to instigate and maintain dune mobility in such settings where wind exposure is higher and there is generally a higher availability of sand, but regular maintenance is required to remove vegetation regrowth in most settings where sand supply from the beach is low to moderate (Arens *et al*., 2013a,b). However, where sand supply is large, for example following beach nourishment operations, the sand supply from the beach is sufficient to bury vegetation and prevent regrowth, at least for a number of years.

Trials in so far conducted in Wales have generally produced similar results. Trials with beach nourishment, for example at Talacre and Prestatyn – Gronant on the coast of North Wales, have shown that an increase in bare sand area and dune mobility can be achieved quickly in areas where the existing frontal dunes are low or dissected, or where new embryo ridges and foredunes develop (Winnard *et al*., 2011). However, the impact on the surface mobility of continuous lines of high, cliffed frontal dunes is minimal. The creation of notches in such settings is required to allow significant quantities of sand from the beach to enter the dune system. The experiments at Kenfig Phases 2 and 3, Merthyr Mawr and Newborough Phases 2 West and 3 have provided further evidence of the effectiveness of this type of intervention, but it is only likely to be sustainable in the medium to longer term at locations where the sediment budget of the mid and upper beach is positive; i.e. there is a continued supply of new sand from the beach.

Notches have been cut in the foredunes in a number of locations on the Dutch coast and vary in size from 10-20 m wide and 6-7 m deep, similar to those in the Welsh trials so far conducted, to more than 100 m in width. Riksen *et al.* (2016) reported that, over a 2-year period of observation, close to experimental notches on the island of Ameland, sand extended only 50-60 m inland from the foredune crest line, and there was a minimal impact on hind dune areas away from the notches. The results so far obtained from the Welsh trials have indicated that the inland extent of blown sand passing through notches is closely related to the morphology and spacing of the notches, the supply of sand available from the beach, and the presence of absence of turf-stripped corridors linking the frontal dune notches with more inland areas.

4.5. Proposals for further intervention work

Figures 91, 92, 93 and 94 indicate areas at Kenfig, Merthyr Mawr and Newborough where it is proposed that further dune rejuvenation works could / should be undertaken.

At Kenfig it is clear that the original Phase 1 works have not delivered the full benefits originally intended. It is therefore proposed that additional measures should be taken in this area to increase the flow of wind, and potentially of sand, between the frontal dune area and the hind dune area. Specifically, it is proposed to excavate two notches through the frontal dune area west of the haul road and to place the excavated sand immediately on both sides of the haul road in order to raise the ground level and provide an uninterrupted pathway for sand which can be blown along the deflation corridor of the large parabolic dune (Figure 91). A complementary option would be to remove / lower the haul road to encourage movement of sand from Phase 1 West to Phase 1 East, but this would involve disruption to access along the Wales Coast Path, notably at times in winter and spring when the lower ground is often flooded. Further north, opposite the northern Phase 2 and Phase 3 notches, the haul road does not present a topographic obstacle to the eastward movement of sand because the land level on the western side is sufficiently high. Modifications to the surface level west of the haul road in the Phase 1 and southern Phase 2 areas could be made to achieve the same situation.

It is also proposed that a 3 m deep, 10 m wide notch (rectangular in plan) should be excavated in the crest of the parabolic dune in order to accelerate local wind flow and encourage the movement of sand onto the slip face. Minor works should also be undertaken to clear piles of accumulated sand and pioneer vegetation from the seaward ends of the Phase 3 notches. Further turf stripping on the east side of the haul road, to the north of those areas stripped in Phase 2 and Phase 3, could be undertaken but it is considered that it would not be feasible to create a sustainable mobile sand surface in this area without a substantial increase in the supply of mobile sand from the west side of the haul road, something which is not likely to occur unless the entire frontal dune ridge is de-vegetated and mobilised.

At Merthyr Mawr it is proposed that four further notches should be excavated through the frontal dunes to the north of the existing Phase 3 notches to encourage sand flow from the beach into the hind-dune area (Figure 92). These notches should be slightly deeper than the phase 3 notches and have a trapezoidal form in plan but should retain a convex long profile similar to the Phase 3 notches. It is also proposed that turf stripping be undertaken on the windward slopes, crest and upper leeward slopes of the large parabolic dune identified by Pye & Blott (2011b) as ‘Dune B’. Stripped turf and excavated sand should be placed in positions which will assist in reconstructing the former parabolic morphology of this dune (largely destroyed by gravel extraction operations in the 1960s and 70s). A further notch is proposed through the middle of the artificial dune created by sand deposition Phase 2 which is currently acting as an obstacle to wind flow up the axis of the large parabolic dune south of Dune A (Figure 92).

At Newborough Warren it is proposed that additional turf stripping and frontal dune notching should be undertaken at the southern end of the area identified by Pye & Blott (2012a), to the southeast of the existing Phase 3 works (Figure 93). Three notches (J, K & L) should be cut through the frontal dune, the largest of which (J) will exploit an existing natural blowout. Each notch should have a trapezoidal plan form and a relatively steep seaward facing slope to encourage compression of wind streamlines in both horizontal and vertical dimensions. Excavation should also be undertaken to enlarge an existing low corridor (M) through the ‘nose’ of the large parabolic dune landward of notch J. Smaller scale turf stripping and sand excavation should be undertaken in and adjacent to two recently and partly active blowouts (F and G) in the eastern wall of the large parabolic dune inland of notches K and L. Dune H on the eastern wall of this large dune is still active and requires no further intervention.

At Traeth Penrhos, on the western side of Newborough Forest, it is proposed that additional tree-felling and de-stumping should be undertaken in the area behind the frontal dune ridge, north of the Phase 2 west area. As a further initial phase, two notches, trapezoidal in plan shape, should be cut through the frontal dune to link the beach with the newly cleared hind-dune area (Figure 94). Tree felling should be undertaken, in stages, along the entire length of the primary dune slack and seaward facing dune slope on its landward side in order to create space from the frontal dune ridge to migrate landwards in future in response to sea level rise and coastal erosion.

The proposed further experiment work at Kenfig, Merthyr Mawr and Newborough should examine in more detail the combined effect on sand mobility of variation in the plan shape, cross-sectional profile and long-section profile of artificial notches. Figure 95 illustrates a range of notch design morphologies which could be tested.

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6. Acknowledgments

We thank Nicola Rimington, Emmer Litt, Ceri Seaton, Mike Howe, Scott Hand, John Ratcliffe, Graham Williams and Duncan Ludlow (all CCW, later NRW) for supporting the work at Kenfig, Merthyr Mawr and Newborough. Additional financial and/ or logistic support was provided at Kenfig by David Carrington (Bridgend Council) and at Newborough by Forestry Commission Wales (later NRW) and Welsh Government.

Tables

Table 1. Summary of environmental parameters for the Kenfig, Merthyr Mawr and Newborough sand dune rejuvenation sites

	Kenfig Burrows	Merthyr Mawr Warren	Newborough Warren (Phase 2 West)	Newborough Warren (Phase 2 East and Phase 3)
Location	SS782824	SS859762	SH391637	SH410630
Shoreline orientation	253 º to 073º	236 º to 056º	248 º to 068º	215 º to 035º
Mean spring tidal range	8.7 m	8.9 m	4.1 m	4.1 m
Wave exposure	Moderate - High	Moderate - High	Moderate	Moderate
Prevailing wind direction	222 º to 042º (at Mumbles)	222 º to 042º (at Mumbles)	214 º to 034º (at Valley)	214 º to 034º (at Valley)
Wind exposure	High	High	High	High at coast, moderate inland
Typical median sand size	260 µm	209 µm	249 µm	224 µm

Table 2. Timelines showing sequences of rejuvenation works and monitoring surveys at Kenfig, Merthyr Mawr and Newborough

Rejuvenation works	RTK ground survey	Aerial photograph survey	Aerial LiDAR survey	UAV survey
Kenfig Burrows				
			26 Feb 2006	
		12 Oct 2009		
Feb-Mar 2012 (Phase 1)				
	17 Jul 2012 (Phase 1)			
	09 Oct 2012 (Phase 1)			
Jan-Feb 2013 (Phase 2)				
	08 Mar 2013 (Phase 1)			
	13 May 2013 (Phase 2)			
	10 Mar 2014 (Phase 2)			
			31 Mar 2014	
	27 Apr 2014 (Phase 2)			
Nov-Dec 2014 (Phase 3)				
	3-11 Mar 2015 (Phase 1-3)			
		18 Apr 2015		
				02 Mar 2016 (Phase 1-3)
Merthyr Mawr Warren				
			16-29 Oct 2008	
		13 Sep 2009		
6-19 Dec 2012 (Phase 1)				
	14 May 2013 (Phase 1)			
3-16 Nov 2013 (Phase 2)				
	11 Mar 2014 (Phases 1 &2)			
3-19 Nov 2014 (Phase 3)				
			05 Feb 2015	
	11-12 Mar 2015 (Phases 1-3)			
		18 Apr 2015		
				29 Feb 2016 (Phase 1-3)
Newborough Warren				
		11 May 2009		
			12 May 2009	
	17 Jan 2013 (Phase 1)			
Jan-Mar 2013 (Phase 1)				
	16-17 May 2013 (Phase 1)			
				Jun 2013 (Phase 1, 2W)
	18 Jul 2013 (Phase 2W)			
Dec 2013-Feb 2014 (Phase 2W)				
	13 Mar 2014 (Phase 1)			
			09 Apr 2014	
Dec 2014-Mar 2015 (Phase 2E,3)				
	25-27 Mar 2015 (Phase 1-3)			
				25-29 Jan 2016 (Phase 1-3)
	2 Feb 2016 (Phase 2-3)			

Table 3. Schedule of rejuvenation works undertaken at Kenfig, Merthyr Mawr and Newborough

(a) Kenfig Burrows	Phase 1	Phase 2	Phase 3
Dates of works	Feb to Mar 2012	Jan to Feb 2013	Nov to Dec 2014
Nature of work	Turf stripping of fixed dune grassland either side of the haul road, grading of seaward dune edge, lowering of dune crest west of haul road, placement of turf to enhance parabolic dune morphology; follow up spraying of marram and *Rubus* regrowth in late summer 2012	Four notches in frontal dunes, turf stripping east of haul road adjacent to Phase 1 and opposite two of the notches west of the haul road, placement of turf to enhance parabolic dune morphology	Four notches in frontal dunes, exploiting existing blowouts and working with natural topography, turf stripping behind notches west of the haul road, placement of turf to create dune ‘arm’ extensions behind frontal dunes, stripping and deepening of slacks in the Phase 2 areas which were too wet to work in Jan-Feb 2013
Equipment used	one excavator, two articulated Volvo dump trucks	20 t and 14 t excavators with digging and grading buckets, two large dump trucks (JCB articulated)	Two 20t excavators and one 14t dumper during first two weeks, 14t and 20 t excavators and 1 small bulldozer during third week
Contractor	Jones Brothers (Henllan Ltd.)	Jones Brothers (Henllan Ltd.)	Jones Brothers (Henllan Ltd.)
Cost	£35K	£78k	£36k
Funding	Welsh Govt. (ERDF) £15K; Plantlife £20K; follow-up spraying CCW £1.5K	SITA Trust (£67k) and NRW (£11k)	SITA Trust – Enriching Nature fund
Area of bare sand created	2.6 ha	5.3 ha	2.5 ha

(b) Methyr Mawr	Phase 1	Phase 2	Phase 3
Dates of works	6-19 Dec 2012	3-16 Nov 2013	3-19 Nov 2014
Nature of work	Widening and deepening of deflation corridor of a large parabolic dune (still active), creation of a new dune slack	Completion of removal of sand from the Phase 1 parabolic dune deflation corridor, excavated material moved to create a new dune to the south	Creation of six notches in the frontal dunes, surf stripping and sand excavation to create three bare corridors linking notches with Phase 1 and 2 areas inland, later vegetation regrowth removed by hand pulling, glyphosphate spraying and weeding with flame gun
Equipment used	20t and 8t excavators, two dump trucks, one bulldozer	20t and 8t excavators, three dump trucks	Two 20t excavators, two JCB articulated dump trucks, 1 small bulldozer
Contractor	Jones Brothers (Henllan Ltd.)	Jones Brothers (Henllan Ltd.)	Jones Brothers (Henllan Ltd.)
Cost	£15K	£23k	£36k
Funding	Welsh Govt. (ERDF)	NNR maintenance funds	SITA Trust
Area of bare sand created	2.6 ha	0.3 ha	4.9 ha

Table 3. continued

(c) Newborough Warren	Phase 1	Phase 2 West (notch creation)	Phase 2 West (vegetation removal)
Dates of works	Jan to Feb 2013	Nov 2013 to Jan 2014	Nov 2014 to Feb 2015
Nature of work	Turf stripping of fixed dune grassland on the windward side of two adjacent parabolic dunes (‘Areas 2 and 3’), stripping of the deflation corridor of one of the parabolic dunes, creating of wet slack areas. 500 m south turf stripping of low area (‘Area 4’) to create a wet slack, with removed sand and turf piled into a new dune ridge	Four notches in frontal dunes at locations of existing blowouts	Tree felling and removal, on-site chipping of non-viable timber, removal of brash, de-stumping. Follow-up work to scrape the litter layer, and further removal of brash and litter.
Equipment used	Two 13t excavators, two 25t dump trucks	One 21t excavator, one tractor and trailer	Two 13t excavators, two 25t dump trucks
Contractor	EW Jones	A Lewis	EW Jones (initial work) and Edwin Fray Countryside Ltd (follow-up work)
Cost	£25k	£10k	£17k for initial work, £3.5k for follow-up work
Funding	CCW (£21k) and Pond Conservation (£4k)	CCW	NRW
Area of bare sand created	3.6 ha	0.2 ha	3.7 ha

(d) Newborough Warren	Phase 2 East (tree felling and chipping)	Phase 2 East and Phase 3
Dates of works	Feb 2014 to Feb 2015	Jan to March 2015
Nature of work	Feb 2014: tree felling Nov 2014 to Feb 2015: chipping of on-viable pine, removal of brash, de-stumping and scraping of litter, removal of material to area 400 m inland	Three notches in frontal dunes of Phase 2 East area, six notches in the frontal dunes of the Phase 3 area, five slacks scraped, turf stripping of three existing parabolic dunes, with material deposited in arms of parabolic dunes, or in sacrificial heaps, landward relocation of stock fence
Equipment used	Two 13t excavators, two 25t dump trucks, one bulldozer	Two 21t excavators, two 25t dump trucks, 1 bulldozer
Contractor	EW Jones	EW Jones
Cost	£21k	£78k? for excavations, £11k for relocating fence
Funding	Welsh Government	SITA Fund and NRW
Area of bare sand created	3.1 ha	7.1 ha

Table 4. Initial characteristics of notches created at Kenfig Burrows (measured at the time of first survey, shortly after the rejuvenation works)

	Cut date	Length of cut (m)	Width of surveyed profile crest to crest (m)	Max cut depth (m)	Max elevation of base of trough (m OD)	Long axis orientation
Kenfig Burrows Phase 2						
Notch 1	Jan-Feb 2013	88	25	6.9	8.8	N 98° E
Notch 2	Jan-Feb 2013	78	23	6.1	9.3	N 83° E
Notch 3	Jan-Feb 2013	89	21	6.4	9.1	N 100° E
Notch 4	Jan-Feb 2013	56	21	6.1	9.8	N 73° E
Kenfig Burrows Phase 3						
Notch 5	Nov-Dec 2014	92	21	6.8	11.4	N 80° E
Notch 6	Nov-Dec 2014	88	16	6.4	11.3	N 90° E
Notch 7	Nov-Dec 2014	97	23	3.7	14.2	N 80° E
Notch 8	Nov-Dec 2014	93	20	6.6	12.3	N 65° E

Table 5. Summary of changes in bare sand areas at Kenfig Burrows measured at the time of first survey (shortly after rejuvenation works) and at the time of the UAV survey on 2 March 2016

	Area of bare sand at time of first survey	Area of bare sand remaining on 02/03/2016	Additional bare sand outside of original works	Percentage bare sand on 02/03/2016
Phase 1 W haul road	1.28	0.48	0.00	37.8
Phase 1 E haul road	1.32	1.09	0.00	82.4
Phase 2 W haul road	2.95	2.78	0.24	102.2
Phase 2 E haul road	2.30	2.03	0.00	88.4
Phase 3	2.46	2.34	0.78	126.6
Total	10.31	8.71	1.02	94.4

Table 6. Initial characteristics of notches created at Merthyr Mawr Warren (measured at the time of first survey, shortly after the rejuvenation works)

	Cut date	Length of cut (m)	Width of surveyed profile crest to crest (m)	Max cut depth (m)	Max elevation of base of trough (m OD)	Long axis orientation
Notch A	Nov 2014	185	18	2.1	11.4	N 67° E
Notch B	Nov 2014	183	18	3.6	11.7	N 65° E
Notch C	Nov 2014	172	13	2.0	11.3	N 65° E
Notch D	Nov 2014	56	24	1.6	11.4	N 70° E
Notch E	Nov 2014	65	21	0.2	11.5	N 70° E
Notch F	Nov 2014	50	12	1.2	10.7	N 66° E

Table 7. Summary of changes in bare sand area (ha) at Merthyr Mawr Warren measured at the time of first survey (shortly after rejuvenation works) and at the time of the UAV survey on 29 February 2016

	Area of bare sand at time of first survey	Area of bare sand remaining on 02/03/2016	Additional bare sand outside of original works	Percentage bare sand on 29/02/2016
Phase 1	2.65	2.26	0.20	92.9
Phase 2	0.34	0.33	0.58	266.8
Phase 3	4.95	4.72	0.13	98.1
Total	7.93	7.30	0.91	103.6

Table 8. Initial characteristics of notches created at Newborough (measured at the time of first survey, shortly after the rejuvenation works)

	Cut date	Length of cut (m)	Width of surveyed profile crest to crest (m)	Max cut depth (m)	Max elevation of base of trough (m OD)	Long axis orientation
Phase 2 West						
Notch A	Dec 2013 – Feb 2014	29	17	6.0	4.5	N 72° E
Notch B	Dec 2013 – Feb 2014	22	25	7.4	4.3	N 72° E
Notch C	Dec 2013 – Feb 2014	29	23	6.5	3.8	N 48° E
Notch D	Dec 2013 – Feb 2014	35	26	7.7	6.0+	N 45° E
Phase 2 East						
Notch A	Dec 2013 – Mar 2014	35	29	6.5	5.9	N 15° E
Notch B	Dec 2013 – Mar 2014	37	29	5.7	5.5	N 18° E
Notch C	Dec 2013 – Mar 2014	69	24	5.8	5.9	N 15° E
Phase 3						
Notch D	Dec 2013 – Mar 2014	80	29	5.9	6.2	N 30° E
Notch E	Dec 2013 – Mar 2014	92	38	8.7	5.6	N 12° E
Notch F	Dec 2013 – Mar 2014	49	11	5.1	6.8	N 30° E
Notch G	Dec 2013 – Mar 2014	39	22	7.6	5.6	N 40° E
Notch H	Dec 2013 – Mar 2014	32	32	8.1	6.0	N 22° E
Notch I	Dec 2013 – Mar 2014	62	32	6.5	7.4	N 21° E

Table 9. Summary of changes in bare sand areas (ha) at Newborough, measured at the time of first survey (shortly after rejuvenation works) and at the time of the UAV survey in January 2016

	Area of bare sand at time of first survey	Area of bare sand remaining in late January 2016	Additional bare sand outside of original works	Percentage bare sand in late January 2016
Phase 1 Area 2	1.67	0.91	0.08	59.4
Phase 1 Area 3	0.94	0.34	0.10	47.5
Phase 1 Area 4	0.96	0.08	0.04	12.4
Phase 2 West	3.88	3.59	0.85	114.6
Phase 2 East	3.50	3.38	0.69	116.1
Phase 3	6.69	6.39	2.61	134.5
Total	17.64	14.70	4.37	108.1

Figures

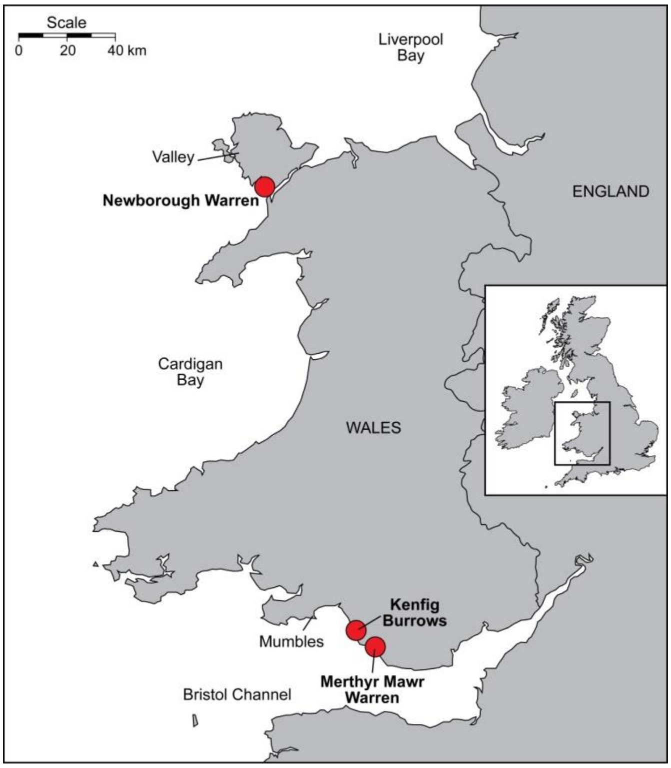


Figure 1. Locations of the dune rejuvenation trials considered in this report. Also shown are the locations of the meteorological stations and Valley and Mumbles

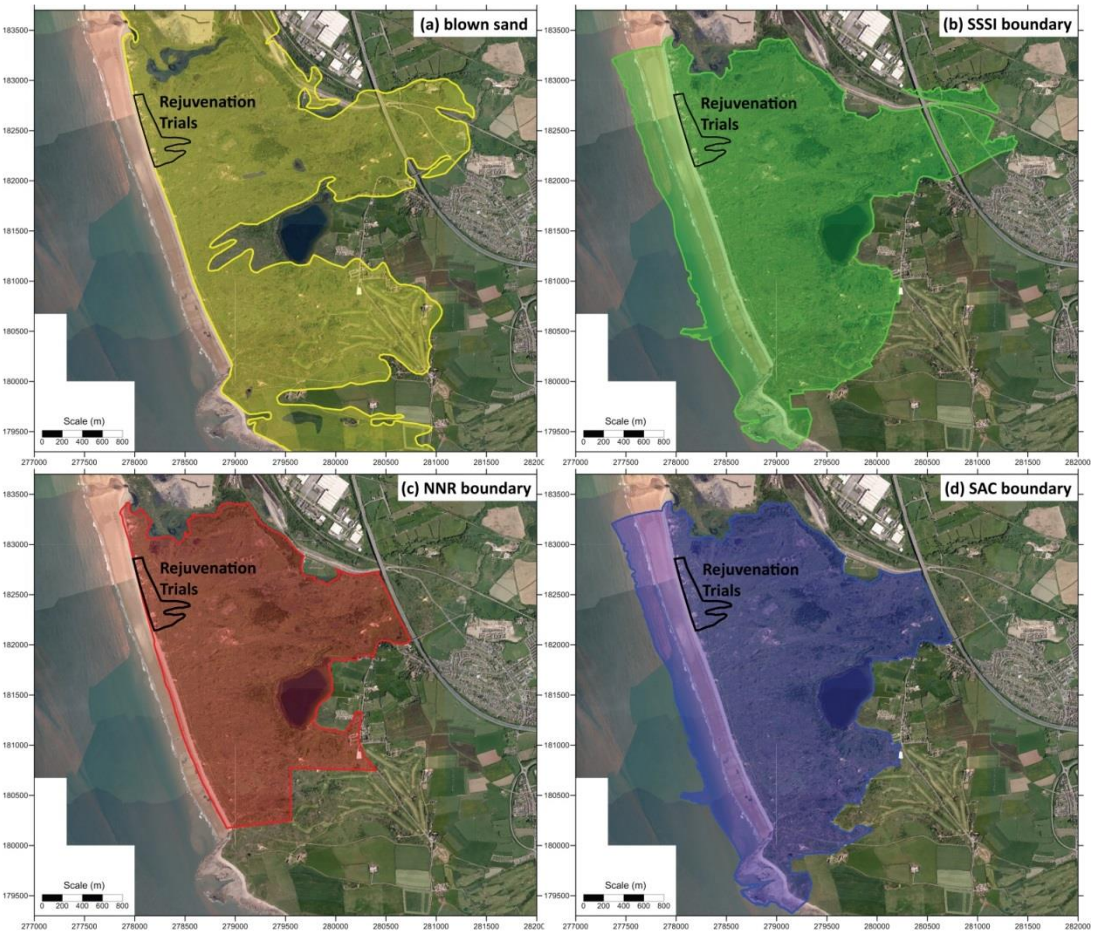


Figure. 2 (a) Extent of windblown sand in the Kenfig area (based BGS mapping); (b) extent of the SSSI at Kenfig Burrows; (c) Extent of Kenfig NNR; (d) extent of the SAC at Kenfig Burrows. Nature conservation boundaries from JNCC website

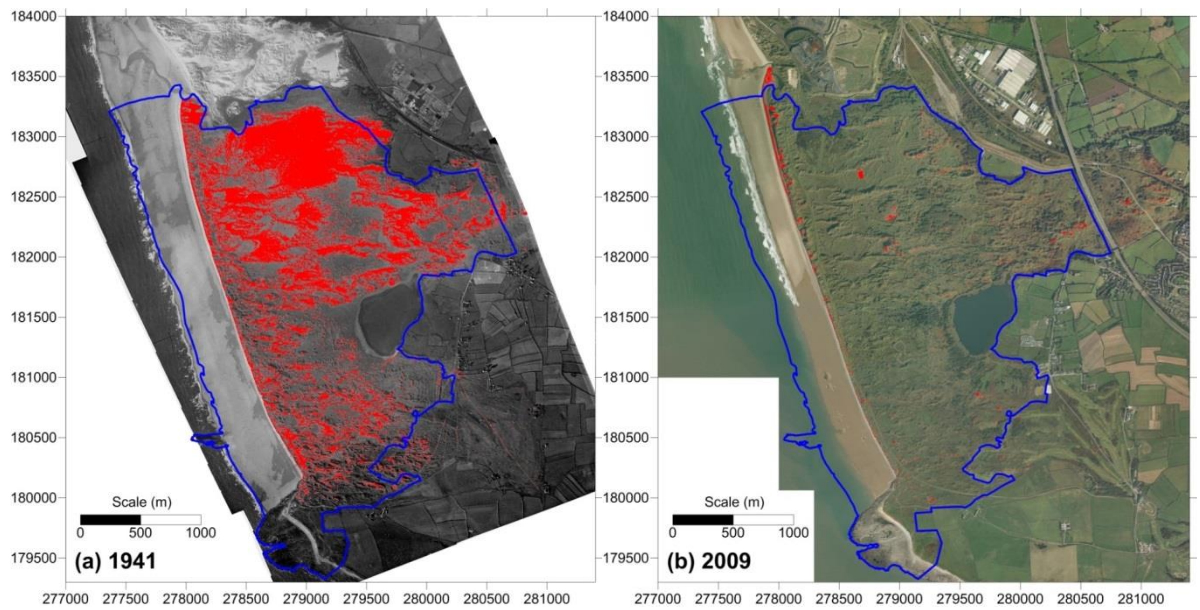


Figure 3. The extent of bare sand (red) at Kenfig Burrows in (a) 1941, and (b) 2009. The blue line indicates the SAC boundary

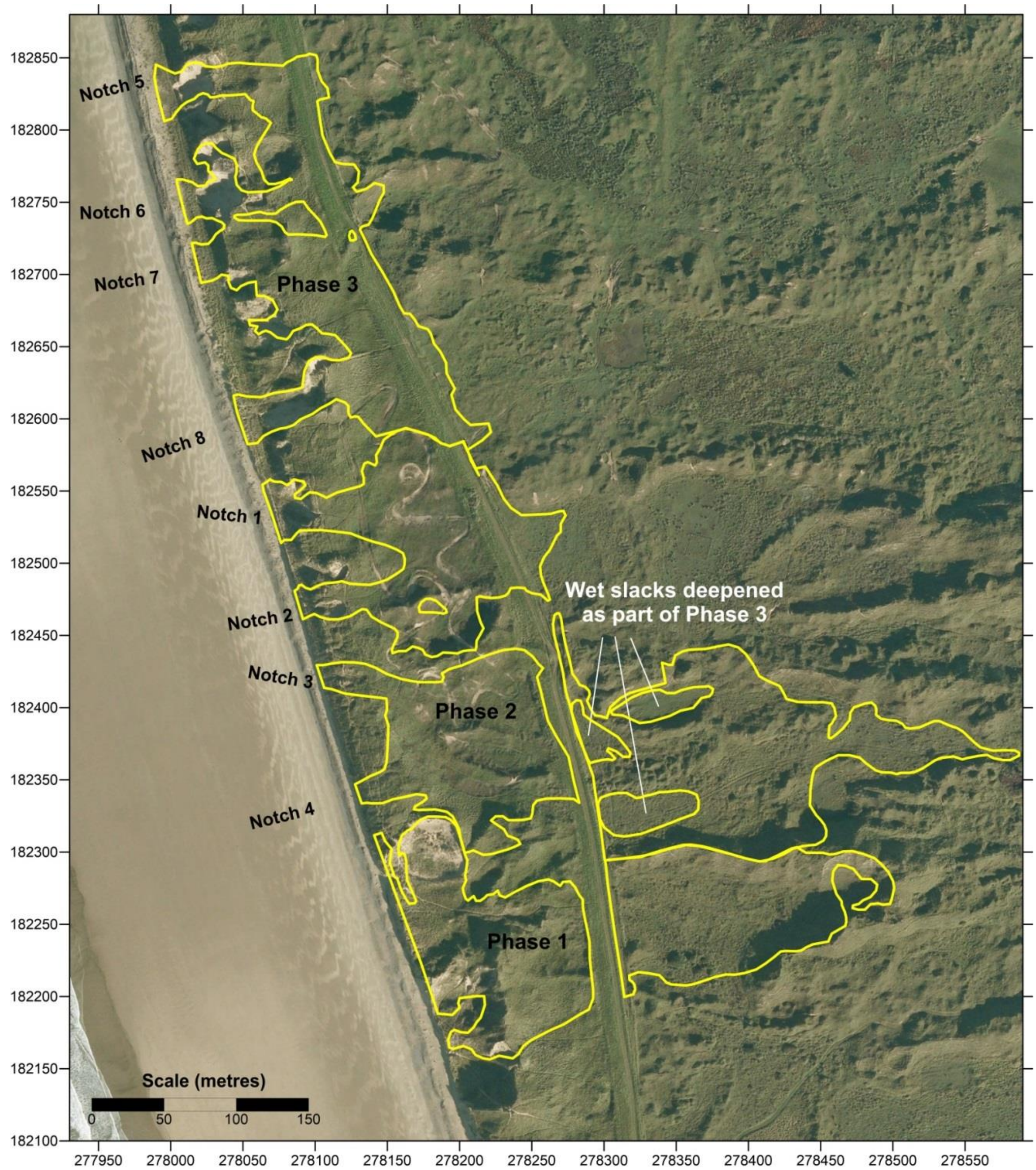


Figure 4. Pre-works aerial photograph flown 12 October 2009, showing boundaries of the Phase 1, 2 and 3 rejuvenation trial areas and positions of the major notches

Figure 5. Turf stripping, Kenfig Phase 1, February 2012 (photograph by David Carrington, Reserve Warden, Bridgend Borough Council)

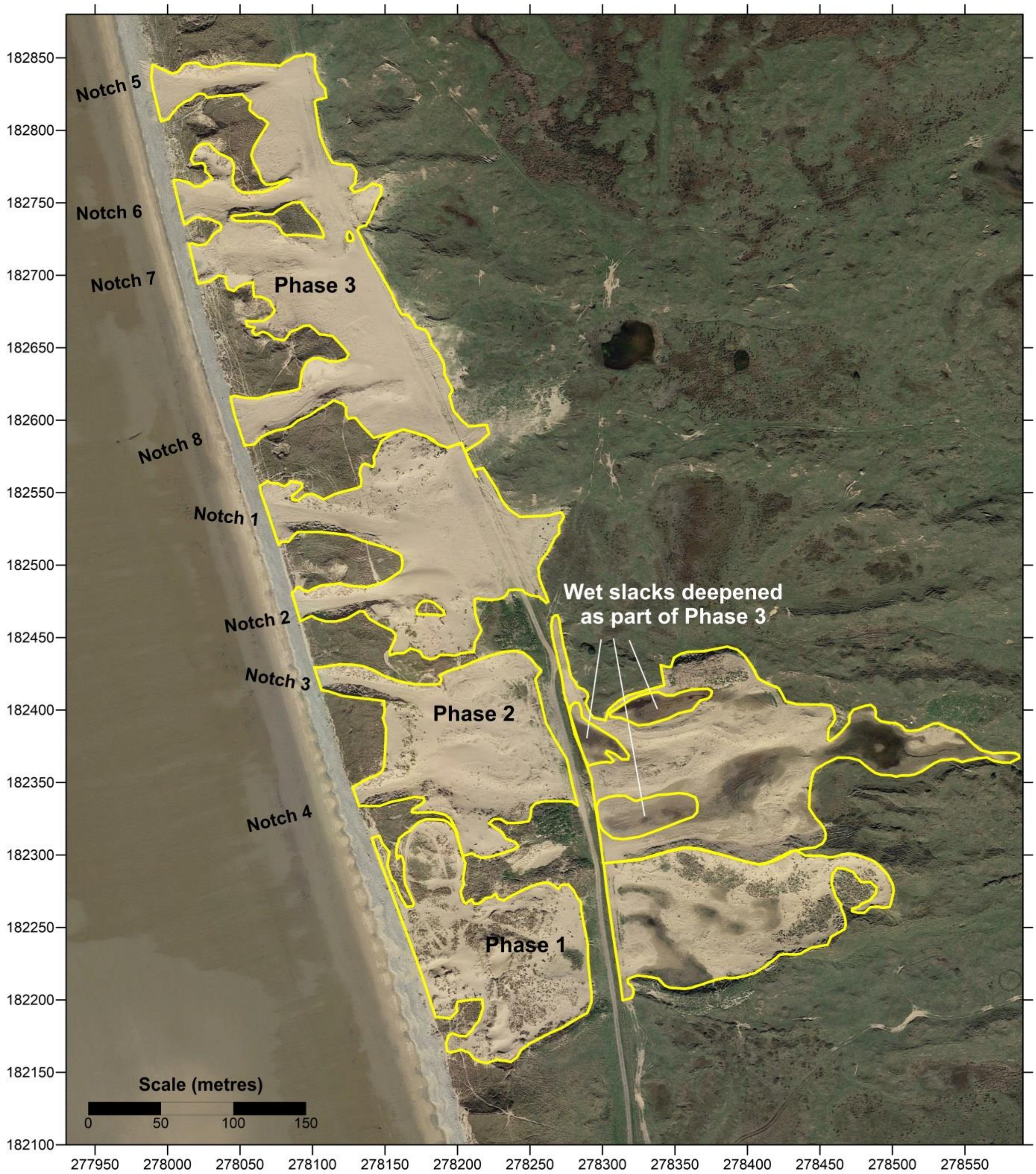


Figure 6. Aerial photograph flown 18 April 2015 showing extent of bare sand associated with the three phases of dune rejuvenation works at Kenfig undertaken February to March 2012 (Phase 1), January to February 2013 (Phase 2) and November to December 2014 (Phase 3) (photograph source: Google Earth)

Figure 7. Photographs of the seaward end of the Phase I area where turf stripping and dune lowering was undertaken: (a) March 2012 (photograph by Mike Howe, NRW); (b) October 2012, showing regrowth of *Rubus* and marram; (c) March 2013, after spraying; (d) January 2014; (e) March 2015; (f) 26 July 2016

Figure 8. Photographs of the deflation corridor of the Phase 1 parabolic dune, view seaward from the dune crest. Note significant vegetation regrowth in 2012, followed by a decrease in 2013 partly due to spraying and partly to burial by blown sand, and further increase in vegetation cover since January 2014

Figure 9. Photographs of the Phase 2 area, taken from the crest of the Phase 1 parabolic dune looking towards the sea: (a) March 2014; (b) May 2014; (c) March 2015; (d) July 2016

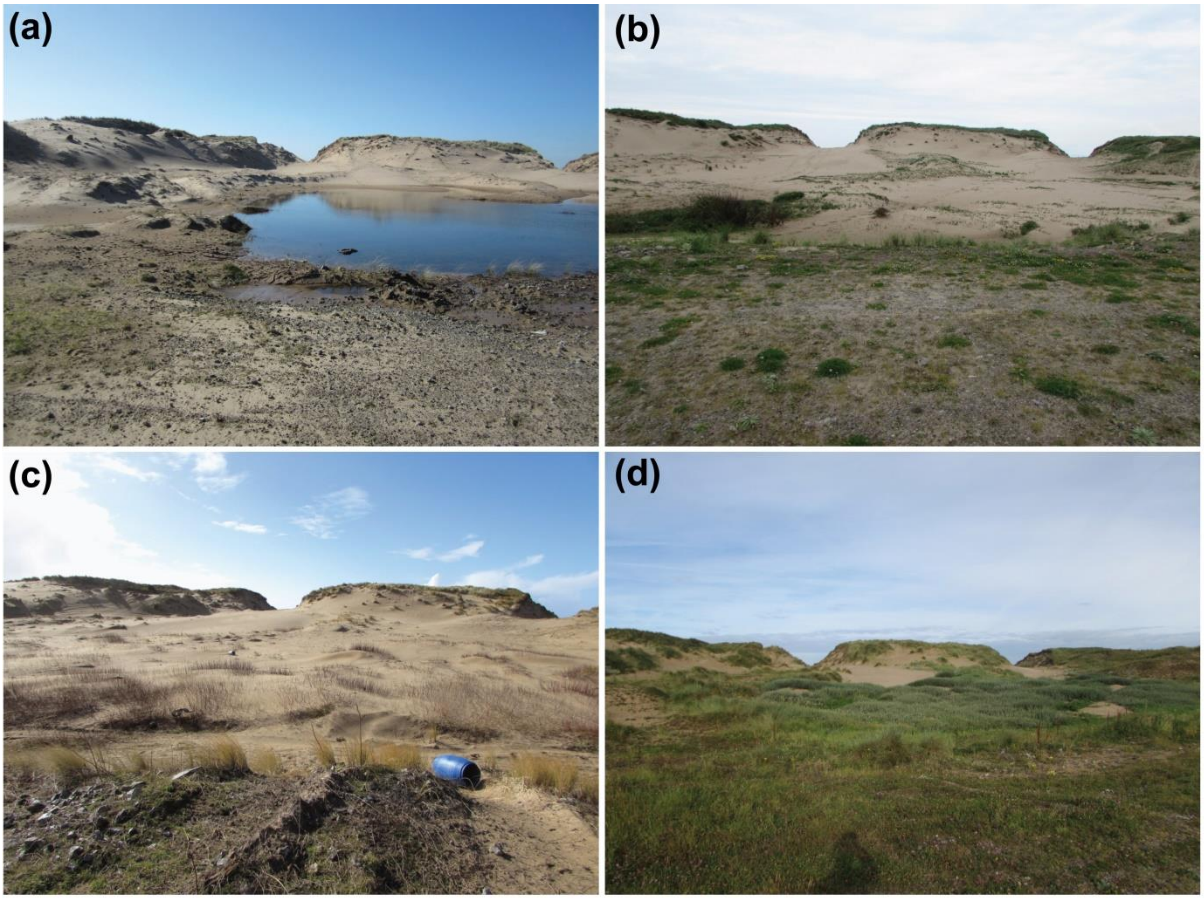


Figure 10. Photographs of the western part of Phase 2, taken from the haul road looking towards the sea: (a) March 2014; (b) May 2014; (c) March 2015; (d) July 2016

Figure 11. Photographs of the Phase 3 area: (a) March 2014; (b) March 2014; (c) March 2015 landward side of haul road behind notches; (d) July 2016; (e) July 2016; (f) July 2016; (g) July 2016; (h) July 20

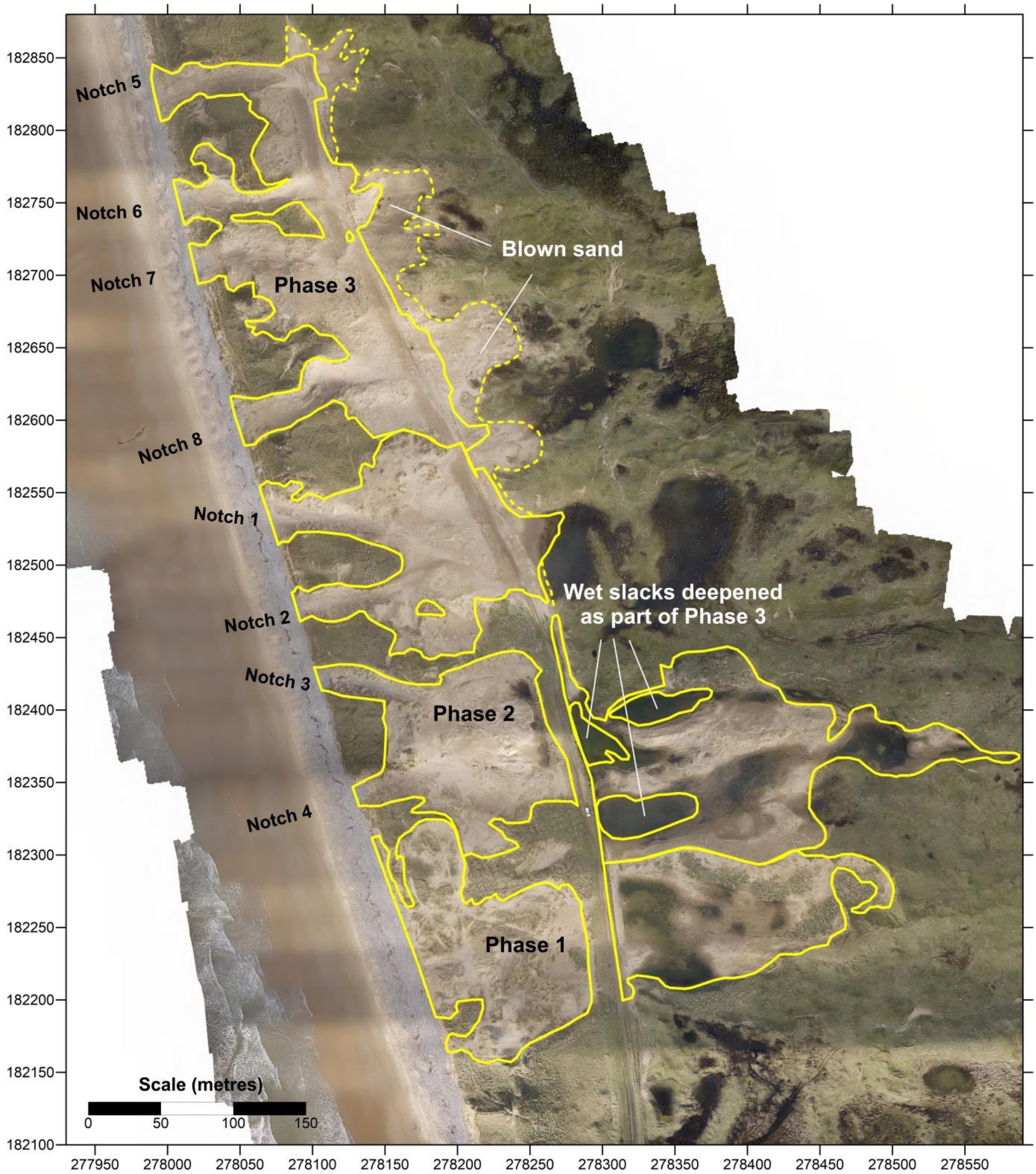


Figure 12. UAV aerial imagery flown February 2016 showing the extent of bare sand associated with the three phases of dune rejuvenation works at Kenfig undertaken February to March 2012 (Phase 1), January to February 2013 (Phase 2) and November to December 2014 (Phase 3)

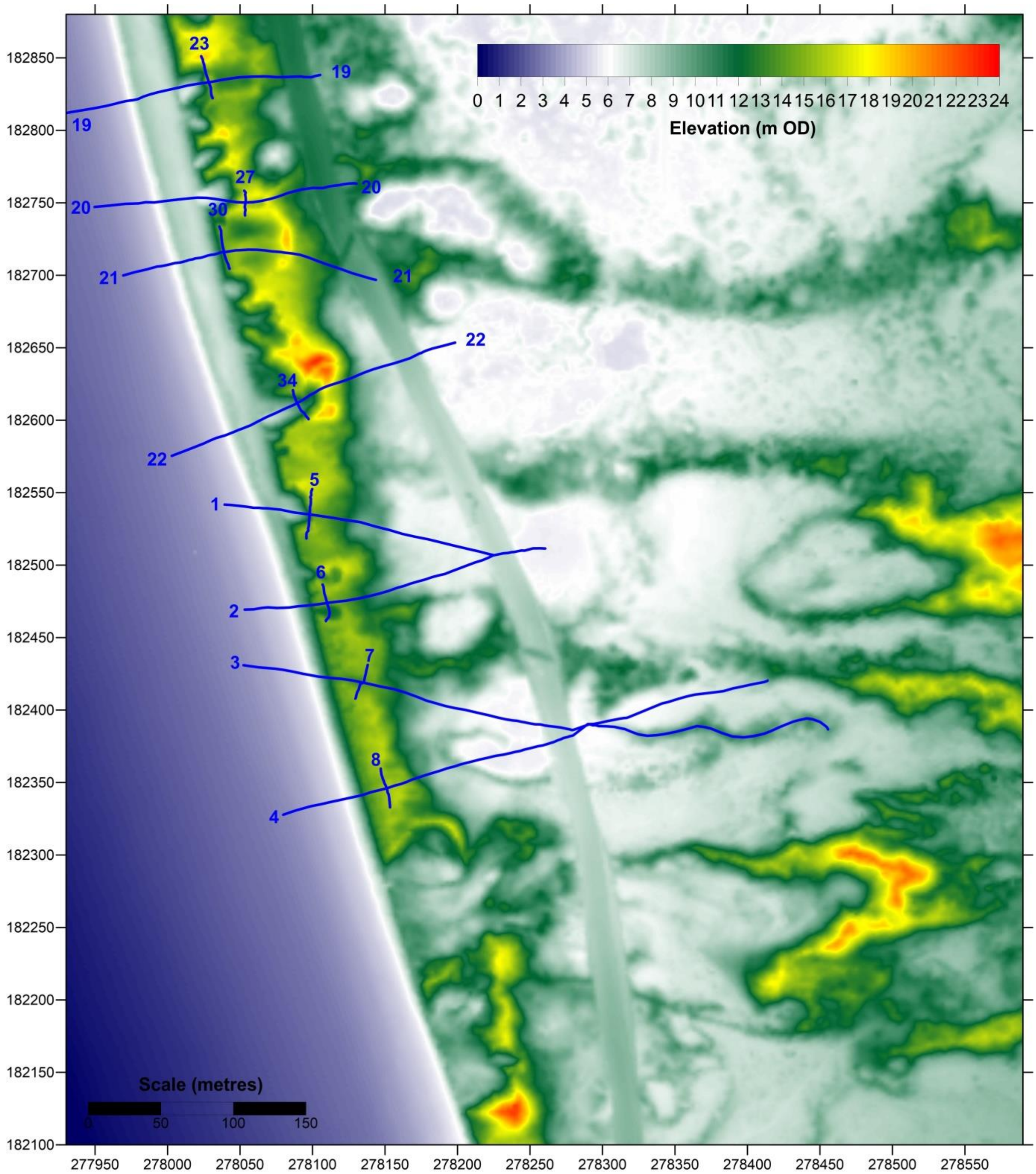


Figure 13. Unfiltered DEM of the Kenfig rejuvenation site, based on an aerial LiDAR survey on 26 February 2006, before the rejuvenation works started

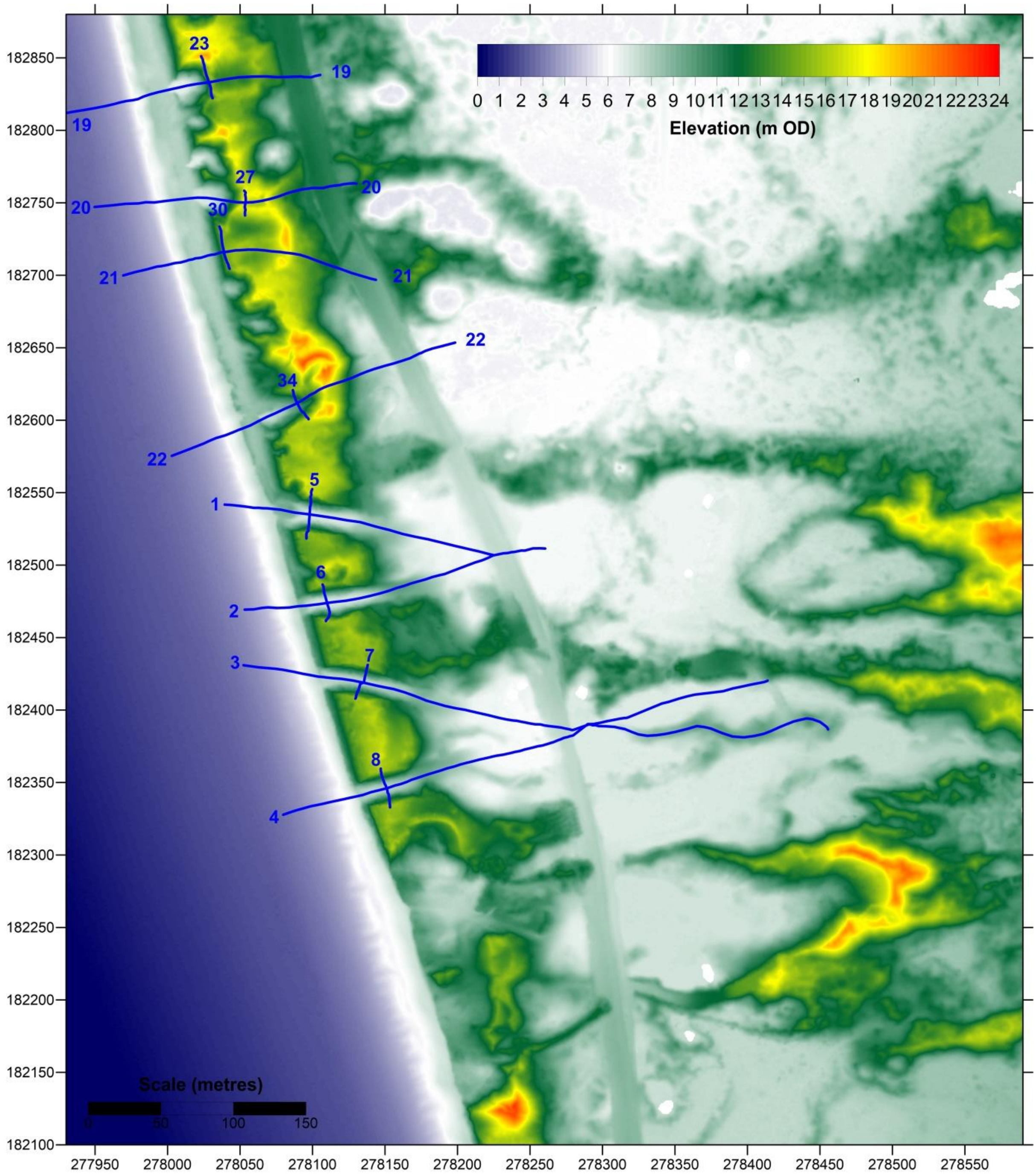


Figure 14. Unfiltered DEM of the Kenfig rejuvenation site based on an aerial LiDAR survey on 31 March 2014, after completion of the Phase 1 and Phase 2 works but before the Phase 3 works

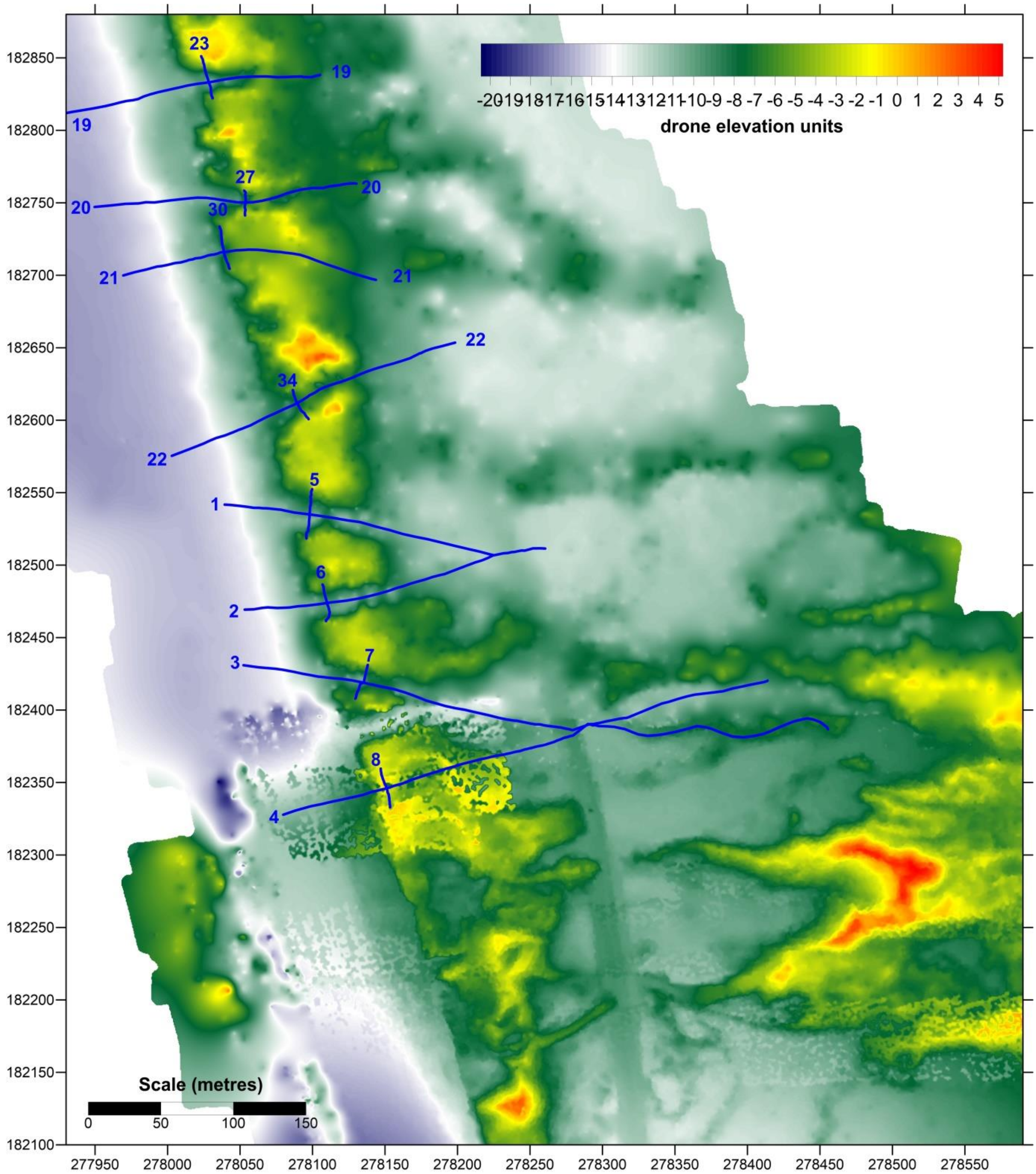


Figure 15. Unfiltered DEM of the Kenfig site based on the UAV survey on 02 March 2016. Data are shown as supplied, without correction to ODN. Note the elevation scale ranges from -20 to + 5

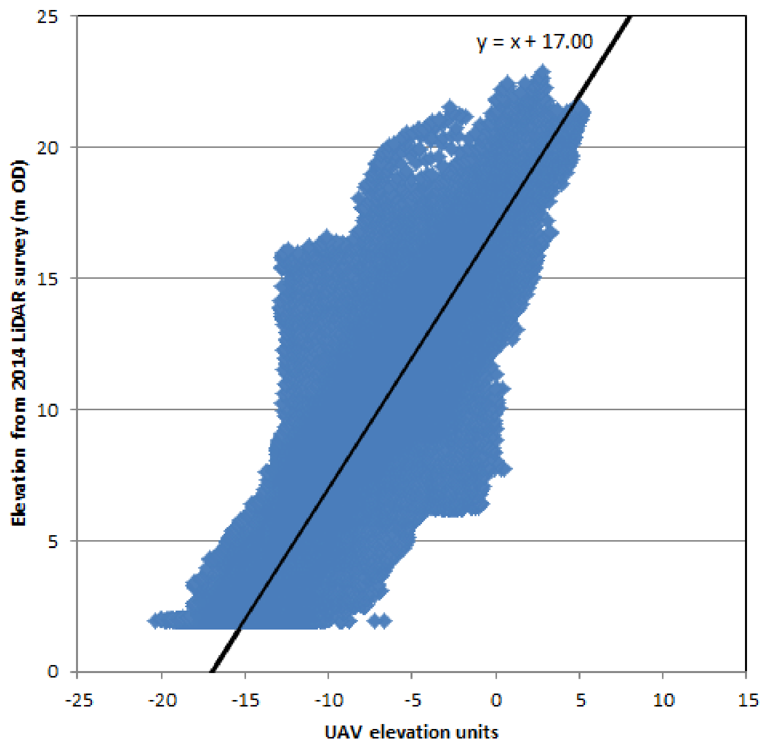


Figure 16. Comparison of elevation units measured during 2014 LiDAR survey and 2016 UAV survey, after translation of 3 m to the south and 5 m to the west. A linear trend line shows that an initial correction of +17.0 m is required to adjust elevation units to ODN

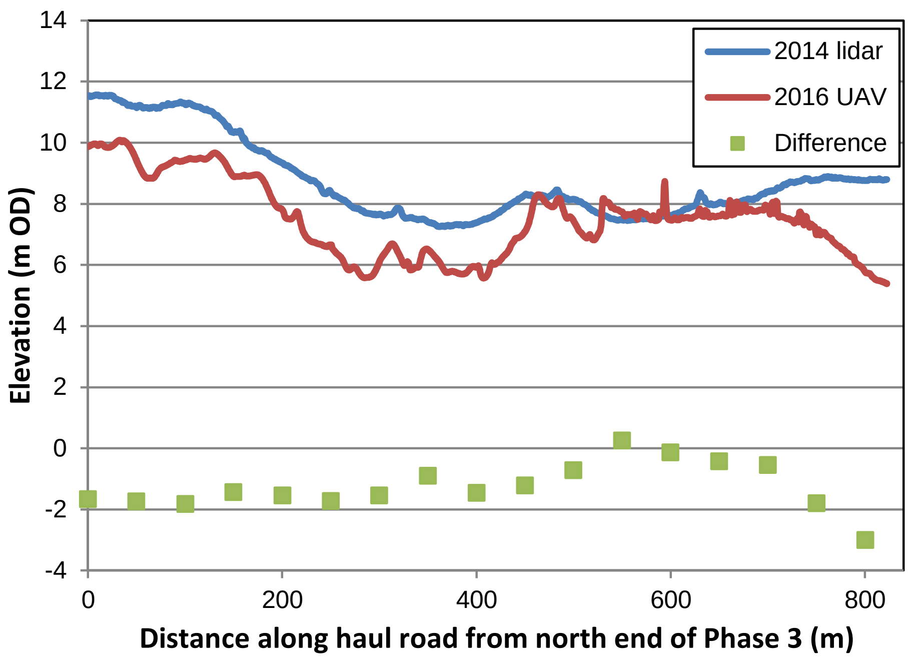


Figure 17. Comparison of elevation units measured during 2014 LiDAR survey and 2016 UAV survey, after translation of 3 m to the south and 5 m to the west, and conversion to m ODN using the addition of +17.0 m. The differences along the haul road were extrapolated in a WSW-ENE direction, and the DEM warped in Surfer

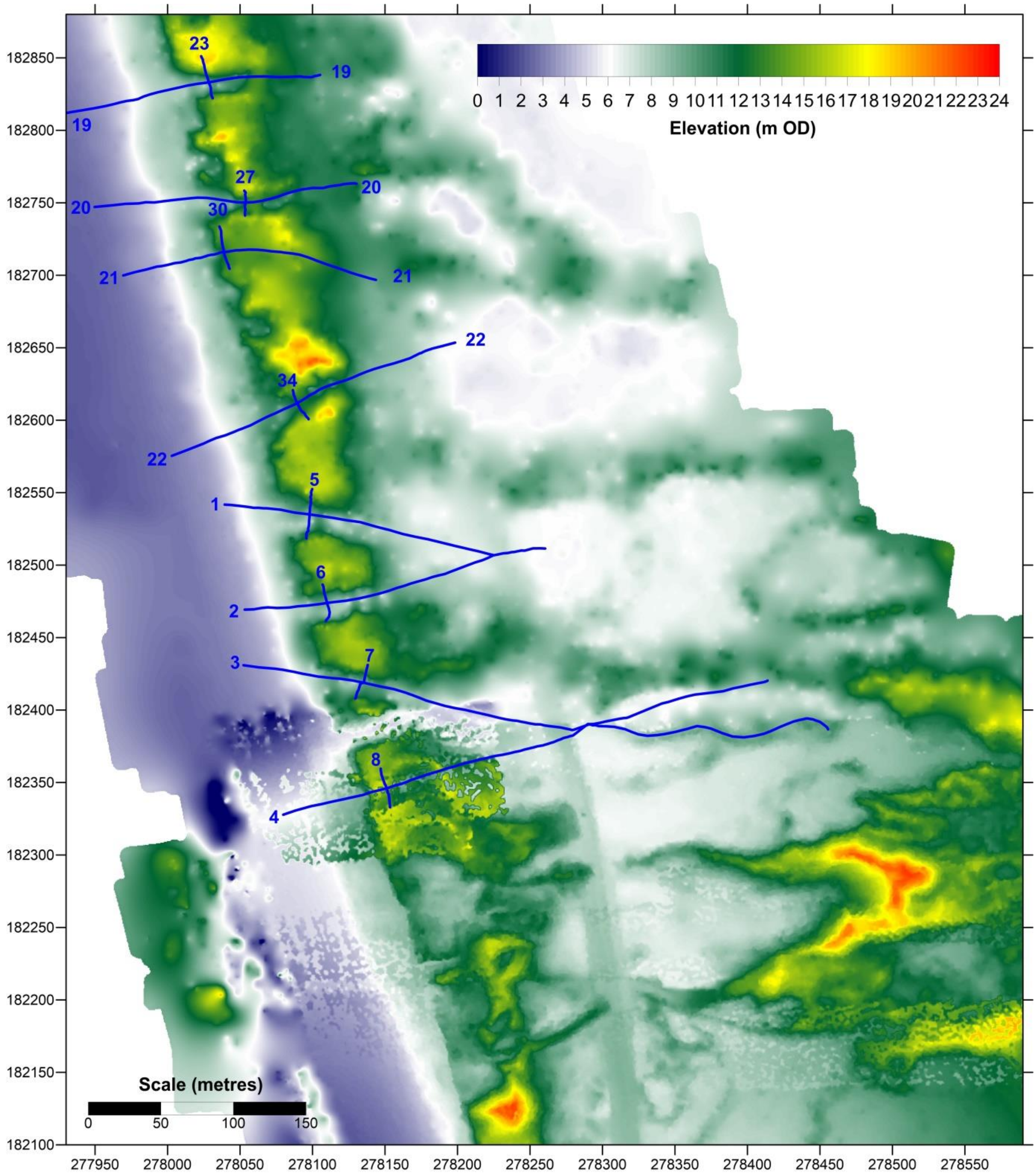


Figure 18. DEM of the Kenfig site based on the UAV survey flown on 02 March 2016, after correction using the elevations recorded along the haul road on the 2014 LiDAR survey

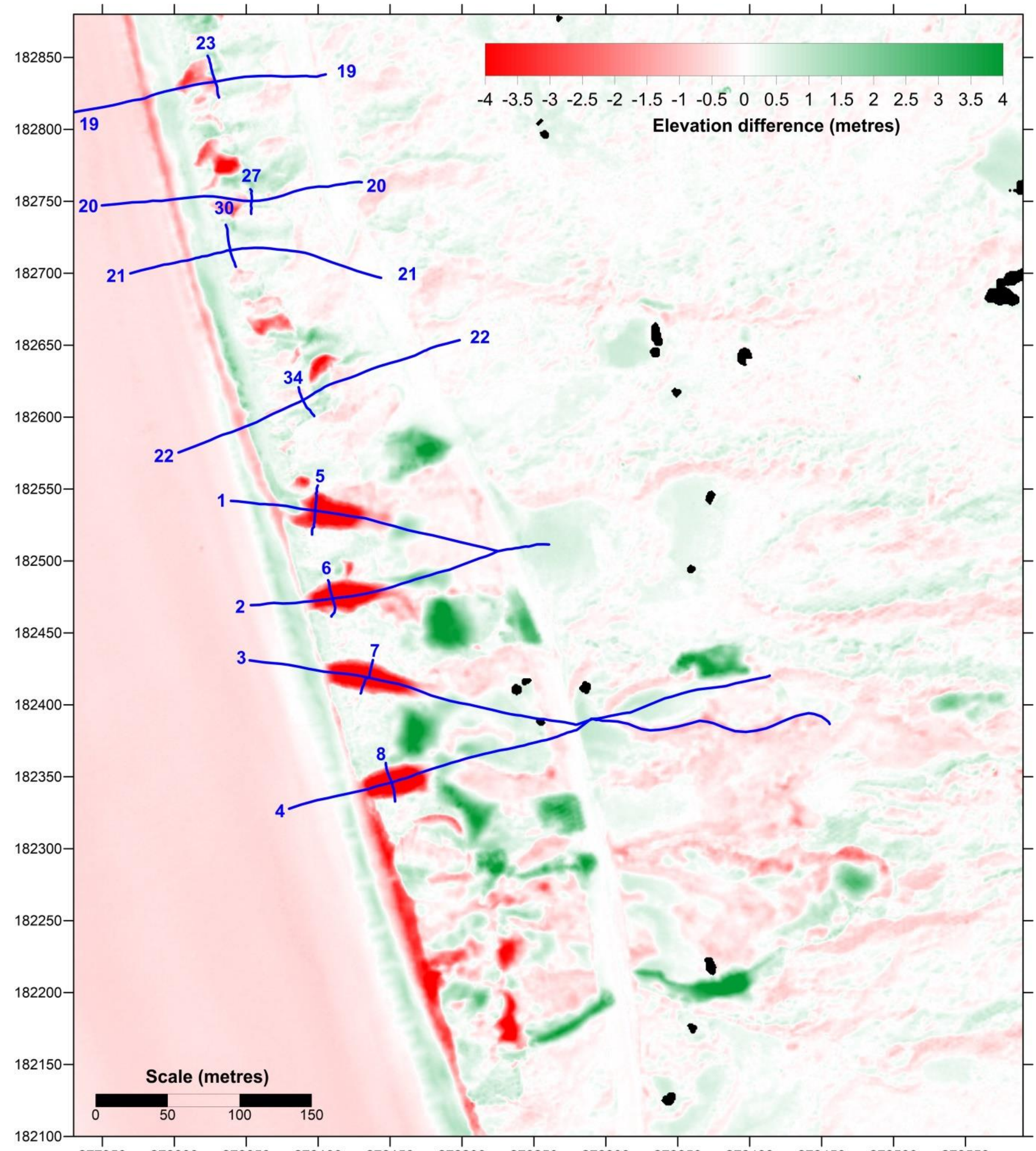


Figure 19. Difference in elevation between 2006 and 2014 aerial Kenfig LiDAR surveys. Over the Phase 1 and Phase 2 areas (those rejuvenated by the time of the 2014 survey), and above the HAT contour in 2006, there was 36880 m^3 of sediment accretion, and 43328 m^3 of sediment erosion, equating to a net sediment loss of 6448 m^3, mostly due to marine erosion of the frontal dunes along the Phase 1 frontage. Changes in the inland parts of the Phase 1 area and in the Phase 2 area are mostly due to the physical intervention works (turf stripping and turf placement, notch cutting); changes north of profile 22 are natural (accretion on the frontal dune platform, deepening of blowouts and sand deposition on their windward sides)

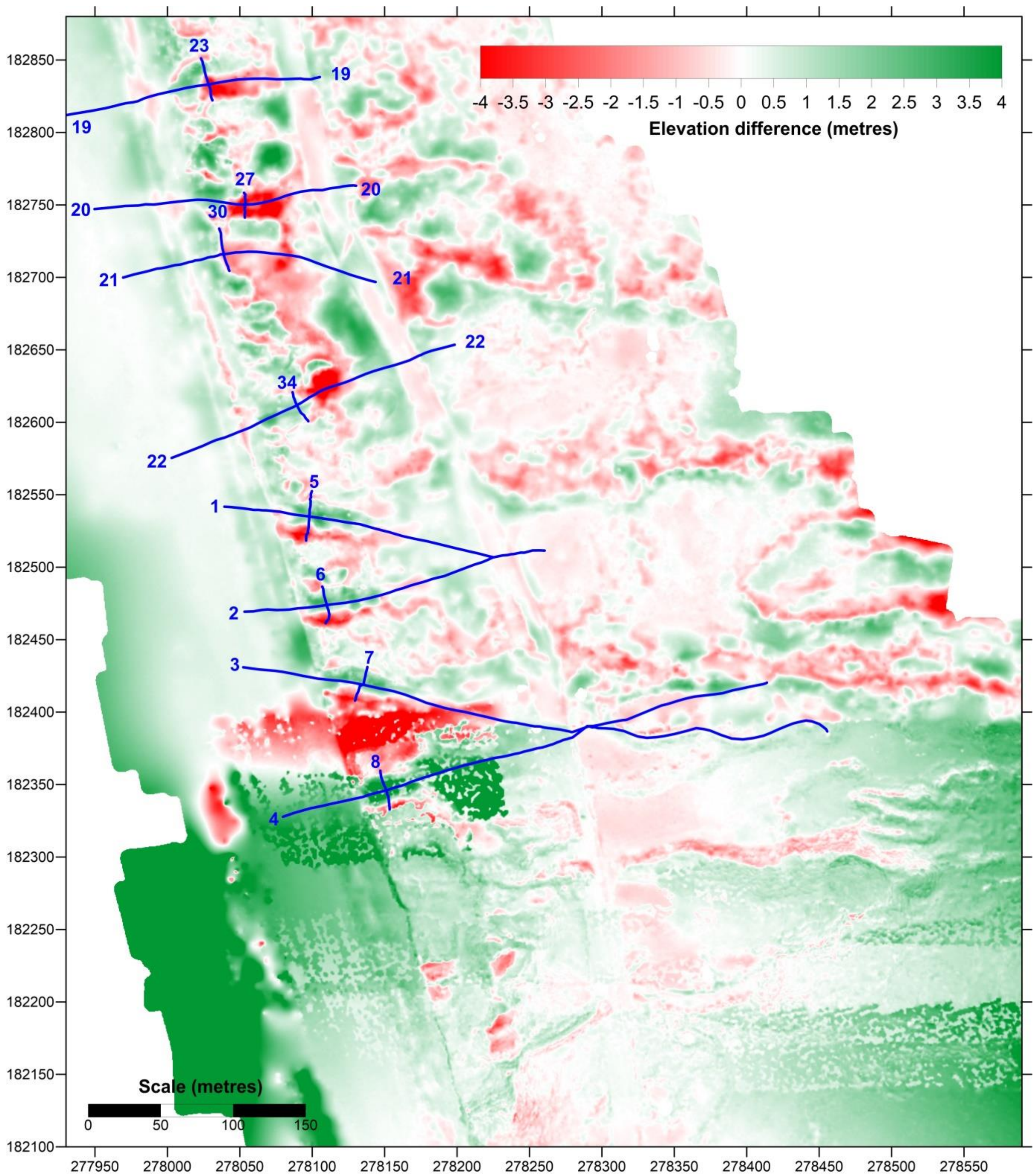


Figure 20. Difference in apparent elevation between the Kenfig 2014 aerial LiDAR and 2016 UAV survey, after corrections using the elevations recorded along the haul road on the 2014 LiDAR survey. Note that the apparent elevations in the southern third of the image are unreliable

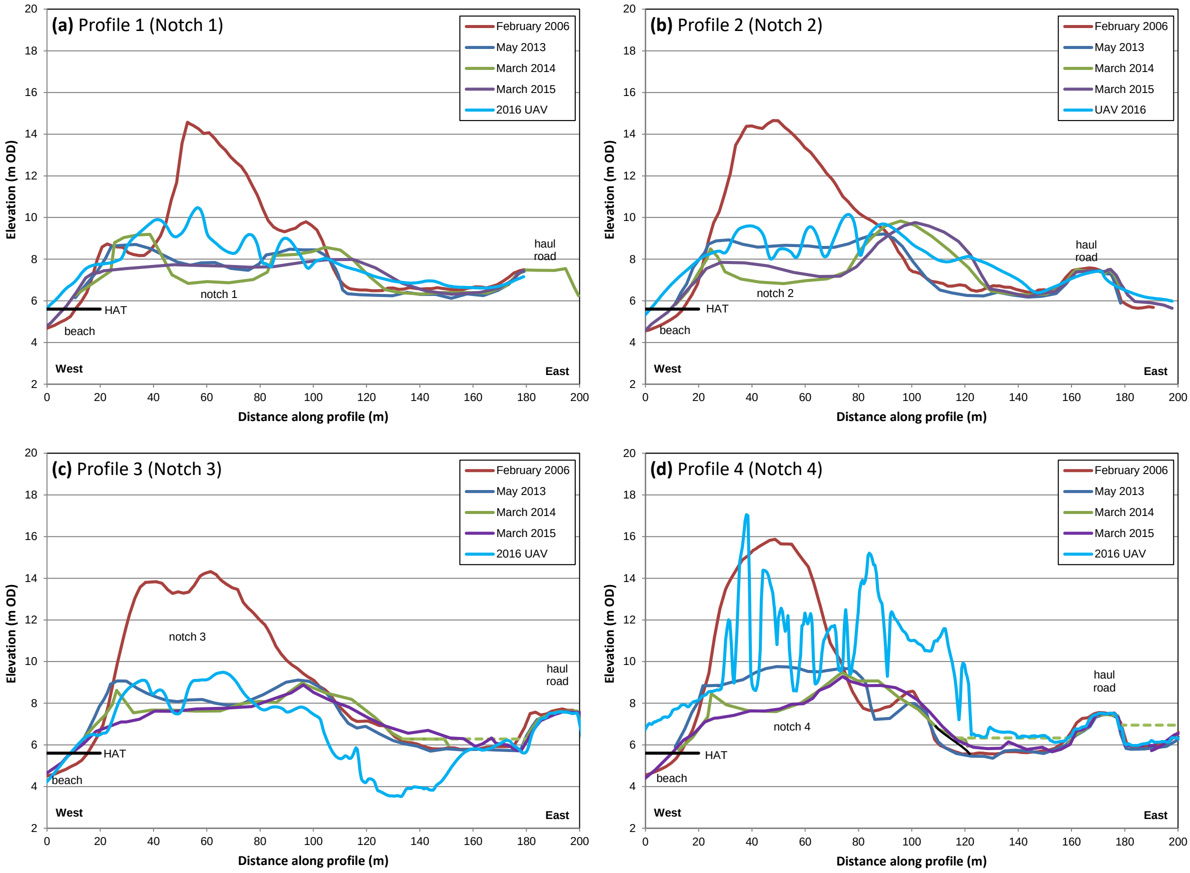


Figure 21. Topographic profiles along the axes of the notches in the Kenfig Phase 2 area. Elevations are shown for the aerial LiDAR survey flown prior to rejuvenation works (26 February 2006), subsequent ground RTK surveys in May 2013, March 2014 and March 2015, and UAV survey on 2 March 2016 (note that although corrections have been made, the data are still some unreliable). The level of HAT (at 5.6 m ODN) is also shown

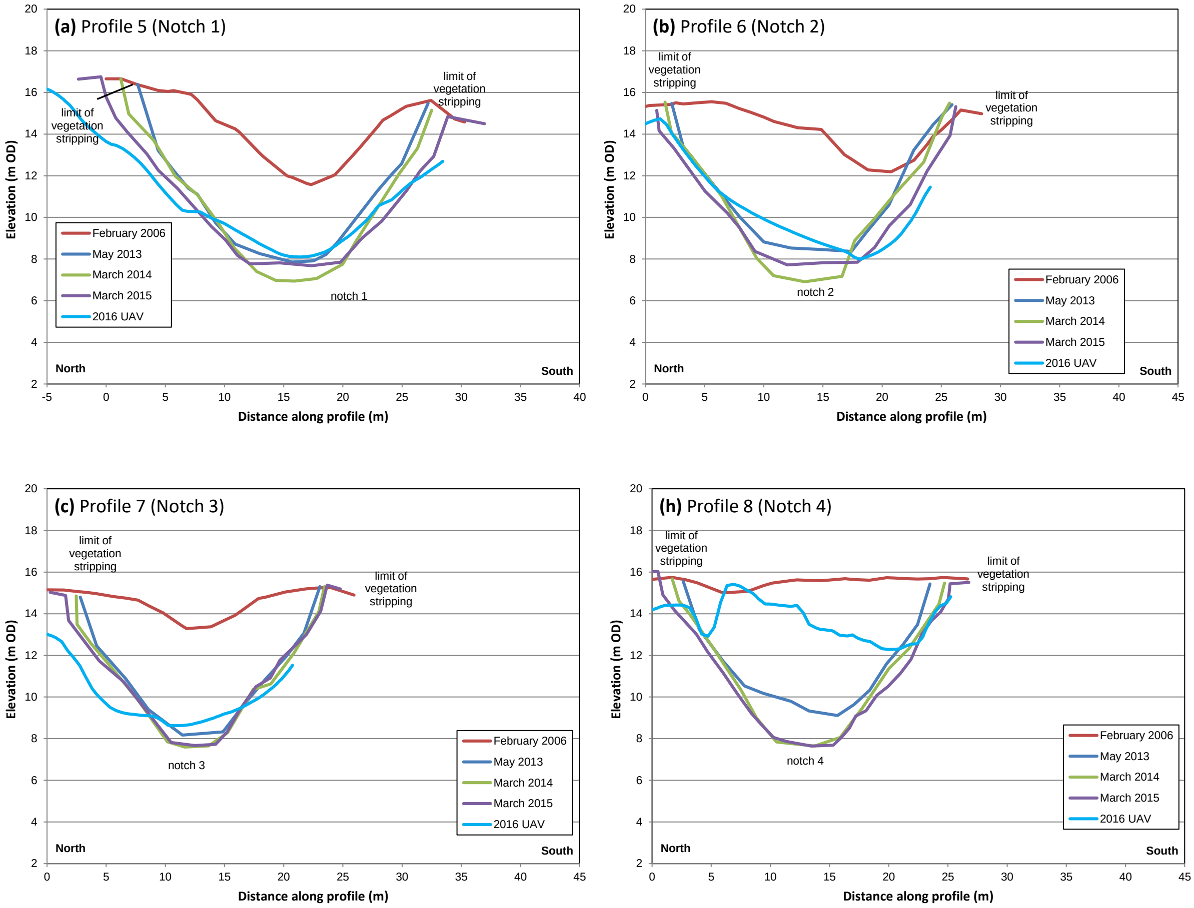


Figure 22. Topographic profiles across the notches in the Kenfig Phase 2 area. Elevations are shown for the aerial LiDAR survey flown prior to rejuvenation works (26 February 2006), subsequent ground RTK surveys in May 2013, March 2014 and March 2015, and UAV survey on 2 March 2016 (note that although corrections have been made, the data are still unreliable, most notably for Notch 4)

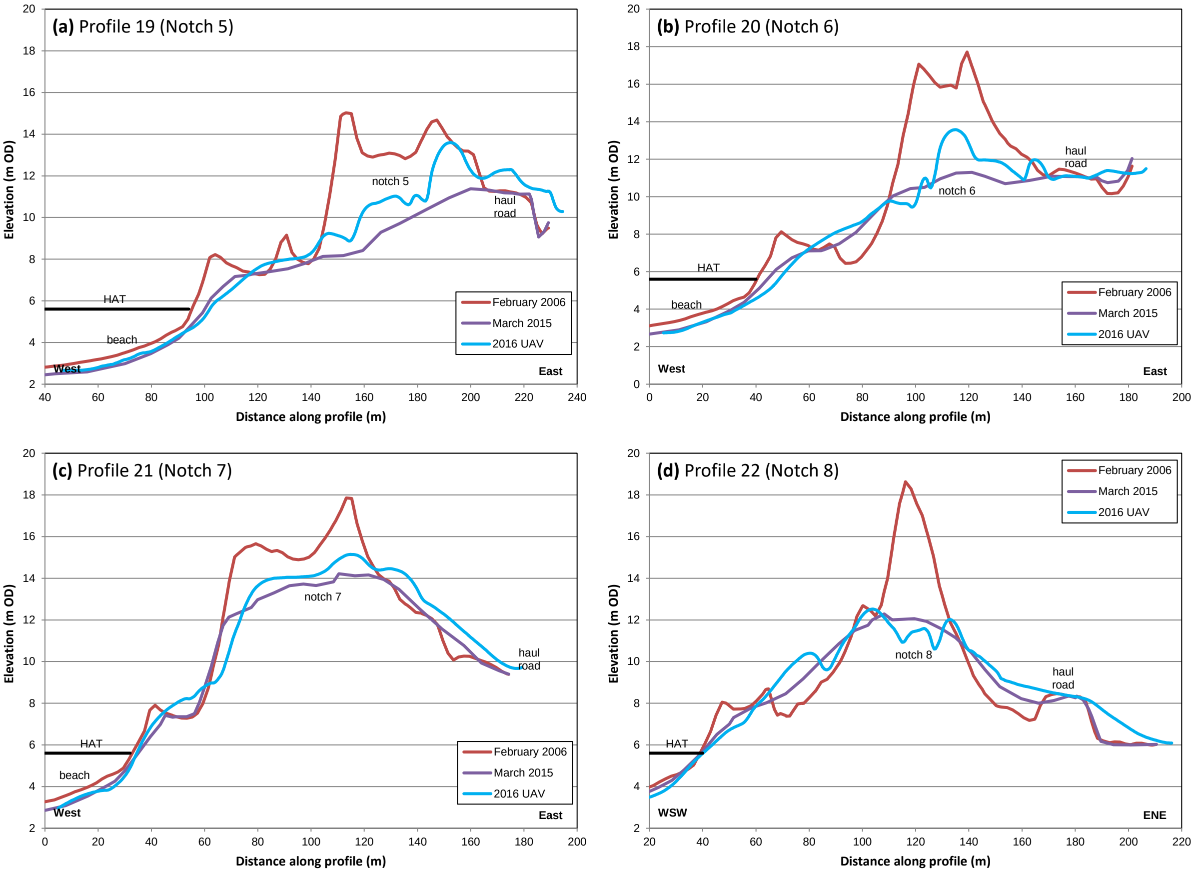


Figure 23. Topographic profiles along the axes of the notches in the Kenfig Phase 3 area. Elevations are shown for the aerial LiDAR survey flown prior to rejuvenation works (26 February 2006), subsequent ground RTK surveys in May 2013, March 2014 and March 2015, and UAV survey on 2 March 2016 (note that although corrections have been made, the data are unreliable). The level of HAT (at 5.6 m ODN) is also shown

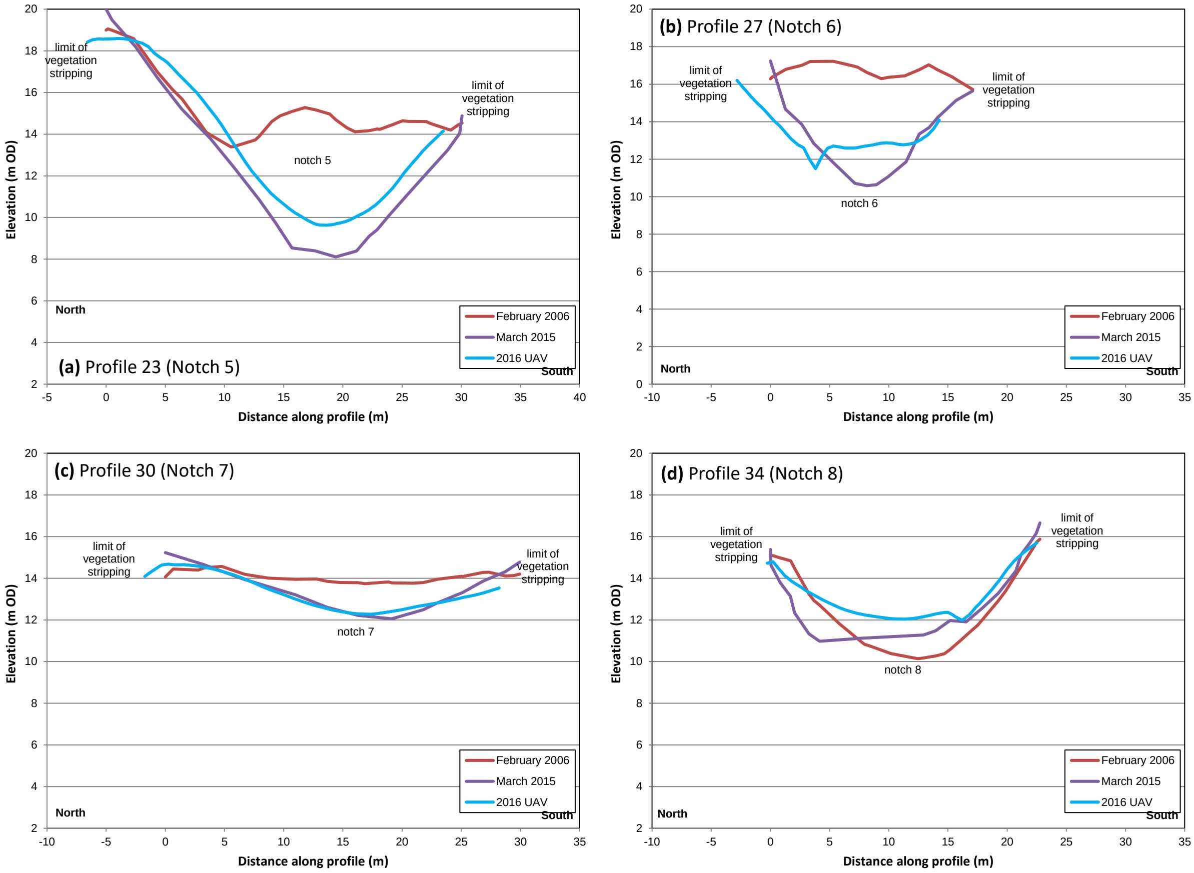


Figure 24. Topographic profiles across the notches in the Kenfig Phase 3 area. Elevations are shown for the aerial LiDAR survey flown prior to rejuvenation works (26 February 2006), subsequent ground RTK surveys in May 2013, March 2014 and March 2015, and UAV survey on 2 March 2016 (note that although corrections have been made, the data are still unreliable, most notable for Notch 4)

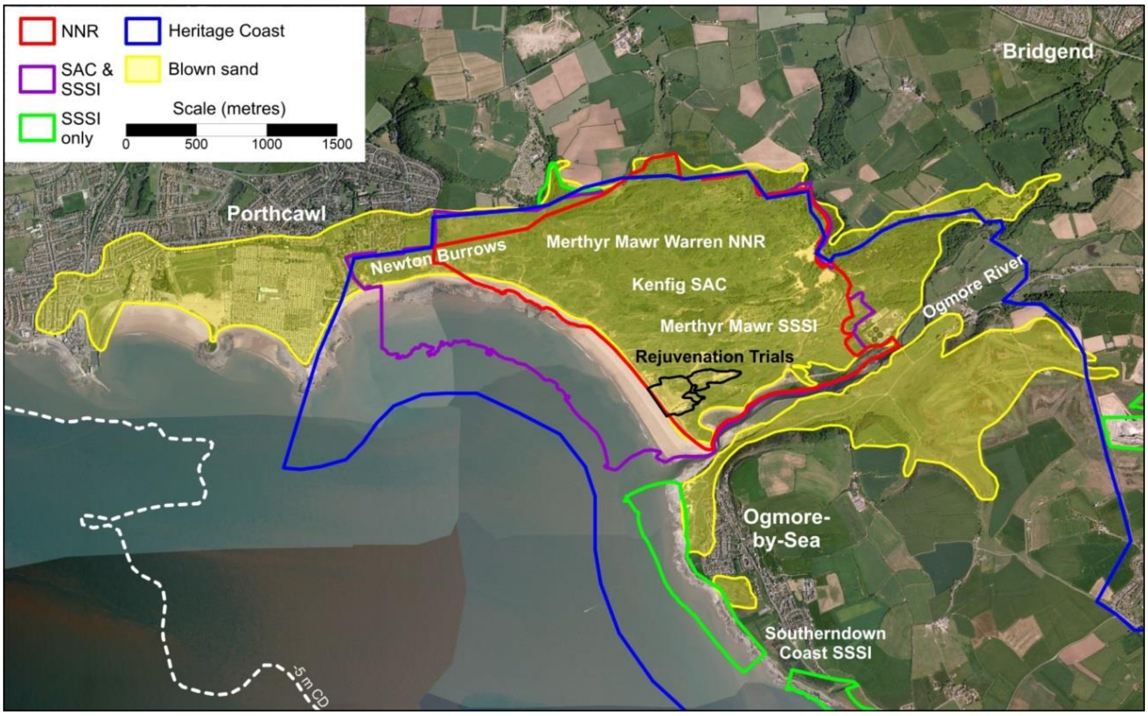
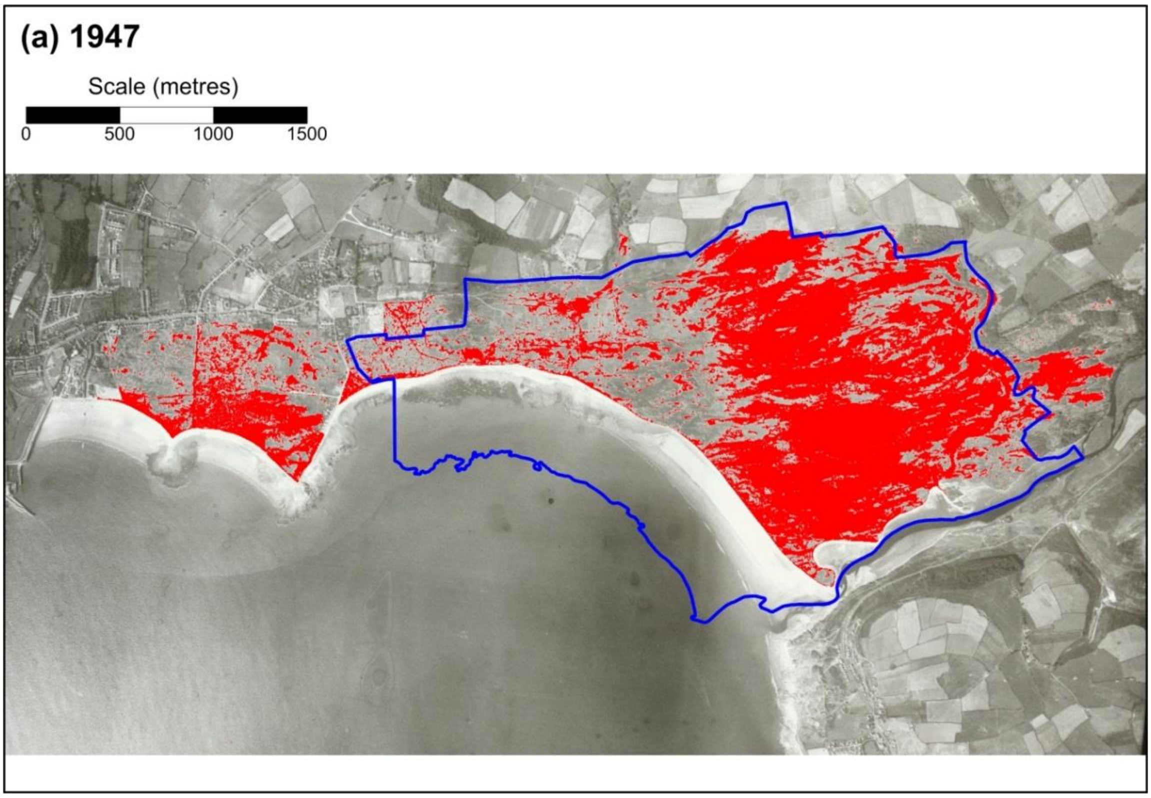


Figure 25. Location of the rejuvenation trials at Merthyr Mawr Warren. NNR, SSSI and SAC boundaries are also shown



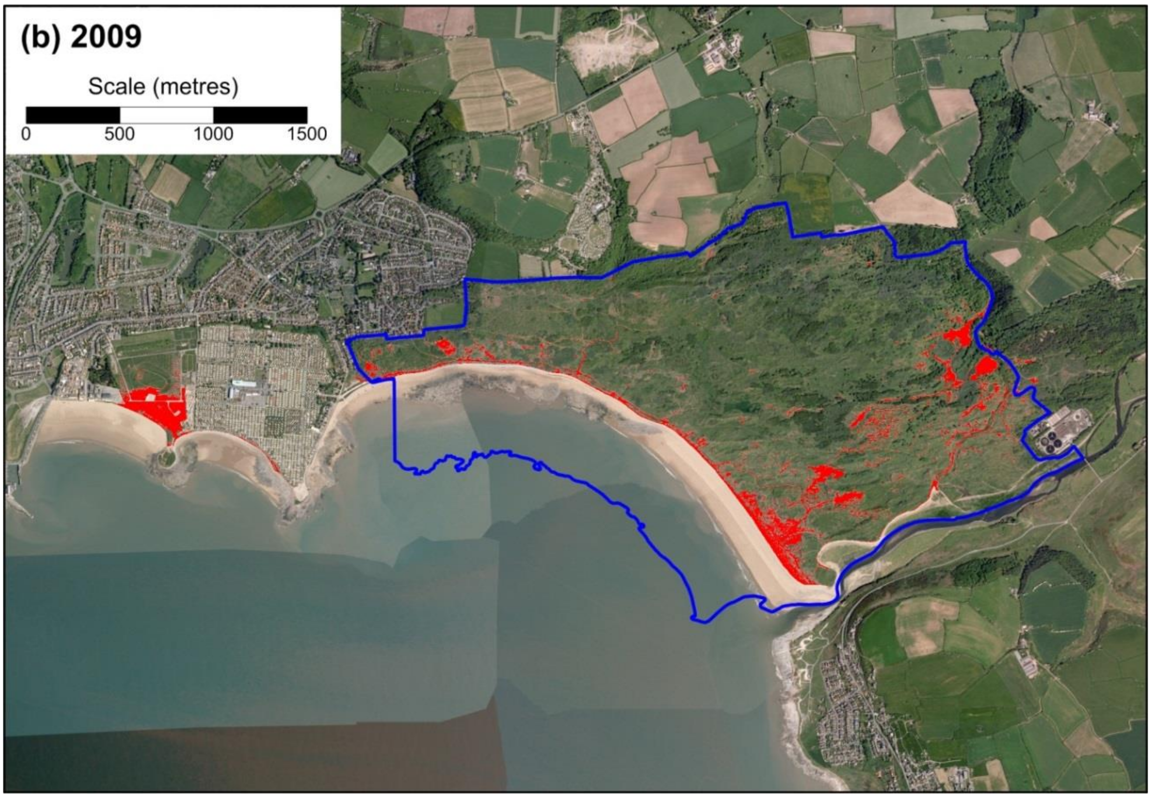


Figure 26. The extent of bare sand (red) at Merthyr-Mawr Warren in (a) 1947, and (b) 2009. The blue line indicates the SAC boundary

Figure 27. View from the crest of the large active parabolic dune (Dune ‘A’) at Merthyr Mawr looking seawards in September 2011

Figure 28. Pre-works aerial photograph of the southeastern part of Merthyr Mawr Warren flown 12 October 2009, showing extent of the Phase 1-3 rejuvenation works undertaken between November 2012 and November

Figure 29. Aerial photograph showing the Merthyr Mawr Phase 3 work completed winter 2014-15 (source: Ludlow, 2014)

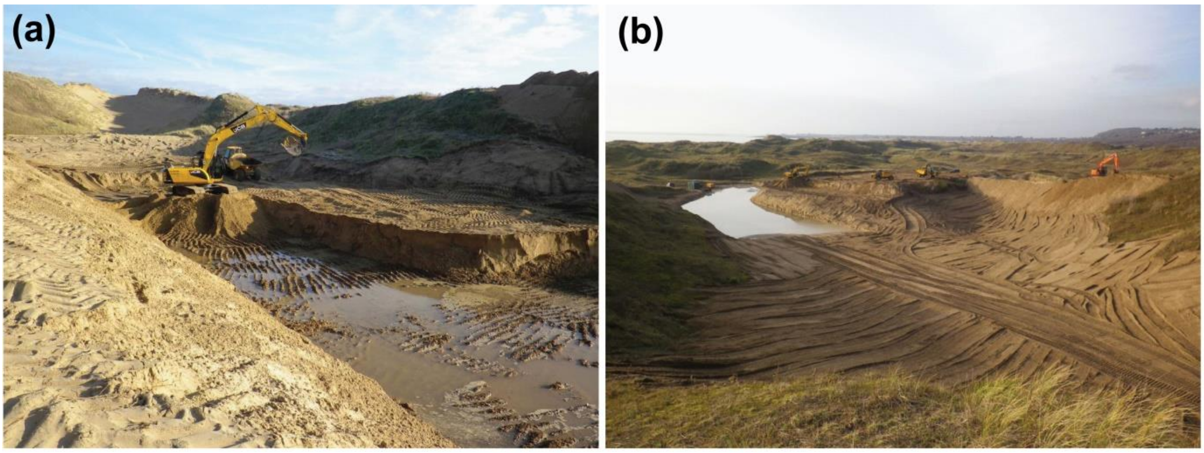


Figure 30. Merthyr Mawr Phase 1, December 2012: (a) Sand excavation in progress to create an artificial slack; (b) work to create slack and extend / raise dune arms near completion (photographs by D. Ludlow, NRW)

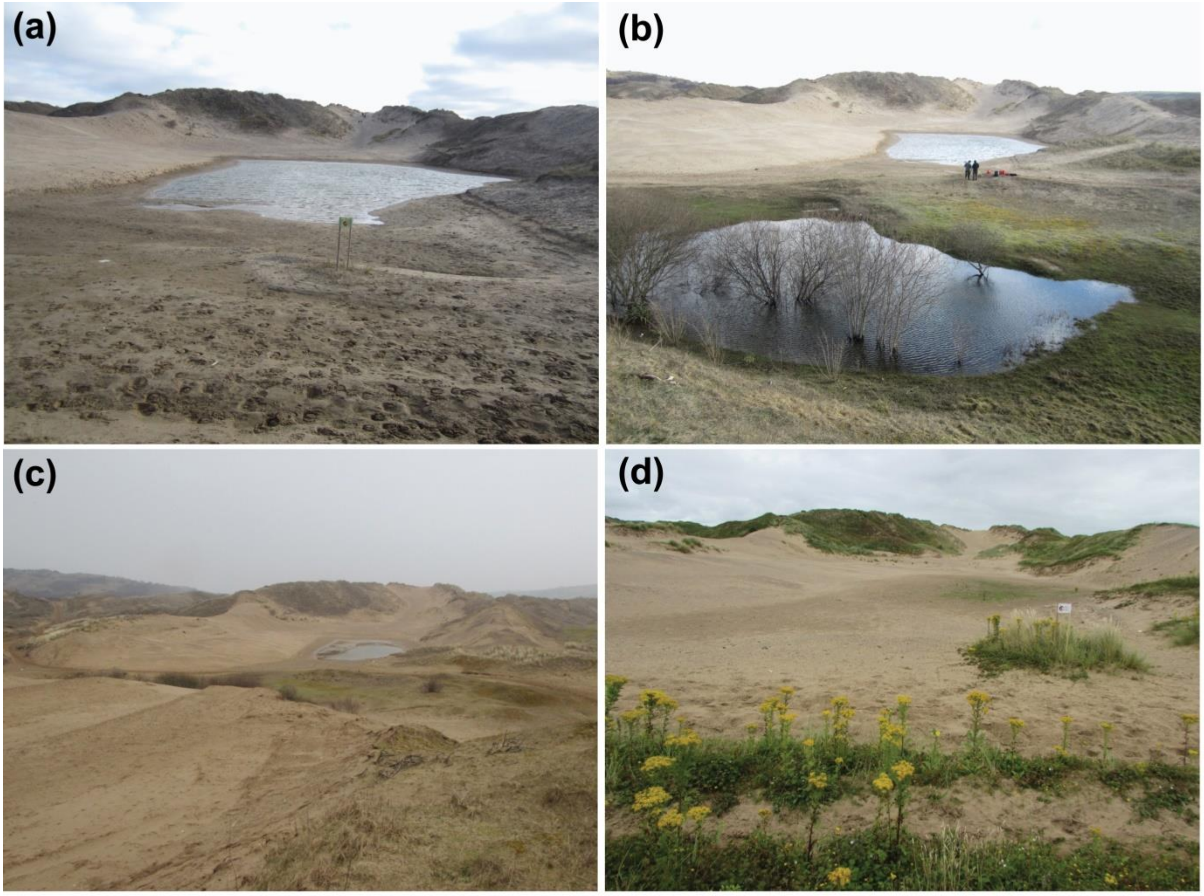


Figure 31. Photographs of the Merthyr Mawr Phase 1 area, looking inland towards Dune ‘A’: (a) May 2013; (b) March 2014; (c) March 2015; (d) July 2016

Figure 32. Merthyr Mawr Phase 2 area. View of work area looking north towards the end of the contract, with artificial dune in the foreground and sand excavation area in the distance (photograph by D Ludlow, NRW)

Figure 33. Merthyr Mawr Phase 2 area. View of work area looking east at end of contract, with area of sand excavation on the left and artificially constructed dune on the right (photograph by D. Ludlow, NRW)

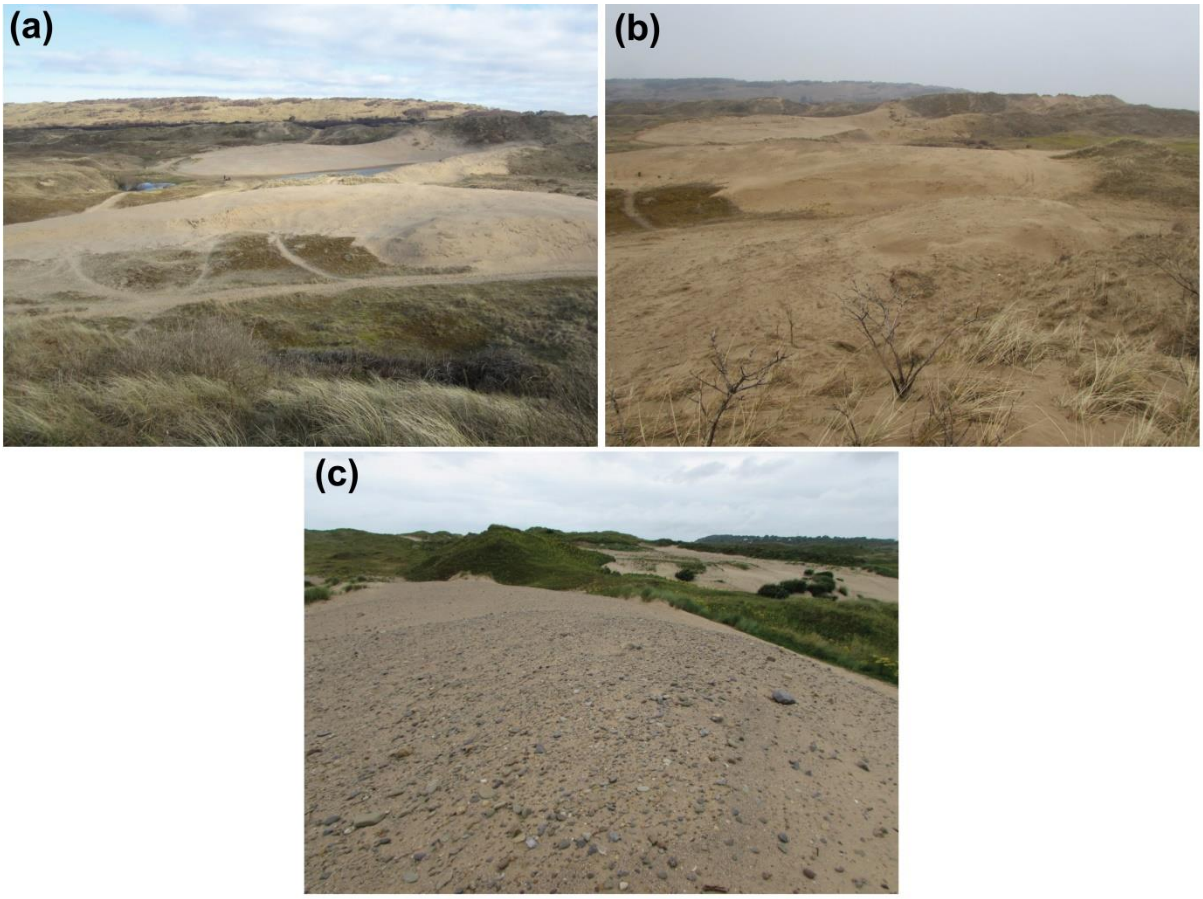


Figure 34. Photographs of the Methyr Mawr Phase 2 site: (a) View west across the artificially constructed dune towards the excavated area in March 2014; (b) the same area in March 2015; (c) Armoured gravel lag on the surface of the artificial dune, July 2016

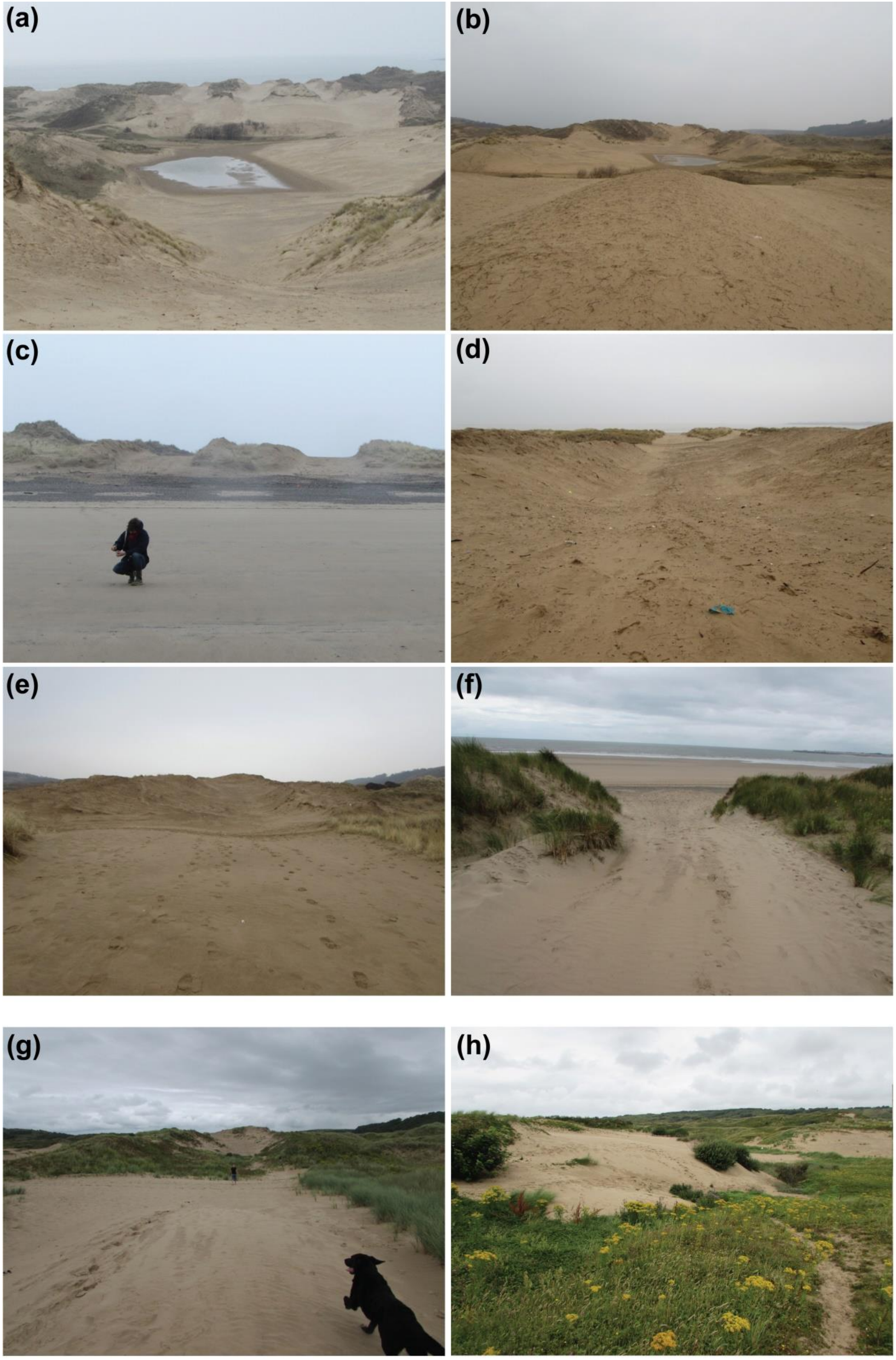


Figure 35. Photographs of the Merthyr Mawr Phase 3 area; (a) stripped deflation corridors in March 2015; (b) view landward March 2015; (c) notches March 2015; (d) Long 'trough' leading to stripped dune; (e) stripped dune at landward end of long trough in March 2015; (f) trough leading to long corridor, July 2016; (g) long corridor leading to stripped dune July 2016; (h) sand lobe transgressing into former shallow pool

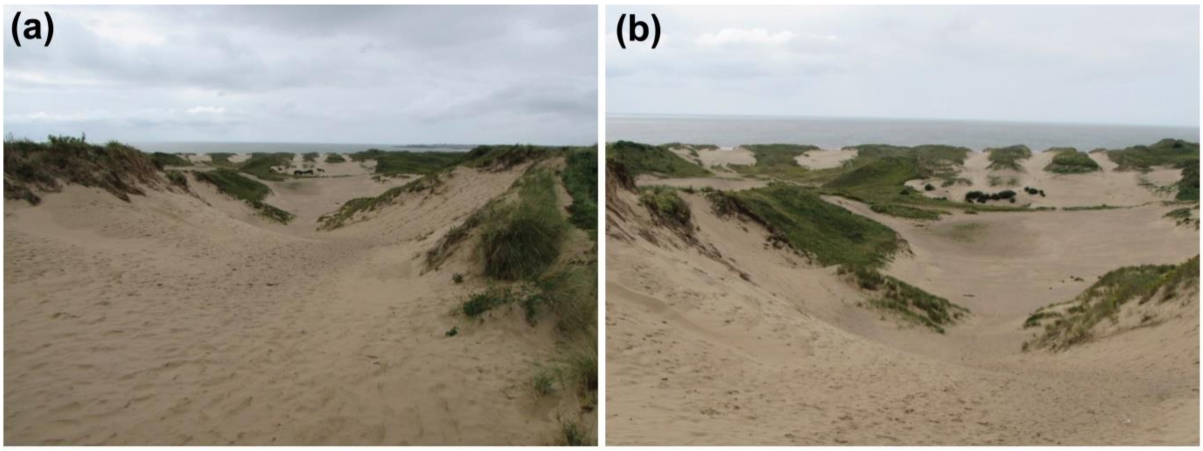


Figure 36. (a) Photograph taken from the crest of 'Dune A' looking seawards in July 2016; (b) closer view of the notches and corridors created in Phase 3

Figure 37. Aerial photograph taken 18 April 2015 showing the three phases of dune rejuvenation works at Merthyr Mawr (source: Google Earth)

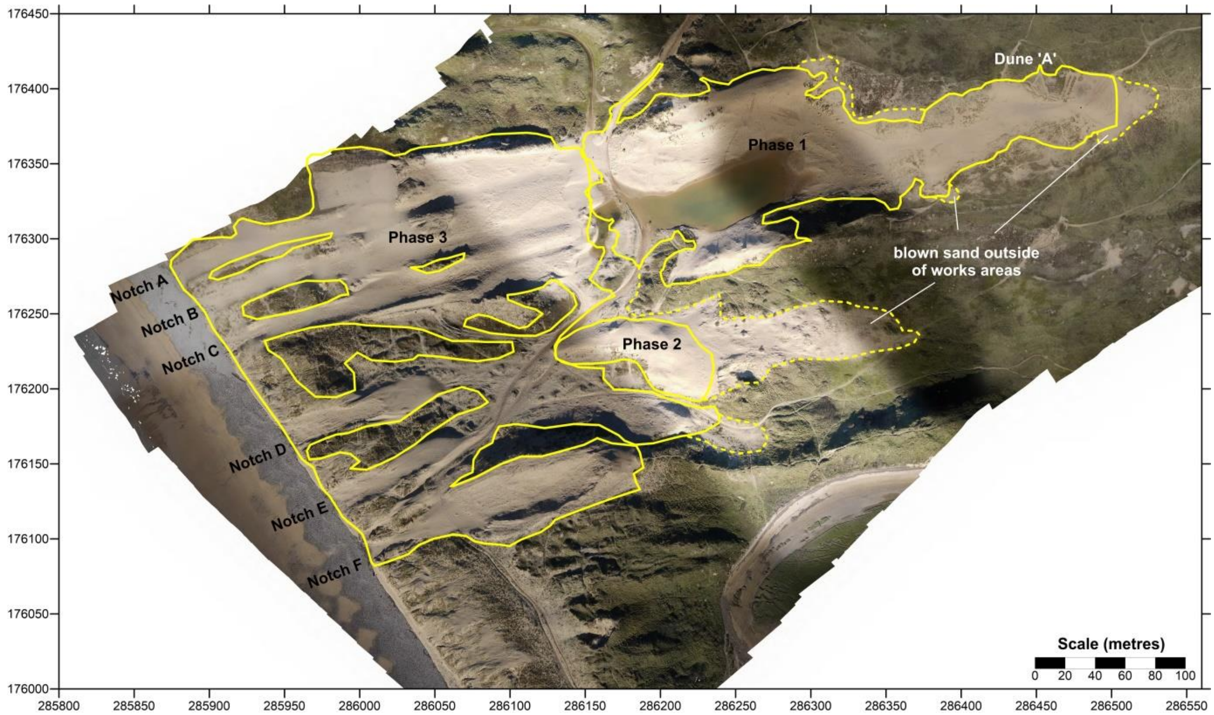


Figure 38. Composite aerial photograph mosaic of the dune rejuvenation area at Merthyr Mawr based on UAV survey 29 February 2016, showing the three phases of dune rejuvenation works

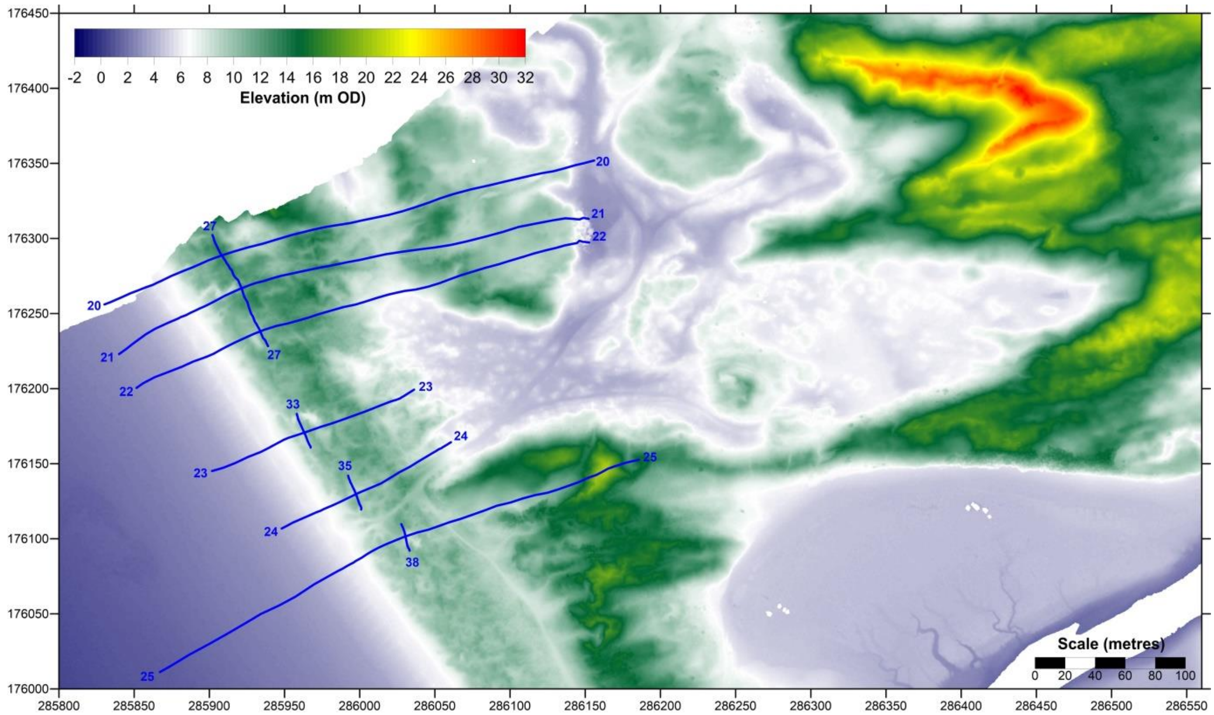


Figure 39. Unfiltered DEM of Merthyr Mawr Warren based on an aerial LiDAR survey on 16-29 October 2008, before rejuvenation works

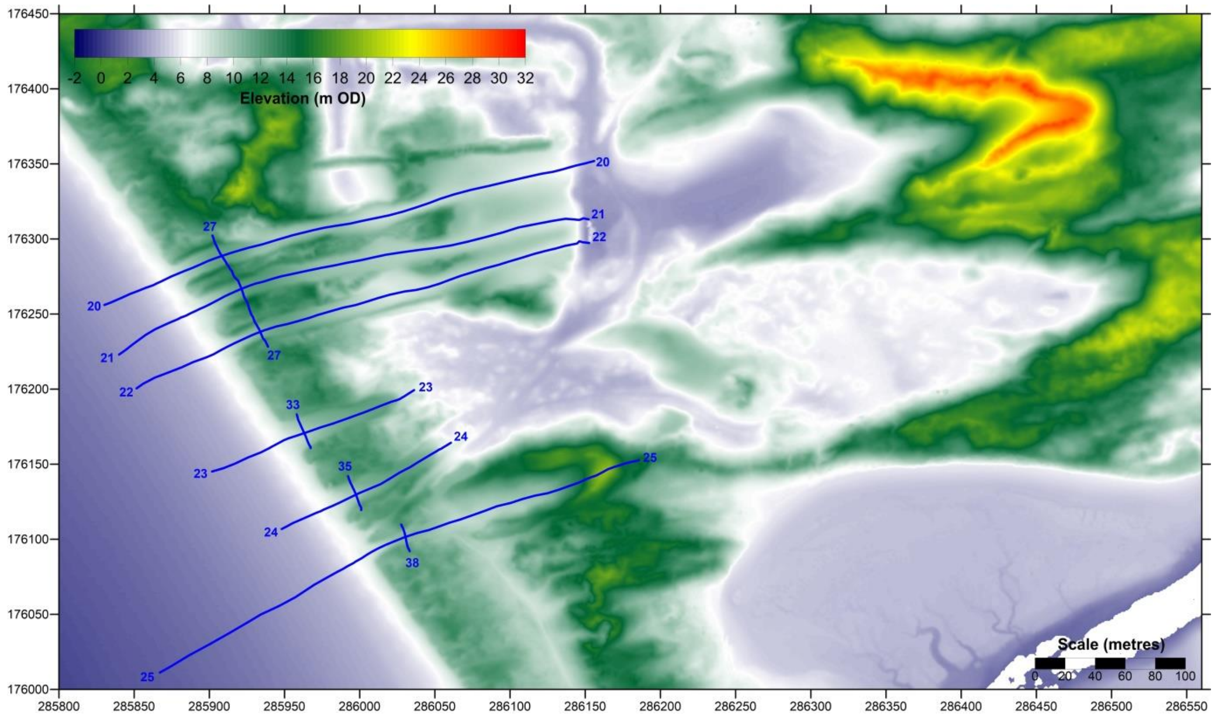


Figure 40. Unfiltered DEM of Merthyr Mawr Warren based on an aerial LiDAR survey on 5 February 2015, after all the rejuvenation works Phases 1-3

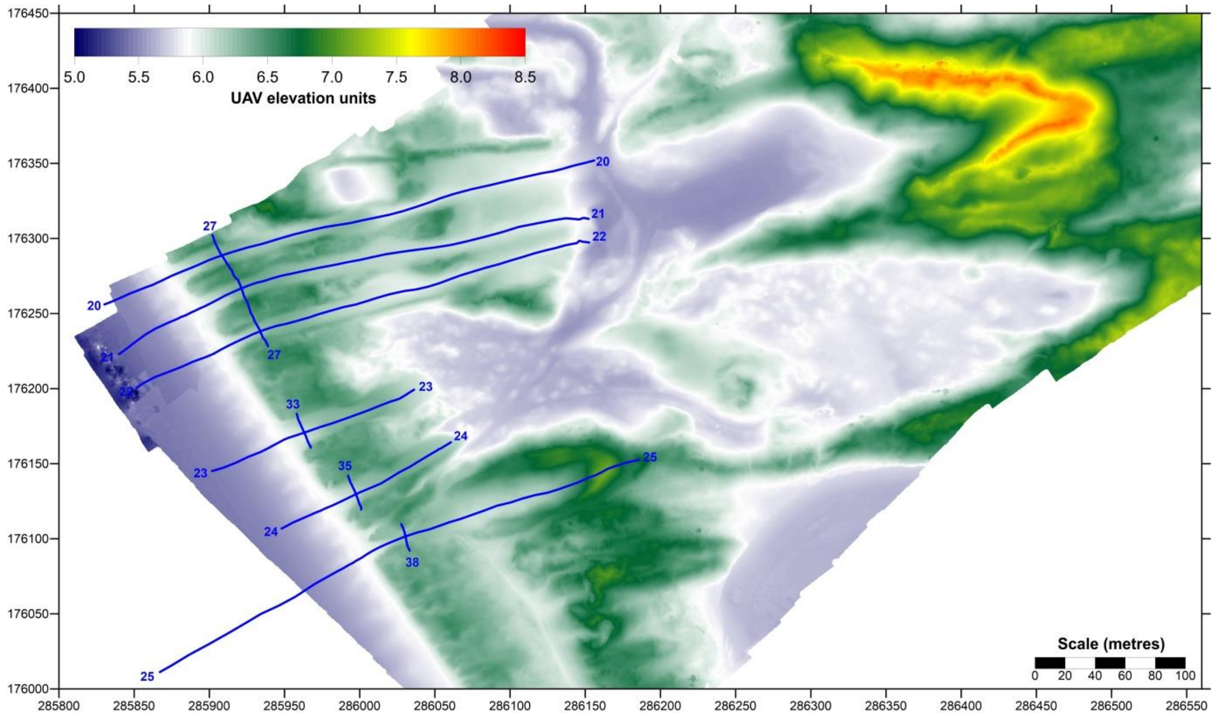


Figure 41. Unfiltered DEM of Merthyr Mawr Warren based on the UAV survey on 29 February 2016. Data are shown as supplied, without correction to ODN. Note the elevation scale ranges from 5.0 to 8.0 units

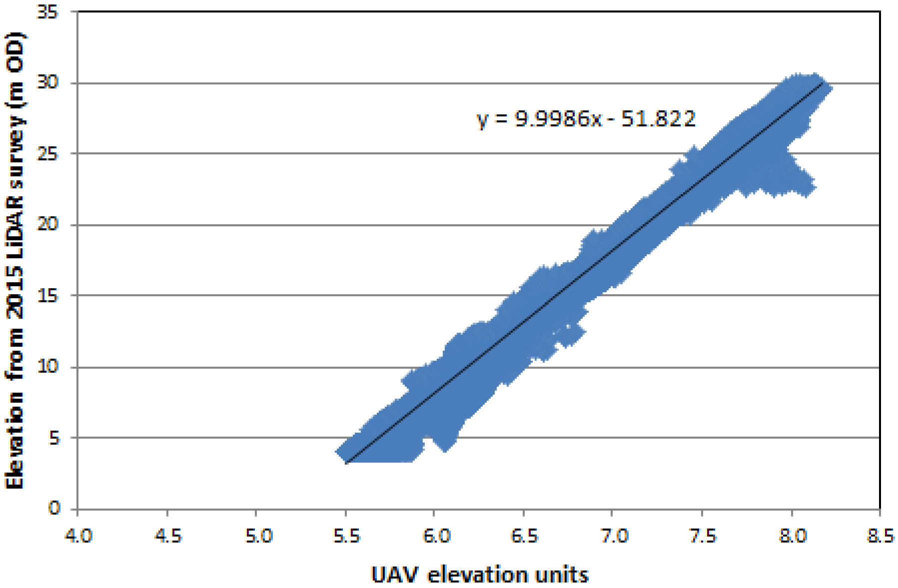


Figure 42. Comparison of elevation units measured during 2014 LiDAR survey and 2016 UAV survey. A linear trend line shows the correction required to adjust elevation units to ODN

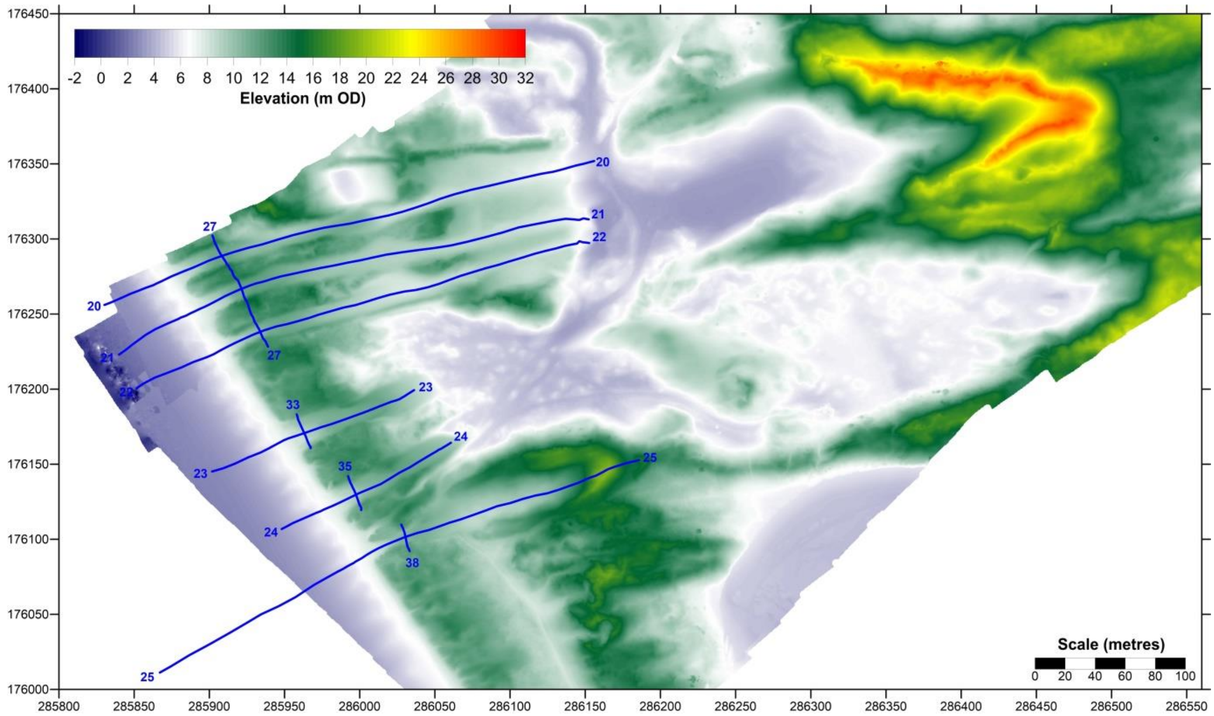


Figure 43. DEM of Merthyr Mawr Warren based on the UAV survey on 29 February 2016, after correction to ODN

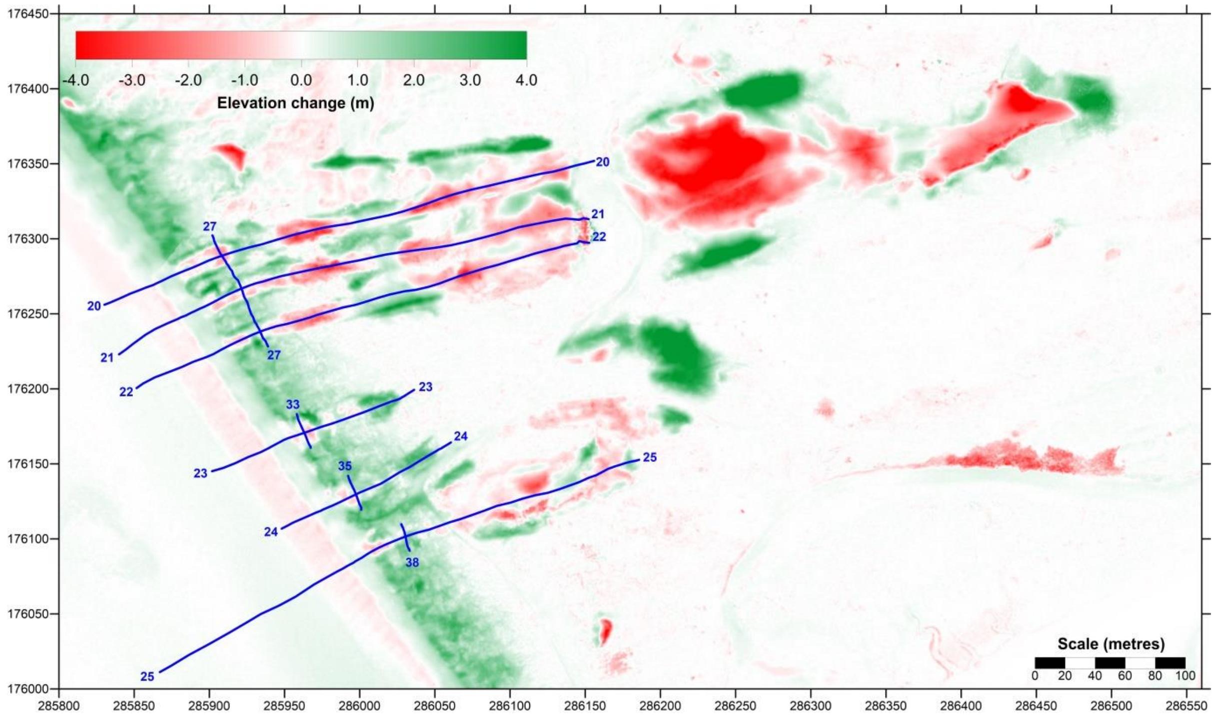


Figure 44. Difference in elevation between 2008 and 2015 aerial LiDAR surveys. Across the Phase 1-3 areas, and above the HAT contour in 2008, there was approximately 54000 m^3 of sediment accretion and 38751 m^3 of erosion, equating to a net sediment volume increase of approximately 15330 m^3 arising from new sediment input from the beach

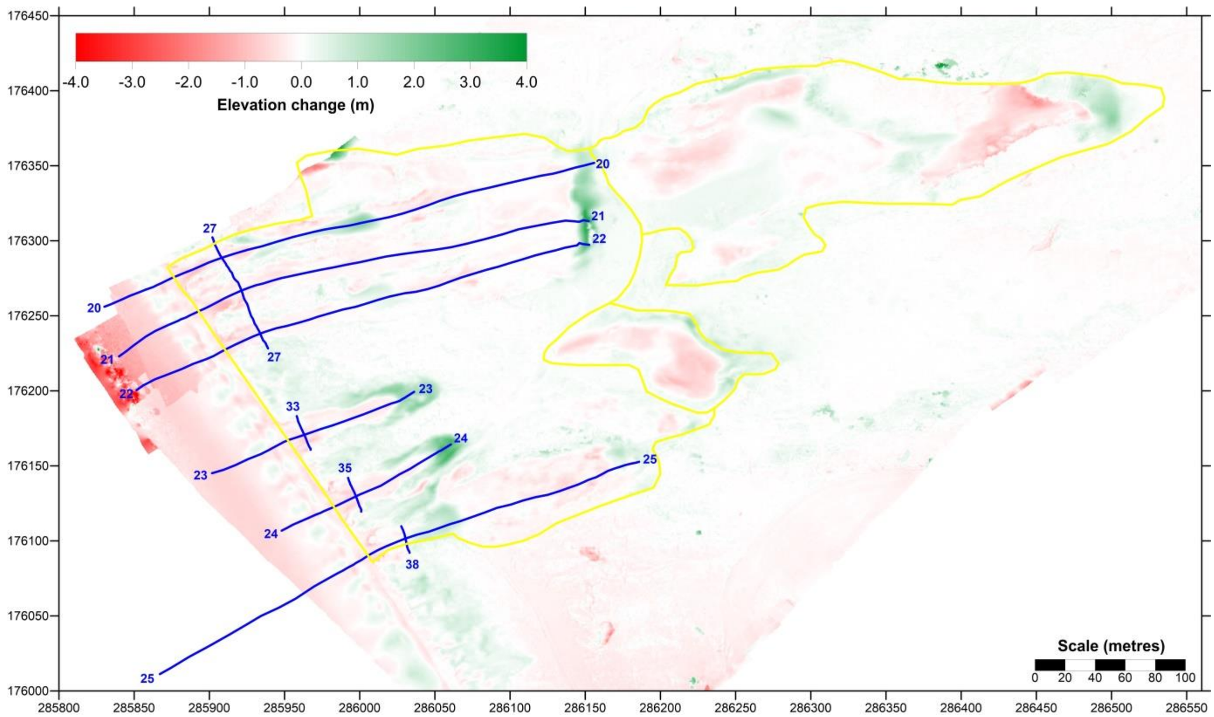


Figure 45. Difference in elevation between 2015 aerial LiDAR and 2016 UAV surveys. Across the Phase 1-3 areas, and above the HAT contour in 2008, there was approximately 13770 m^3 of sediment accretion and approximately 8100 m^3 of sediment erosion, equating to a net volume increase of approximately 5670 m^3 due to input of new sediment from the beach

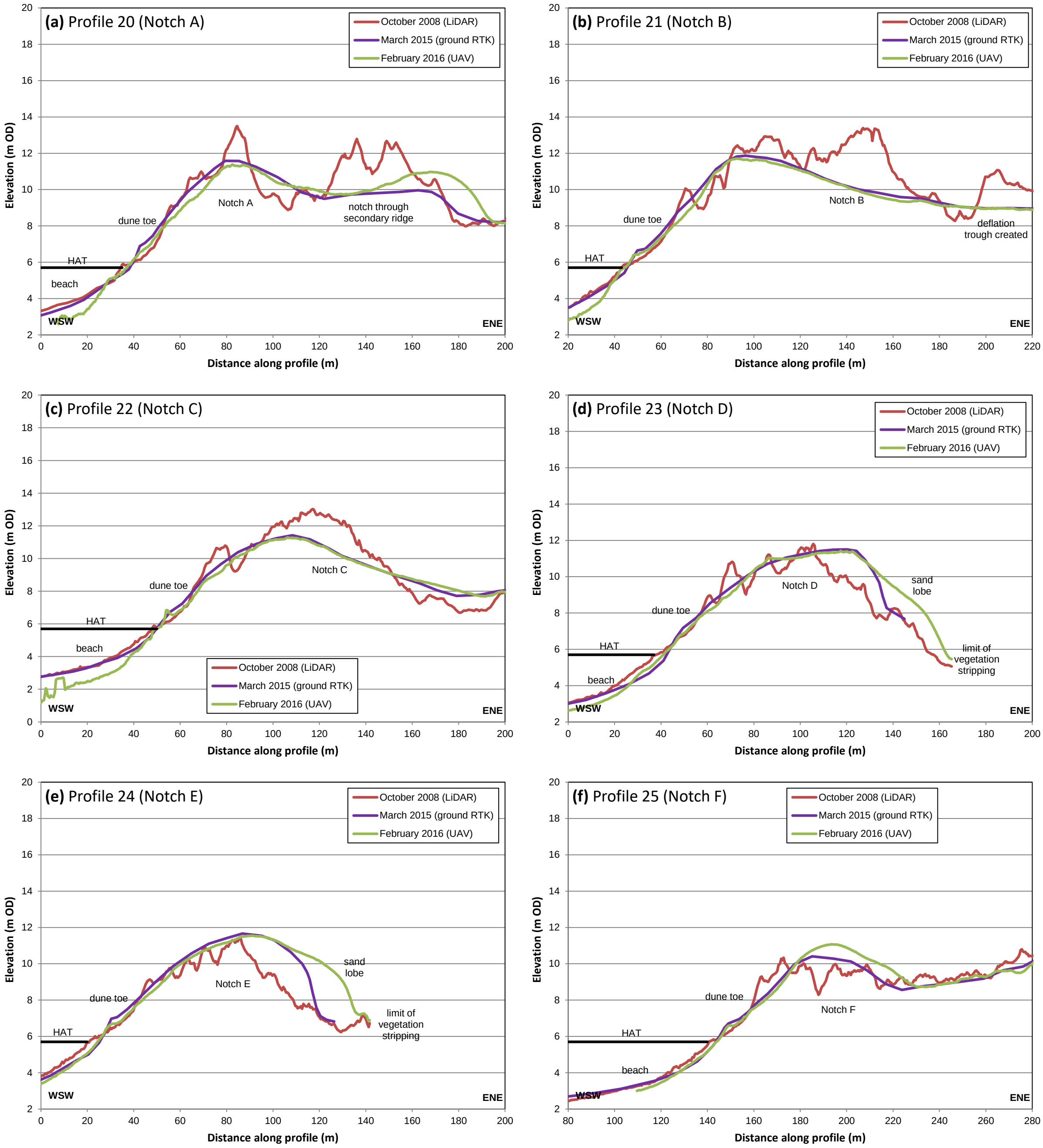


Figure 46. Topographic profiles along the axes of the notches in the Phase 3 area at Merthyr Mawr Warren. Elevations are shown for the aerial LiDAR survey flown prior to rejuvenation works (October 2008), the subsequent ground RTK survey in March 2015 and UAV survey in March 2016. The level of HAT (at 5.7 m ODN) is also shown

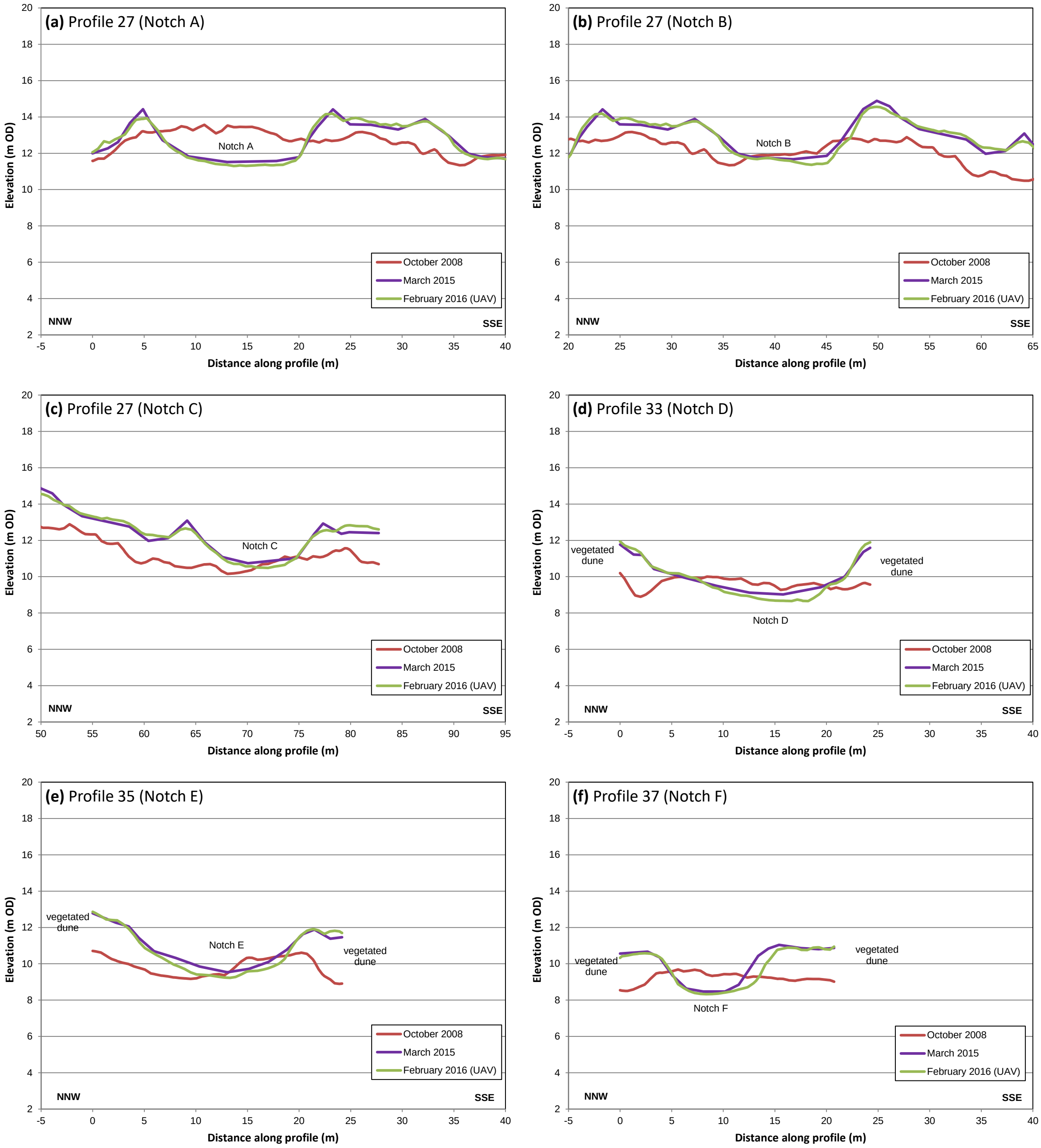


Figure 47. Topographic profiles across notches in the Phase 3 area at Merthyr Mawr Warren. Elevations are shown for the aerial LiDAR survey flown prior to rejuvenation works (October 2008), the subsequent ground RTK survey in March 2015 and aerial drone survey in March 2016

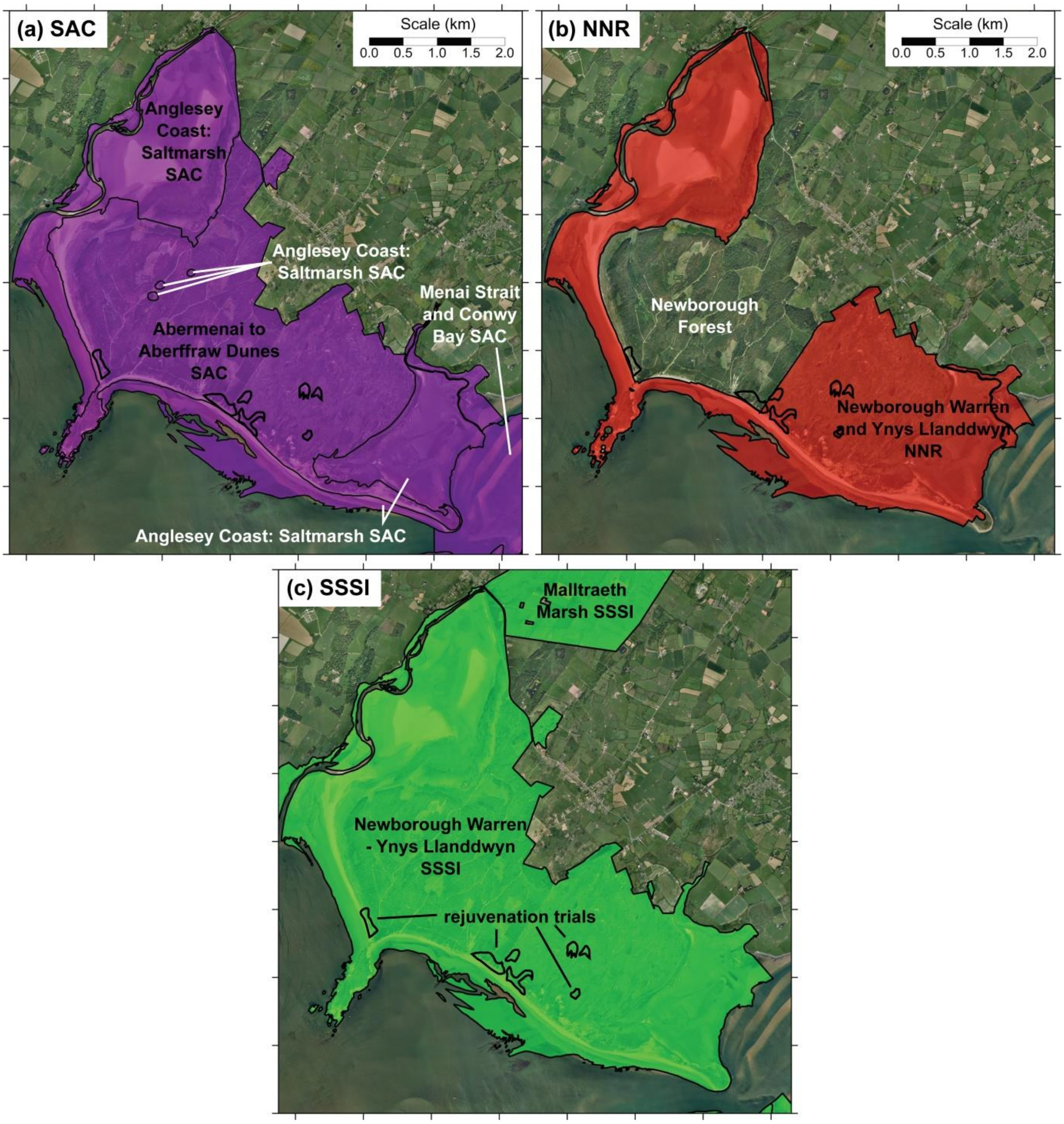


Figure 48. The extent of (a) SAC, (b) NNR and (c) SSSI at Newborough Warren. Black lines show the limits of the rejuvenation trial areas

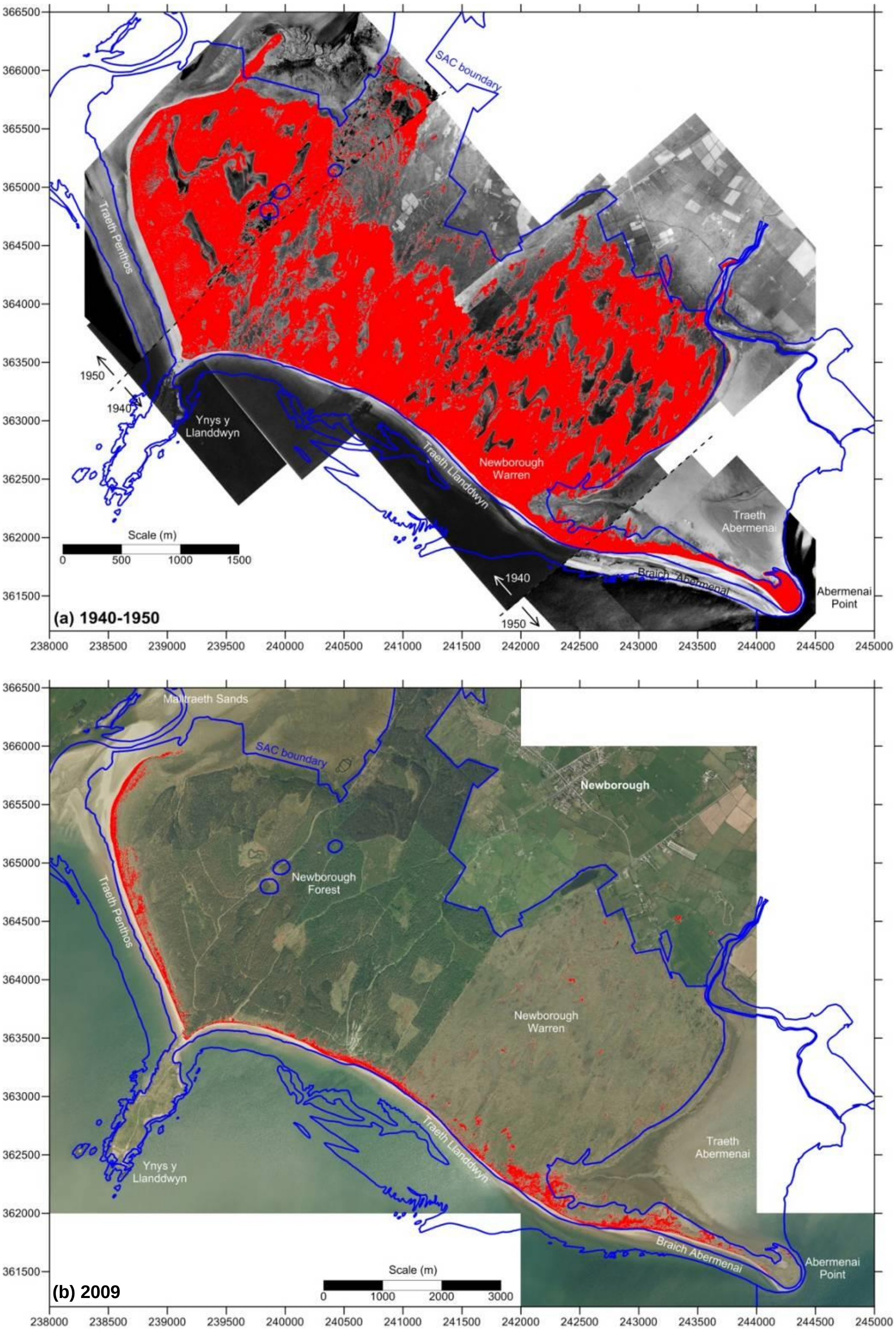


Figure 49. The extent of bare sand (red) at Newborough Warren in (a) 1940-1950 and (b) 2009

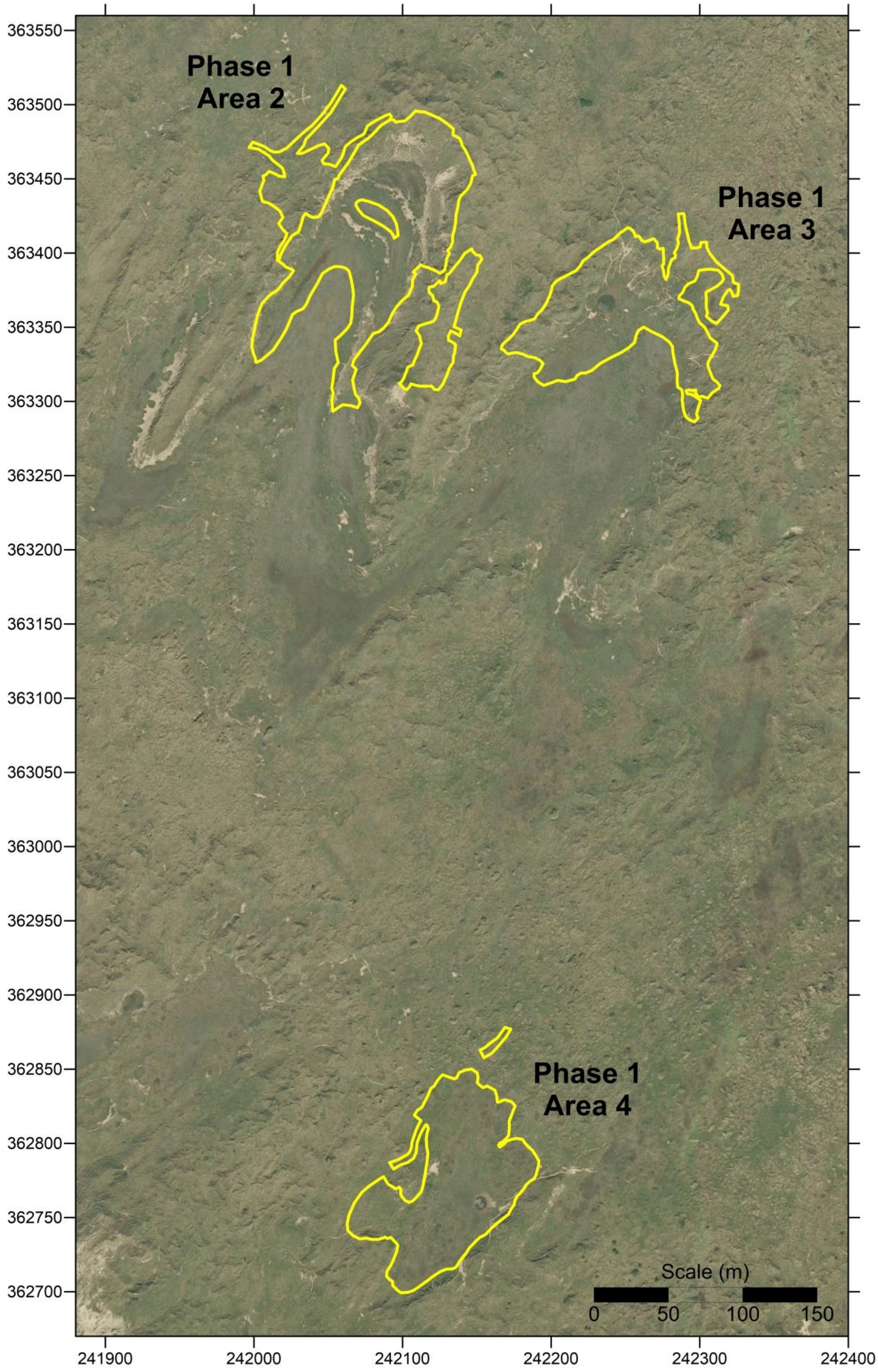


Figure 50. Pre-works aerial photograph flown 11 May 2009, showing boundaries of the Phase 1 rejuvenation trial areas. The yellow lines indicate the areas to be stripped in February to April 2013, as surveyed on 16-17 May 2013 by ground RTK-GPS survey

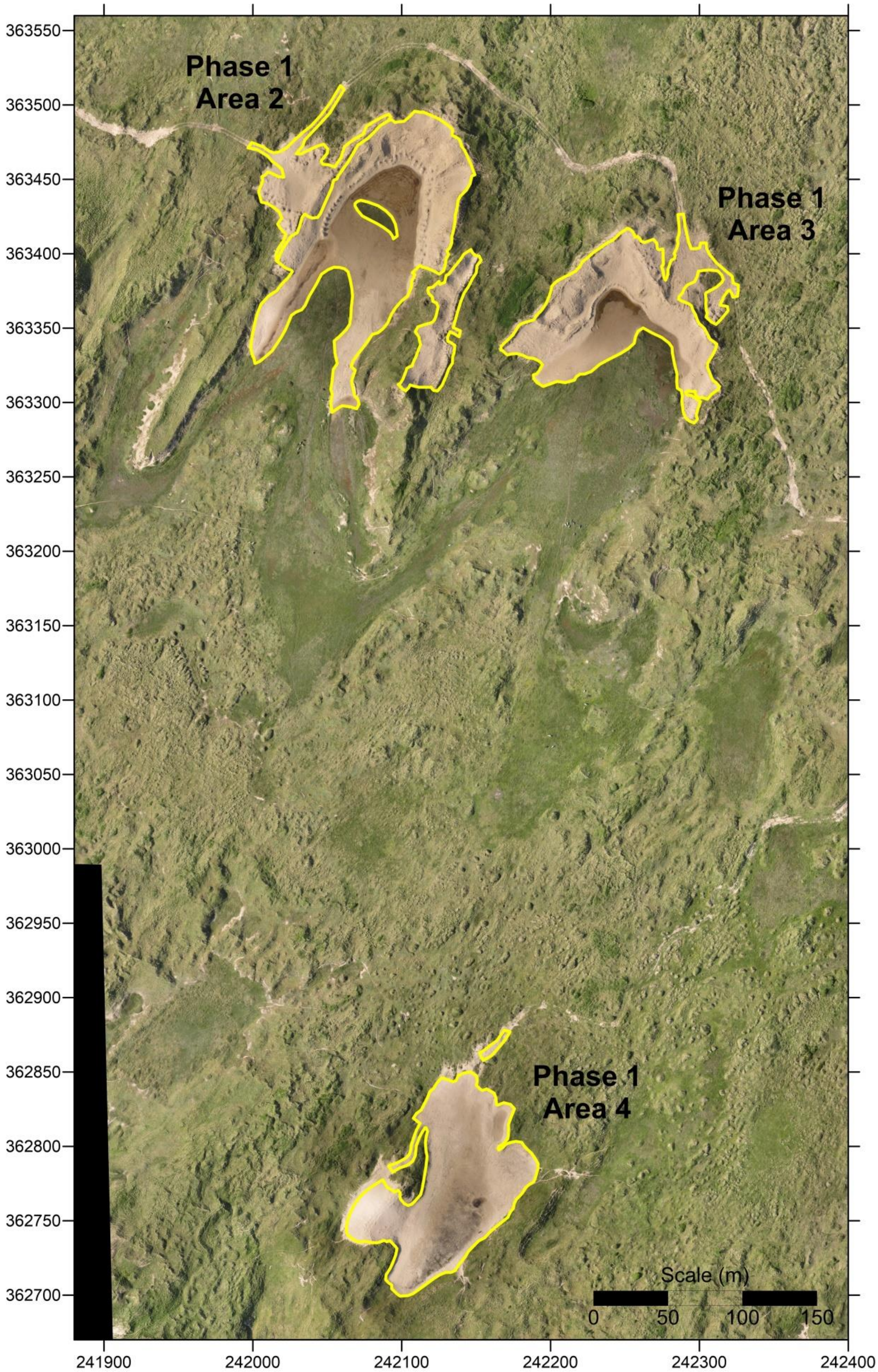


Figure 51. Aerial photograph flown June 2013 by UAV, showing extent of bare sand on the Phase 1 rejuvenation trial areas. The yellow lines indicate the areas to be stripped in February to April 2013, as surveyed on 16-17 May 2013 by ground RTK-GPS survey

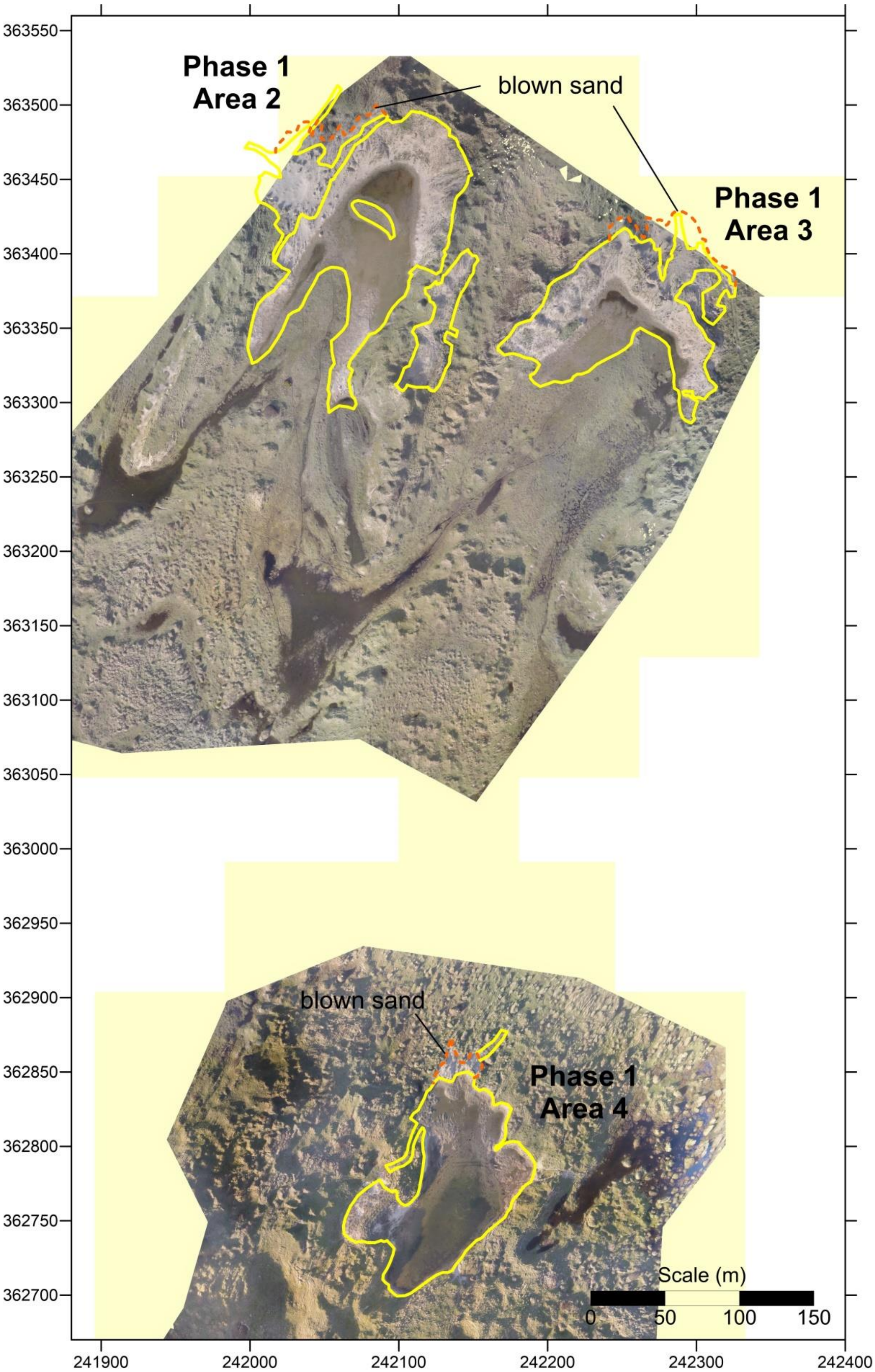


Figure 52. UAV aerial imagery flown January 2016 showing the extent of bare sand on the Phase 1 rejuvenation works at Newborough Warren, undertaken February to April 2013. The yellow lines indicate the areas to be stripped in February to April 2013, the orange dashed lines the areas of blown sand outside the works areas by January 2016 (note that some areas are estimated due to incomplete UAV coverage)

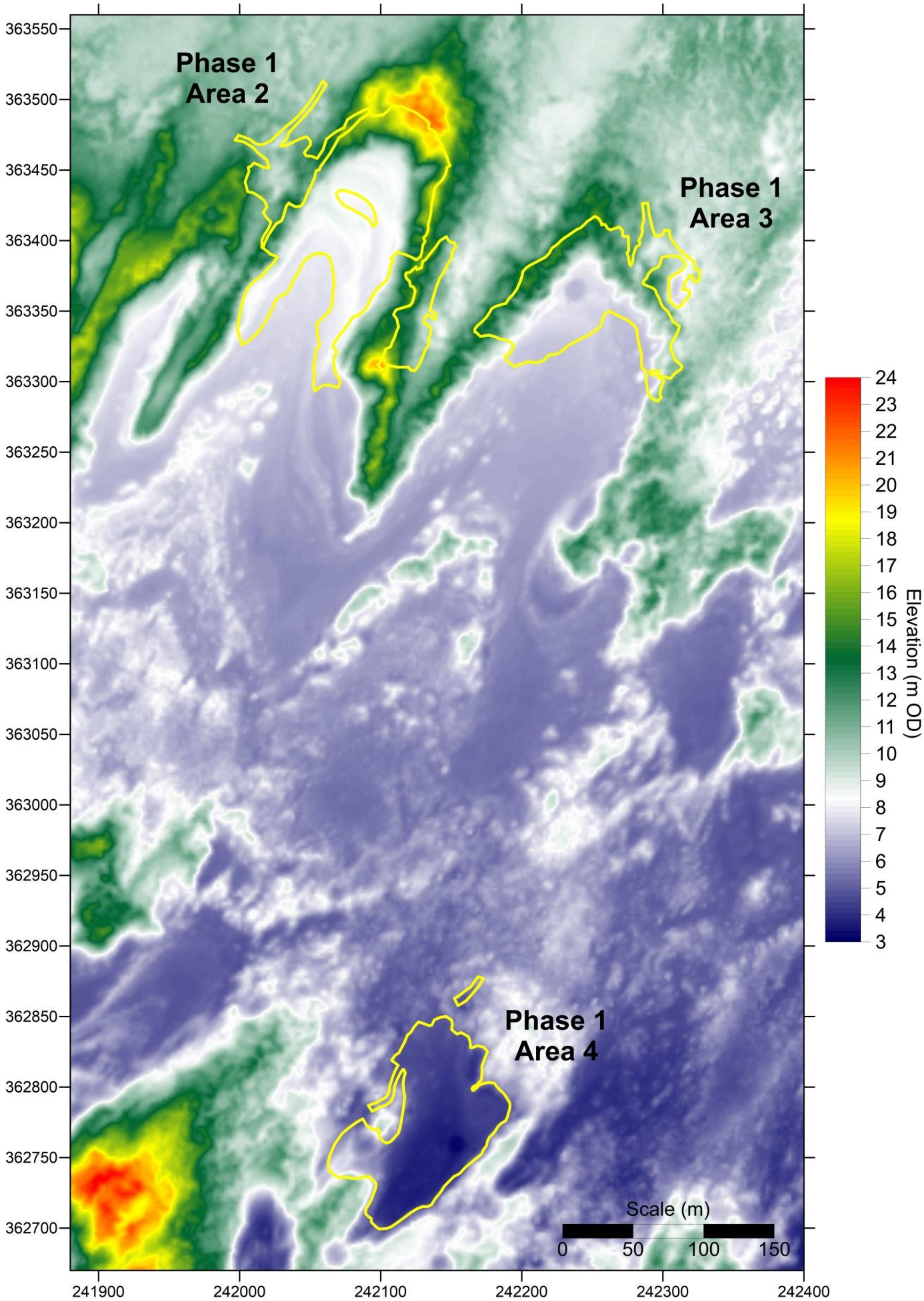


Figure 53. Filtered DEM of Newborough Warren Phase 1 areas, from an aerial LiDAR survey flown on 12 May 2009, before the rejuvenation works

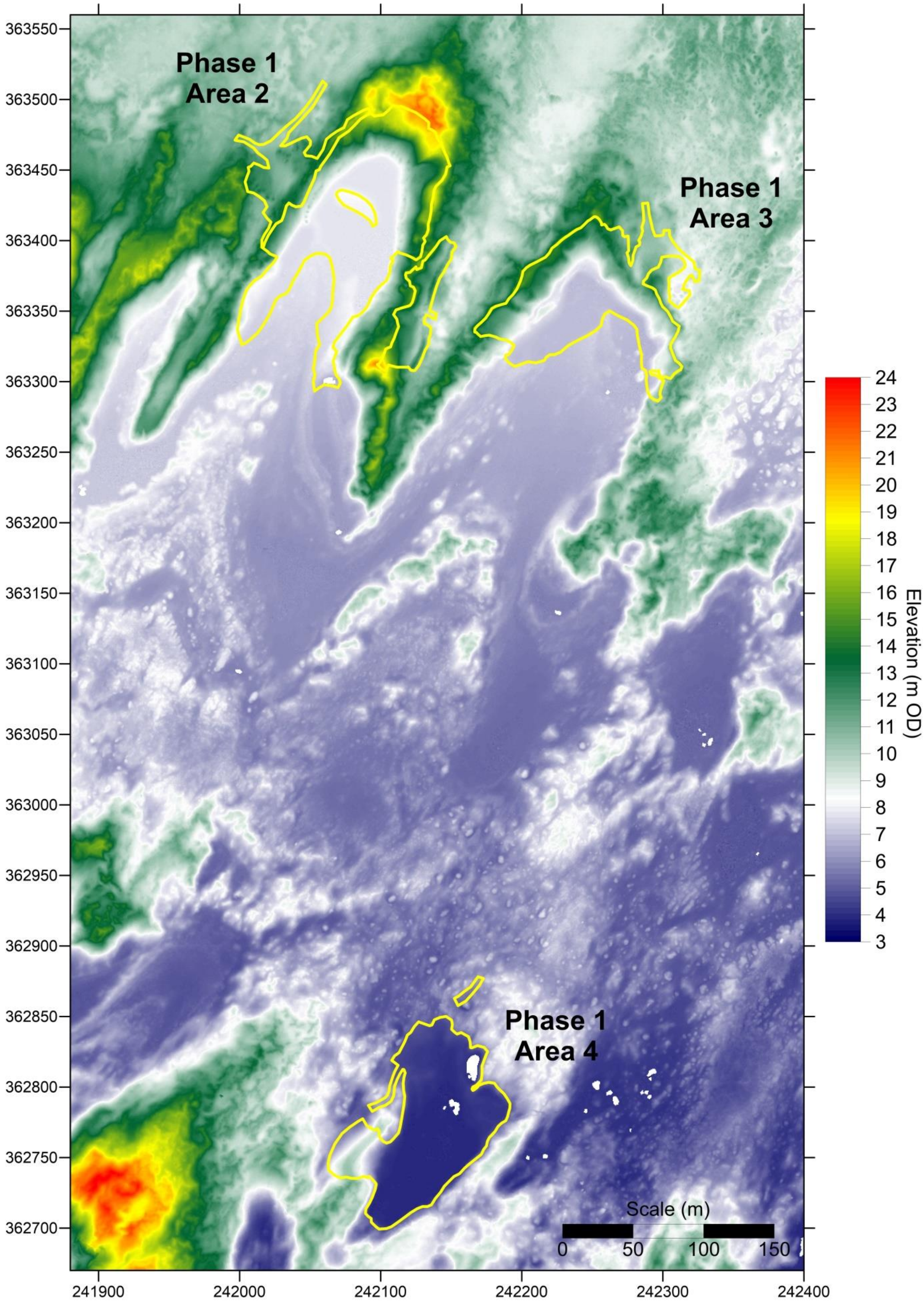


Figure 54. Unfiltered DEM of Newborough Warren Phase 1 areas, from an aerial LiDAR survey flown on 9 April 2014, after the rejuvenation works

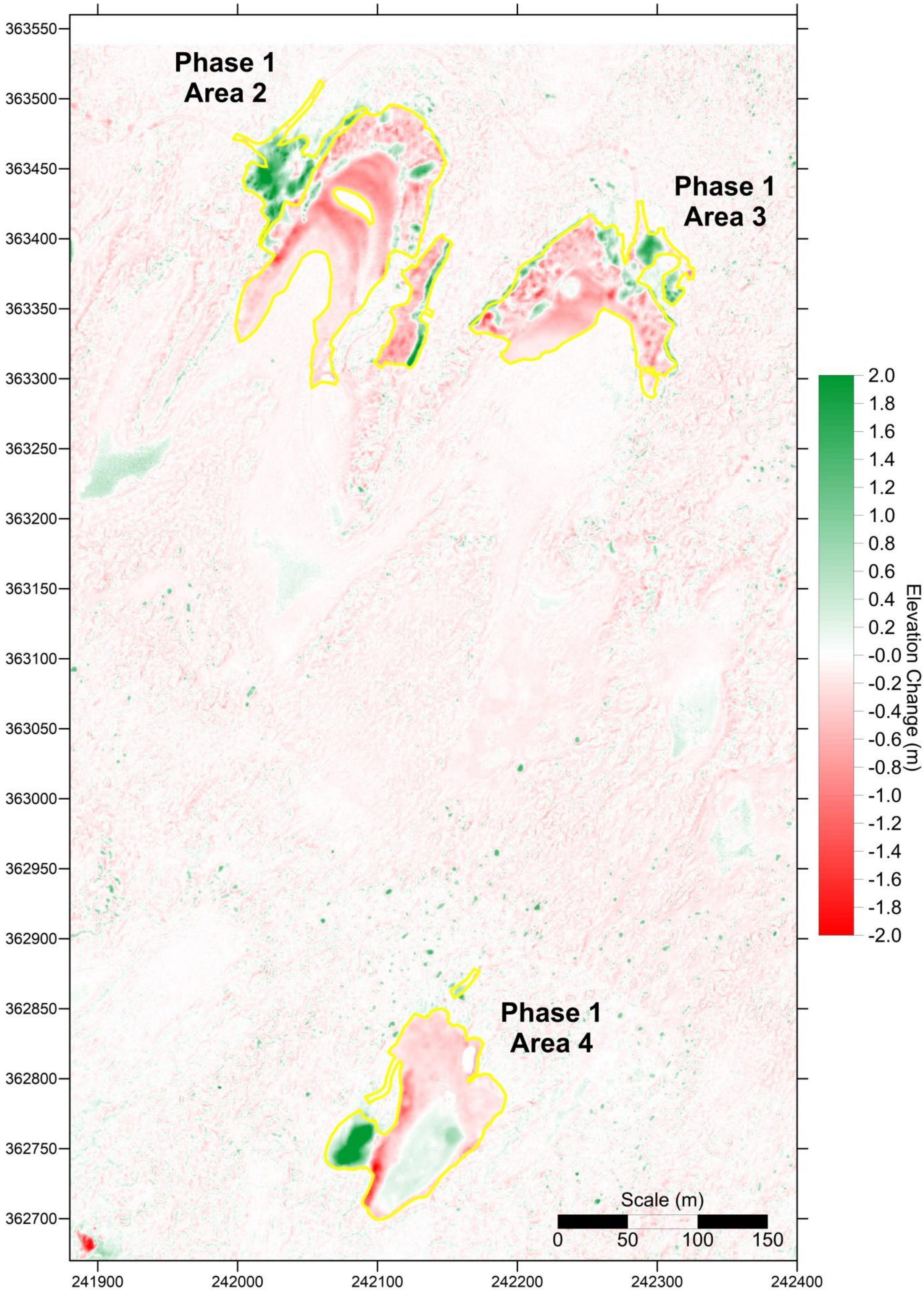


Figure 55. Difference in elevation between May 2009 and April 2014 aerial LiDAR surveys. Total volume changes before and after the works are negligible and within the error limits of the two surveys. The slight apparent increase in elevation within the southern part of Area 4 is due to presence of standing water

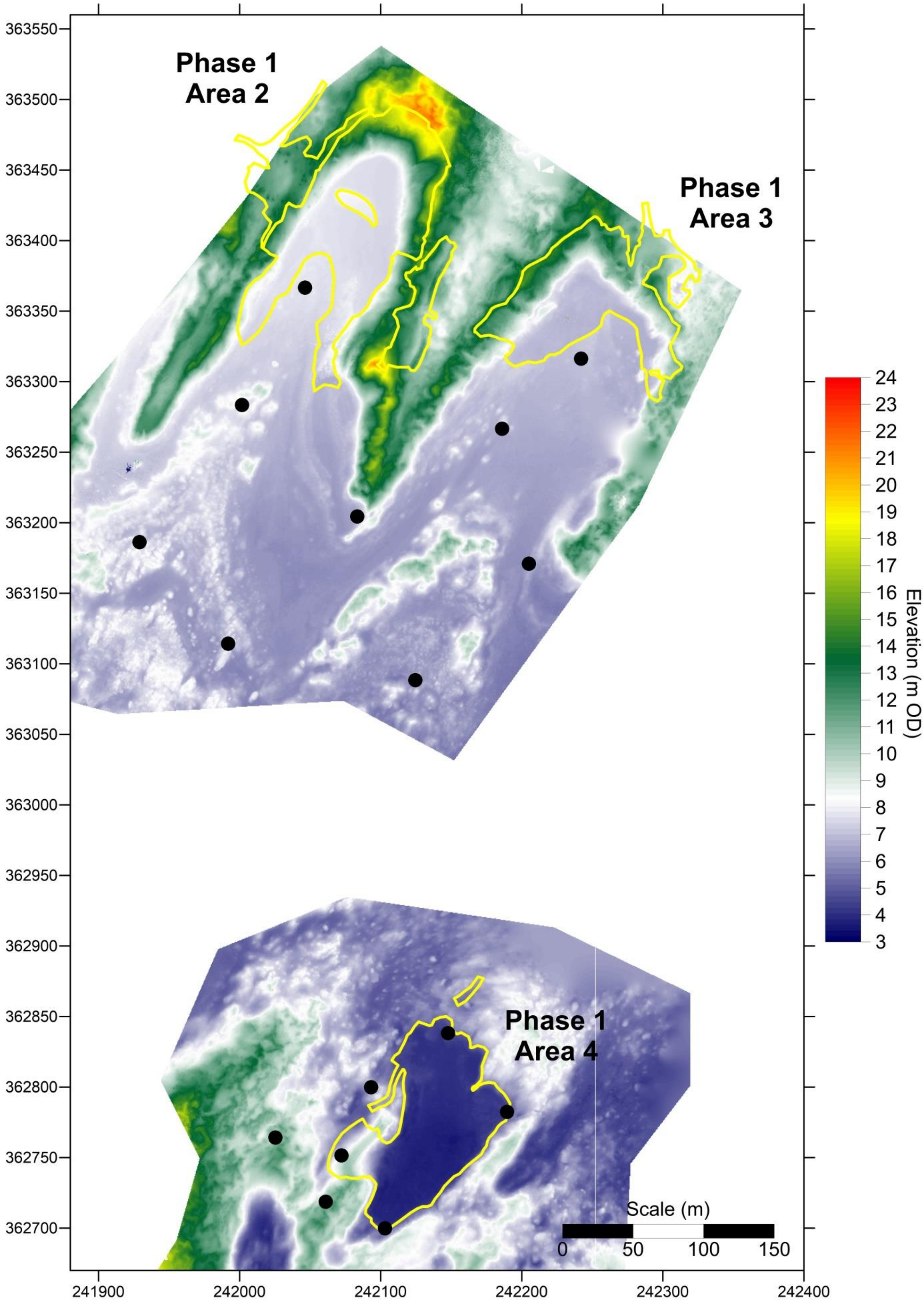


Figure 56. DEM of Newborough Warren Phase 1 areas, from a UAV survey in January 2016, after the rejuvenation works. The calibration points used by the survey company to correct the elevations are shown as black dots

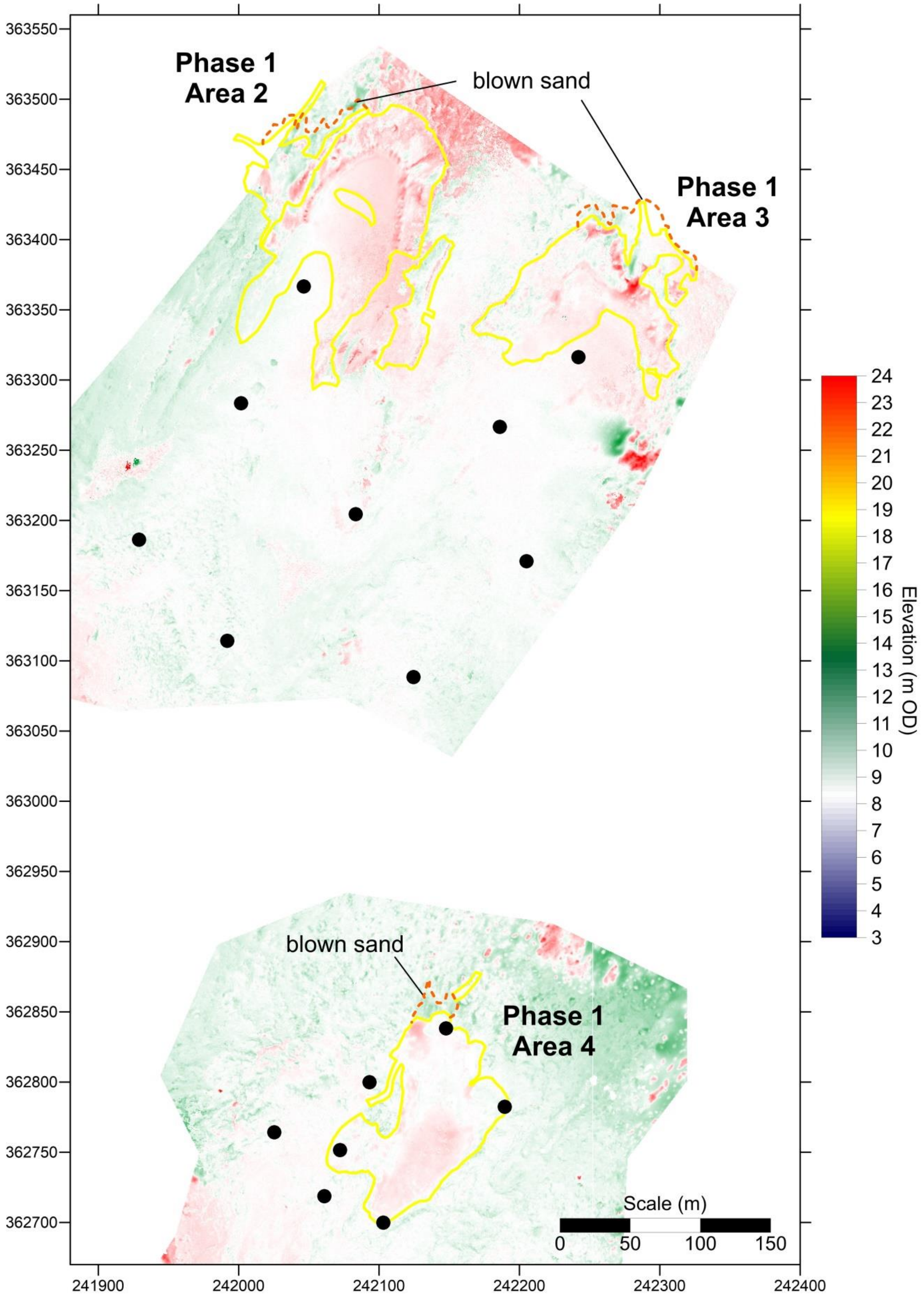


Figure 57. Difference in elevation between 2014 aerial LiDAR survey and 2016 UAV survey. The 2016 UAV DEM is unreliable beyond the limits of the works areas (in particular to the NE of Area 2, leading to apparent lowering of well-vegetated dunes). Within the error limits of the surveys, all erosion losses can be accounted for in the areas of blown sand to the immediately north of the trial areas (indicated by the orange dashed lines). The calibration points used by the survey company to correct the elevations are shown as black dots

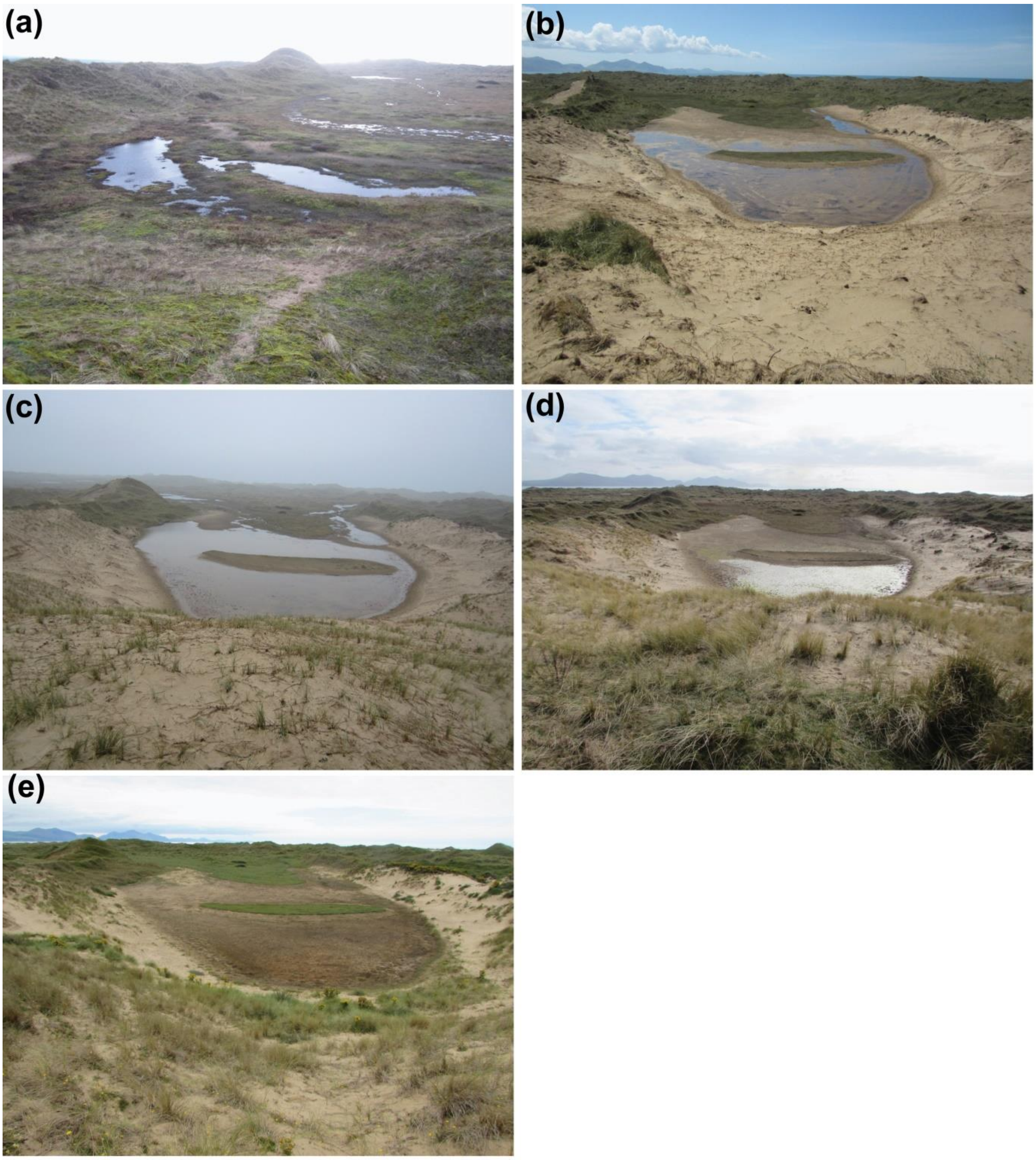


Figure 58. Ground photographs of Phase 1 Area 2: (a) Pre-works on 17 January 2013; (b) May 2013; (c) March 2014; (d) March 2015; (e) August 2016

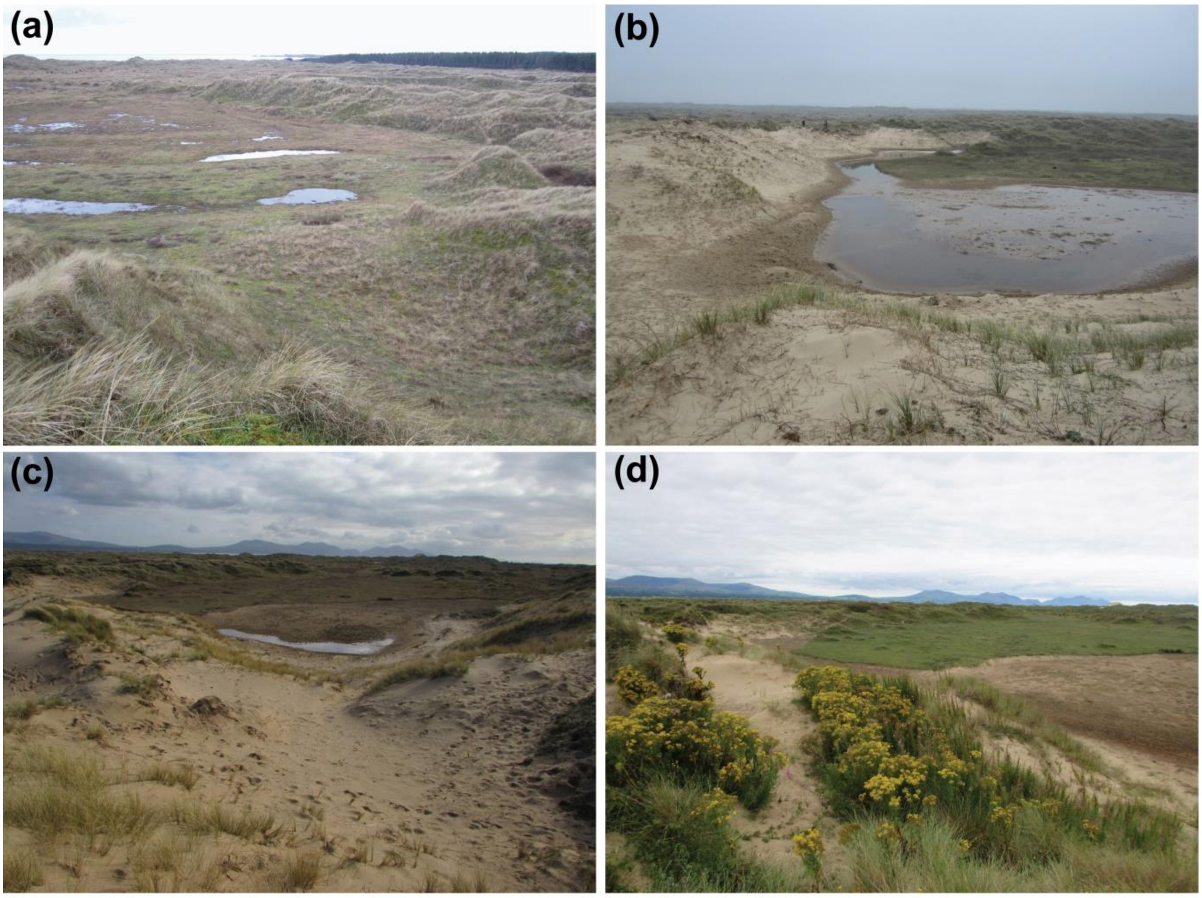


Figure 59. Ground photographs of Phase 1 Area 3: (a) Pre-works on 17 January 2013; (b) March 2014; (c) March 2015; (d) August 2016

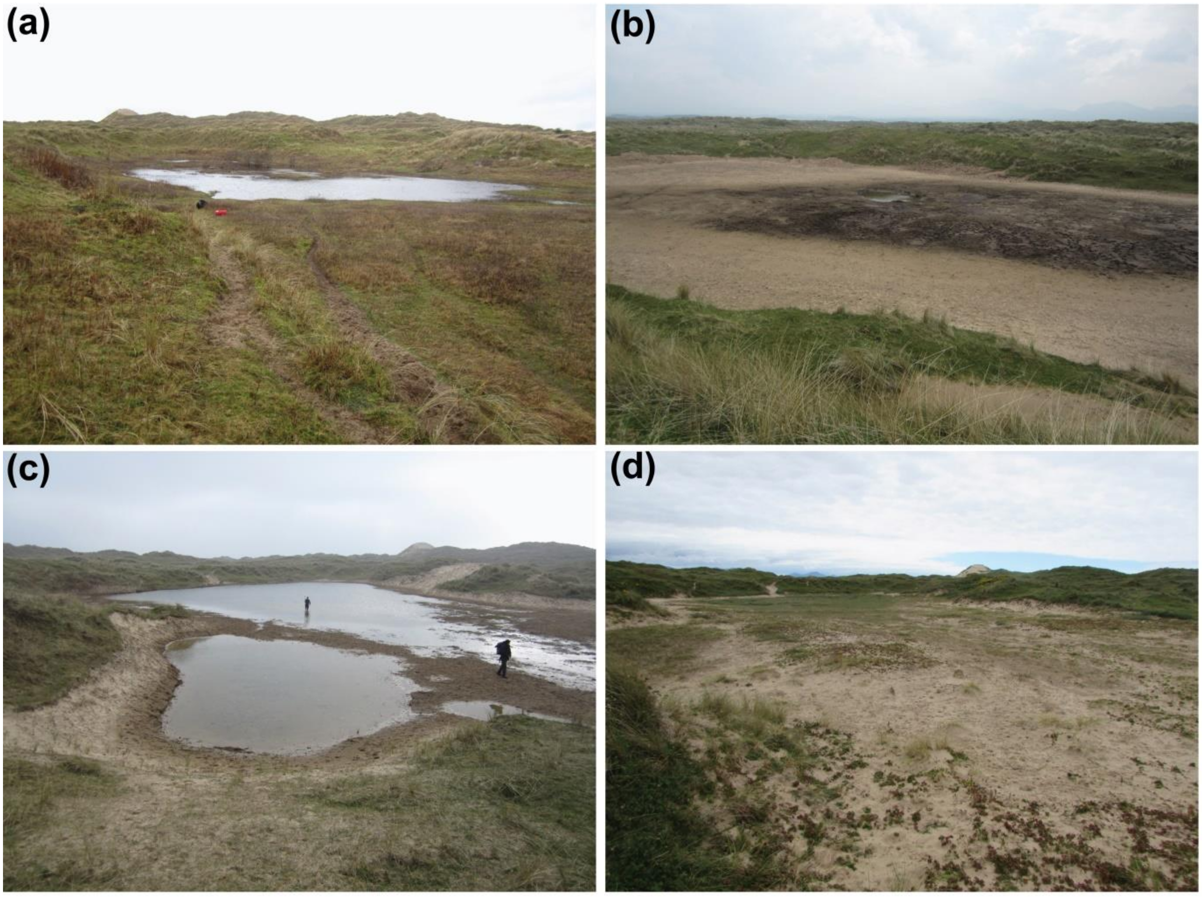


Figure 60. Ground photographs of Phase 1 Area 4: (a) Pre-works on 17 January 2013; (b) May 2013; (c) March 2014; (d) August 2016

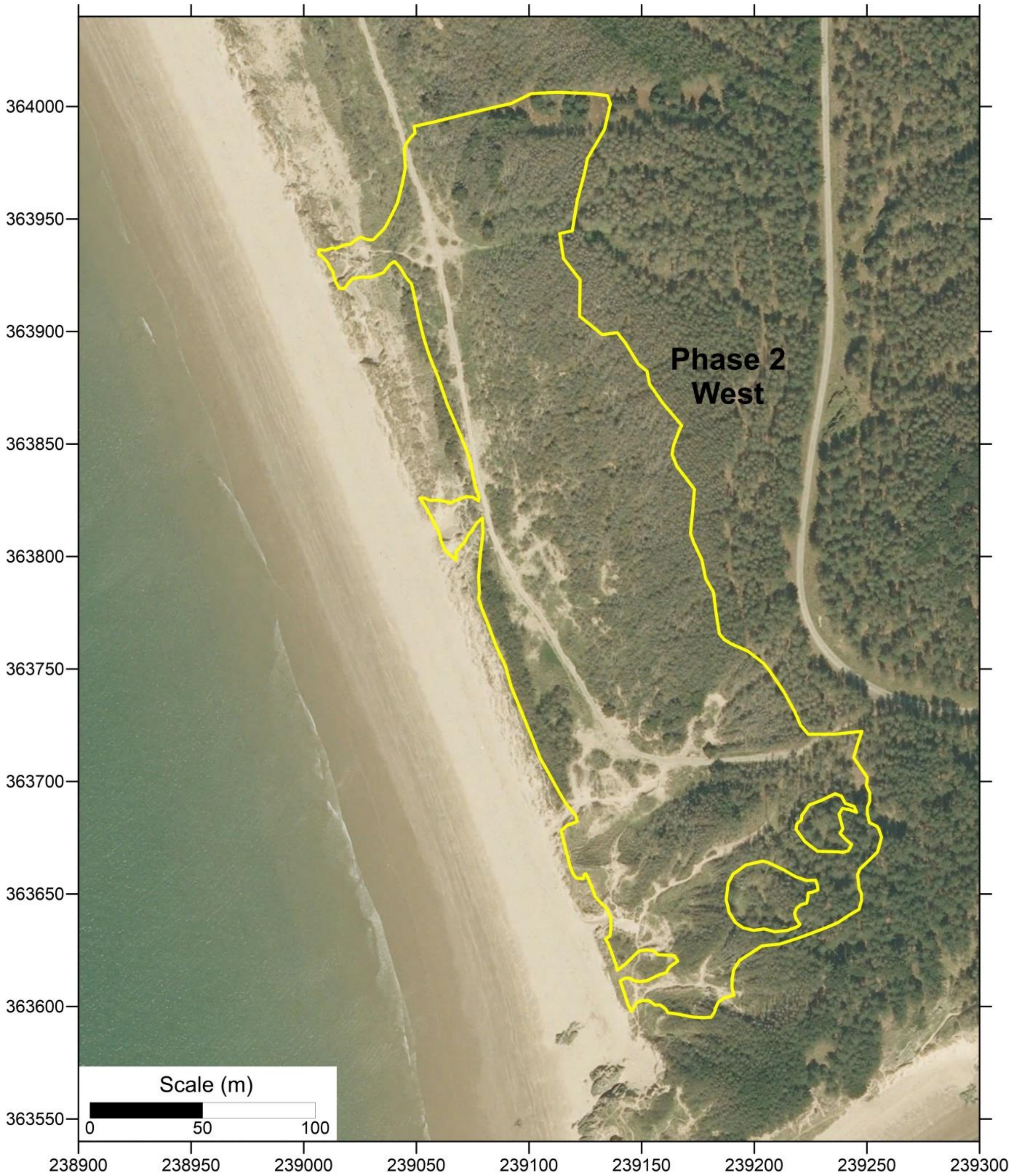


Figure 61. Pre-works aerial photograph flown 11 May 2009 of the Phase 2 West rejuvenation trial area (at Traeth Penrhos). The yellow lines indicate the bare sand (vegetation stripping and sand heaps) created in December 2014 to March 2015, as surveyed on 25-27 March 2015 by ground RTK-GPS survey

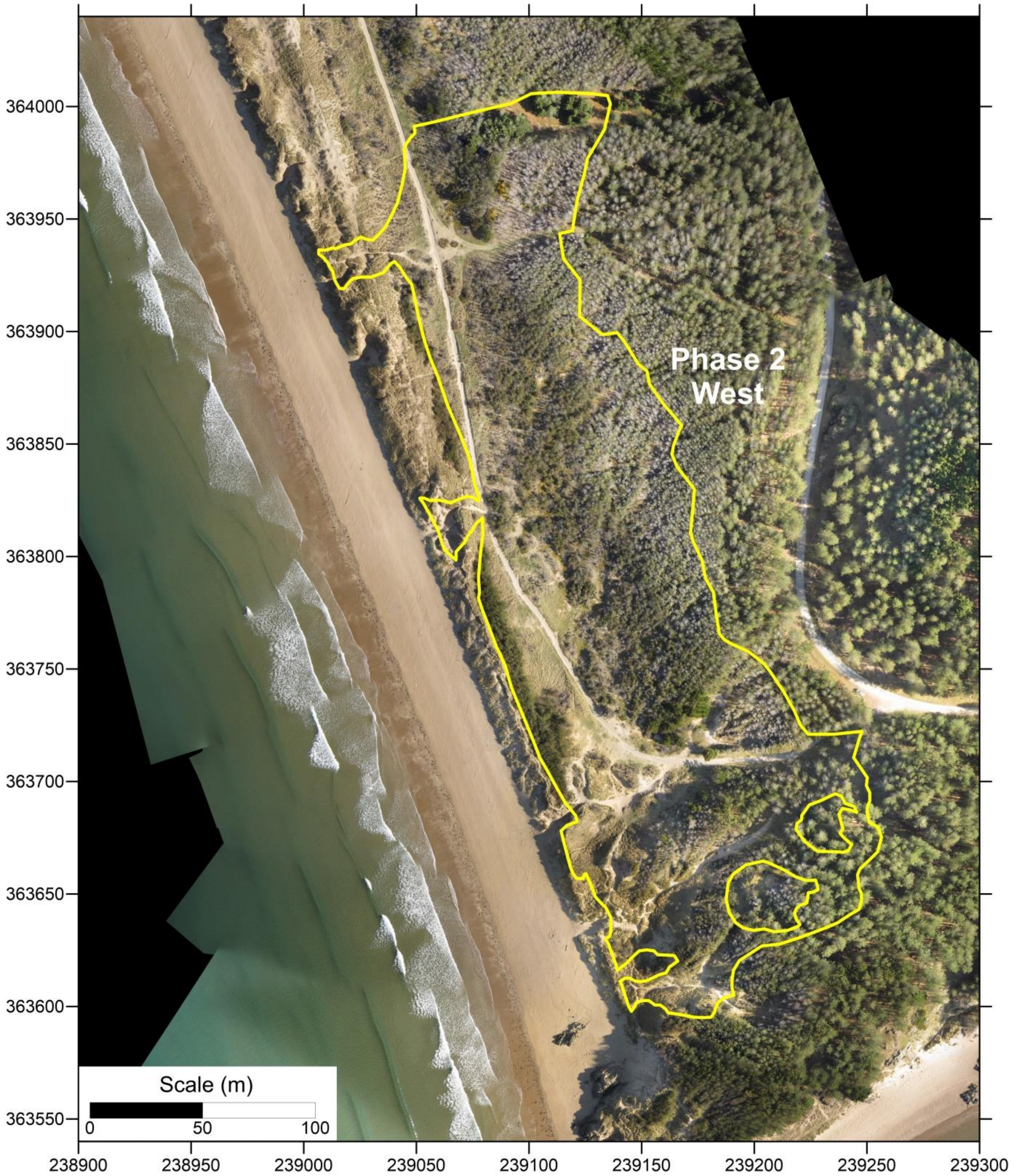


Figure 62. Pre-works aerial photograph flown June 2013 by UAV of the Phase 2 West rejuvenation trial area (at Traeth Penrhos). The yellow lines indicate the bare sand (vegetation stripping and sand heaps) created in December 2014 to March 2015, as surveyed on 25-27 March 2015 by ground RTK-GPS survey

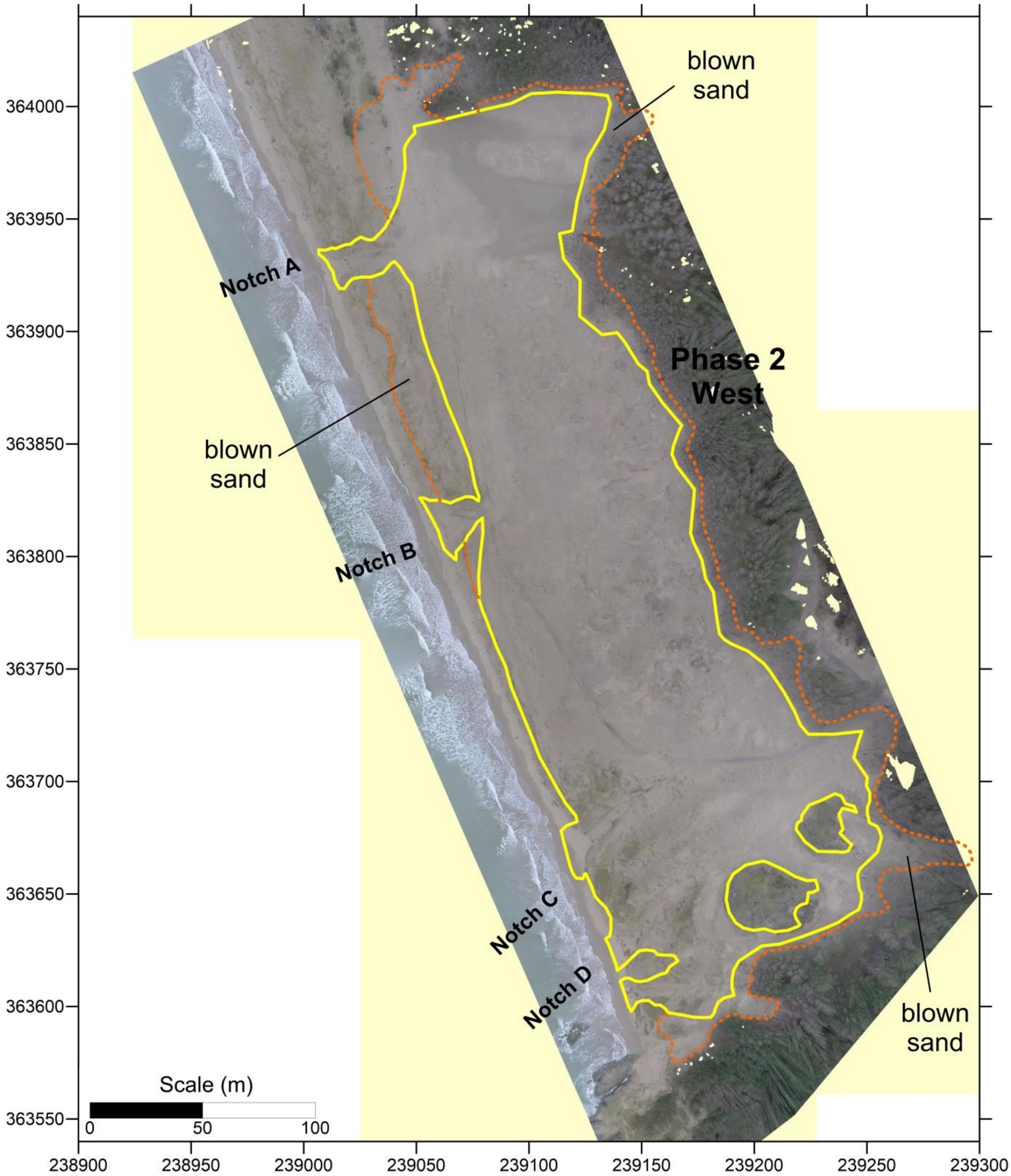


Figure 63. UAV aerial imagery flown January 2016 showing the extent of bare sand on the Phase 2 West works at Newborough, undertaken December 2014 to March 2015. The yellow lines indicate the bare sand areas created in December 2014 to March 2015, the orange dashed lines the areas of blown sand outside the works areas by January 2016 (note that some areas are estimated due to incomplete UAV coverage)

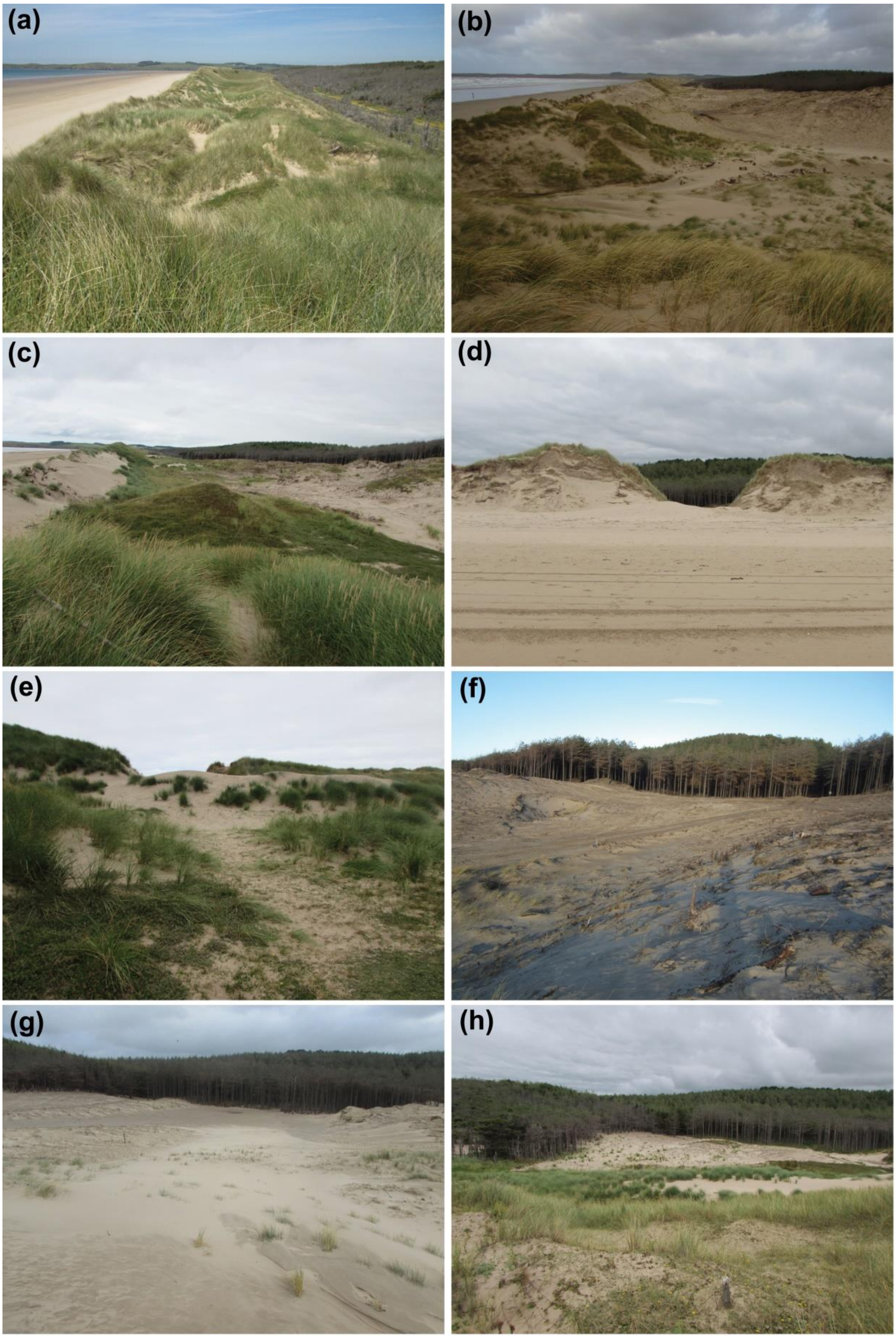


Figure 64. Ground photographs of Phase 2 West: (a) Pre-works June 2013; (b) February 2016; (c) August 2016; (d) Notch A looking landward August 2016; (e) Notch A looking seaward August 2016 (f) February 2015; (g) February 2016; (h) August 2016

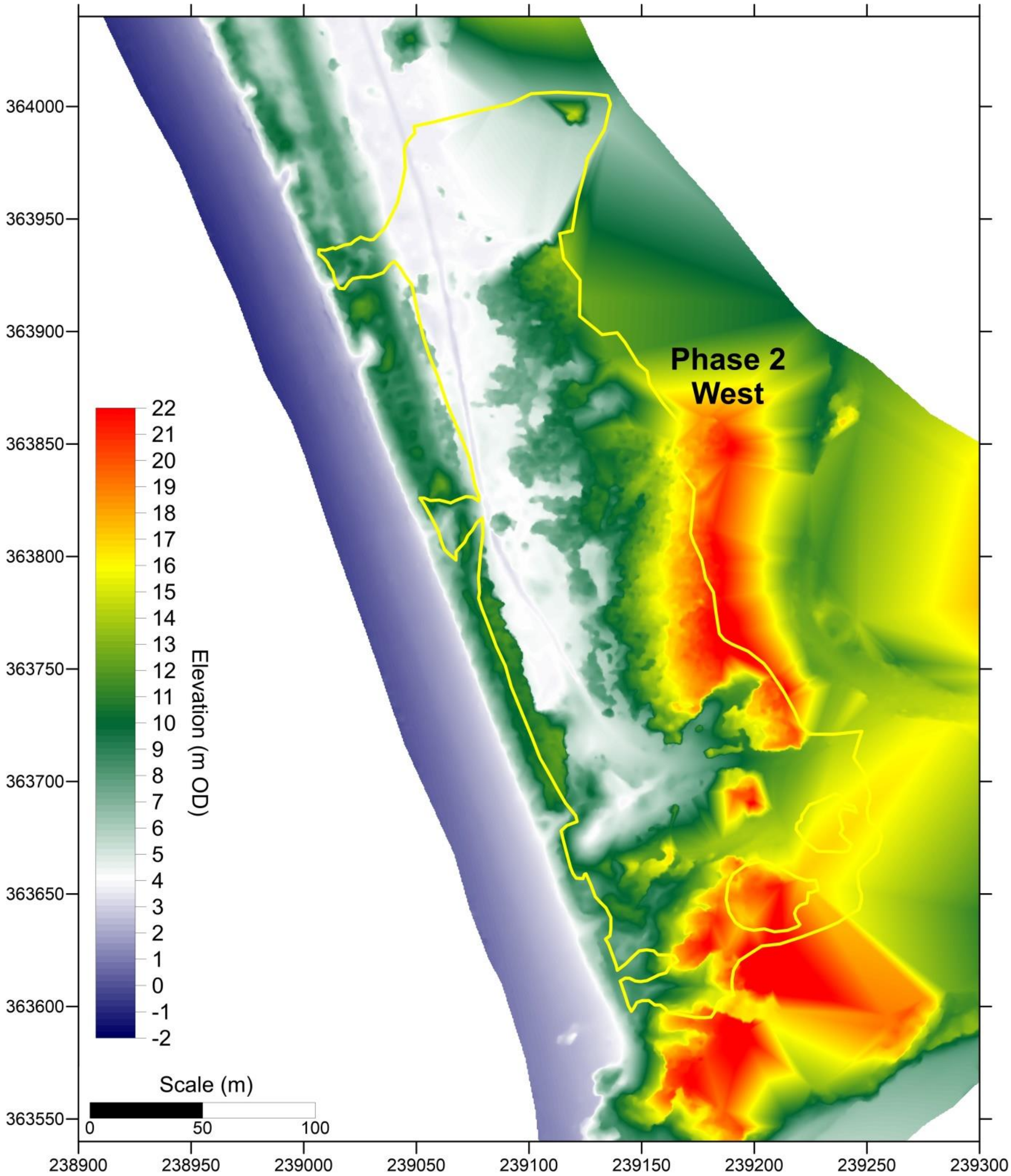


Figure 65. DEM of Newborough Phase 2 West area, from a UAV survey in June 2013, before the rejuvenation works

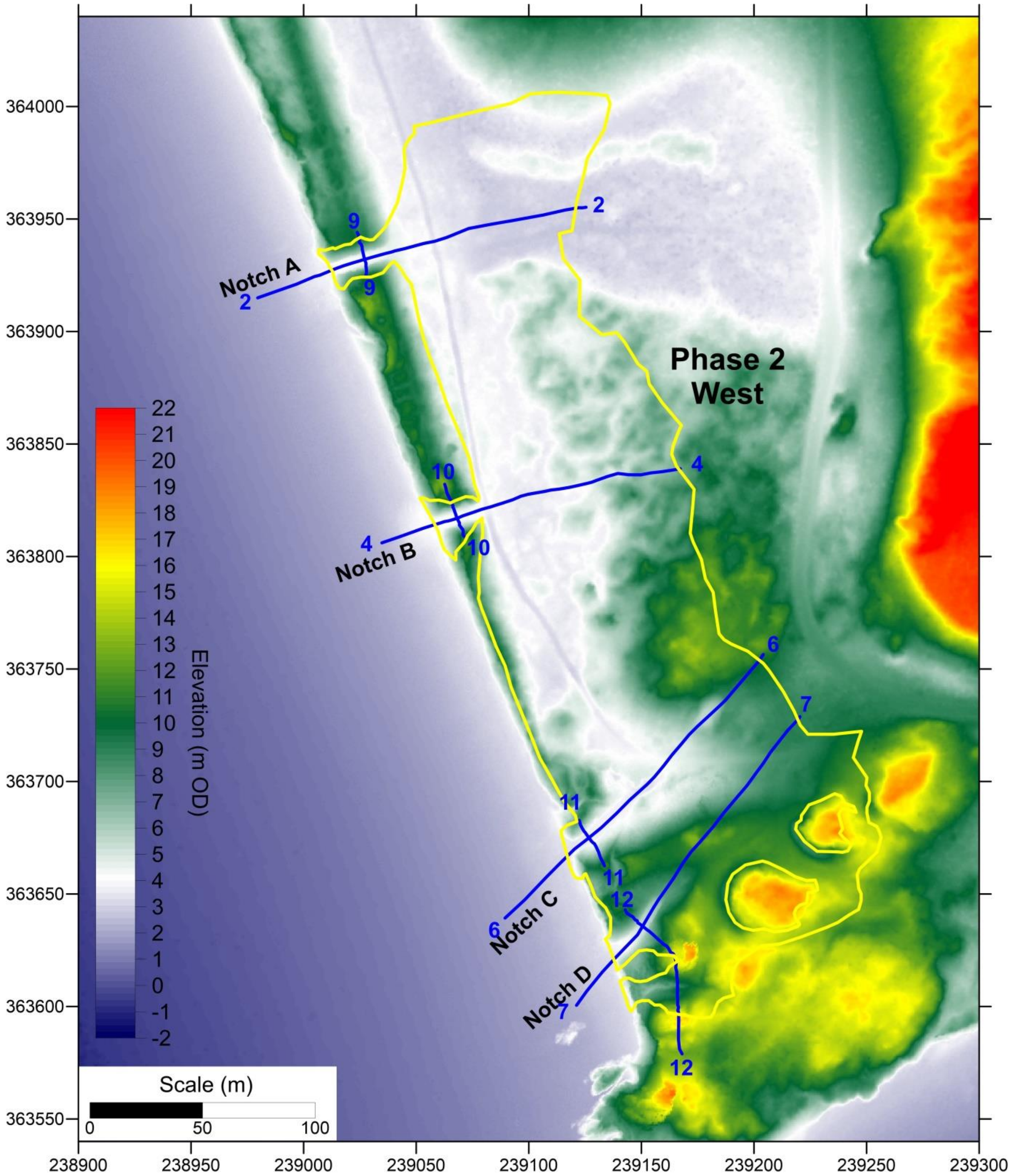


Figure 66. Filtered DEM of Newborough Warren Phase 2 West area, from an aerial LiDAR survey on 9 April 2014, after the rejuvenation works

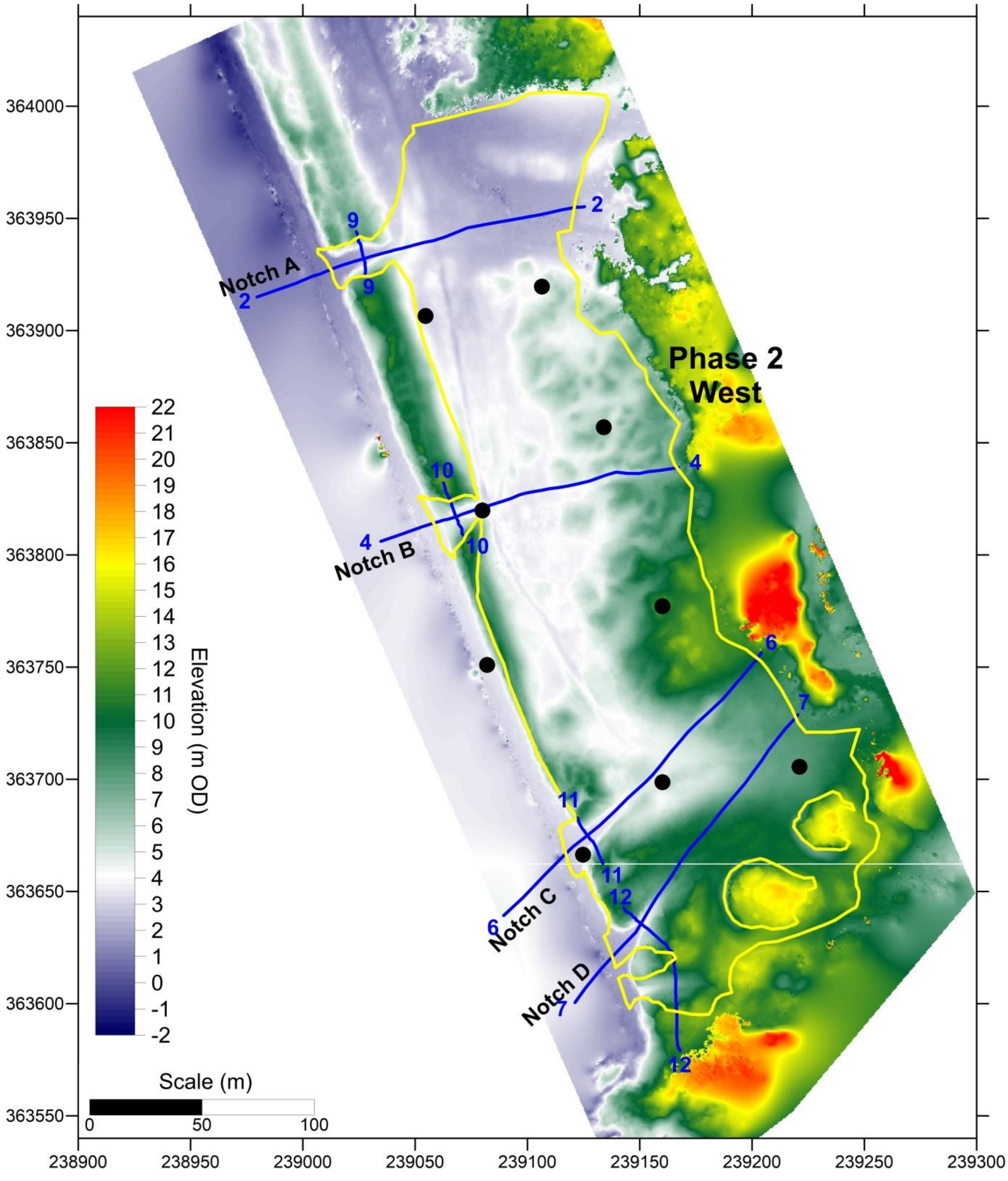


Figure 67. DEM of Newborough Phase 2 West area, from a UAV survey flown in January 2016, after the rejuvenation works. The calibration points used by the survey company to correct the elevations are shown as black dots

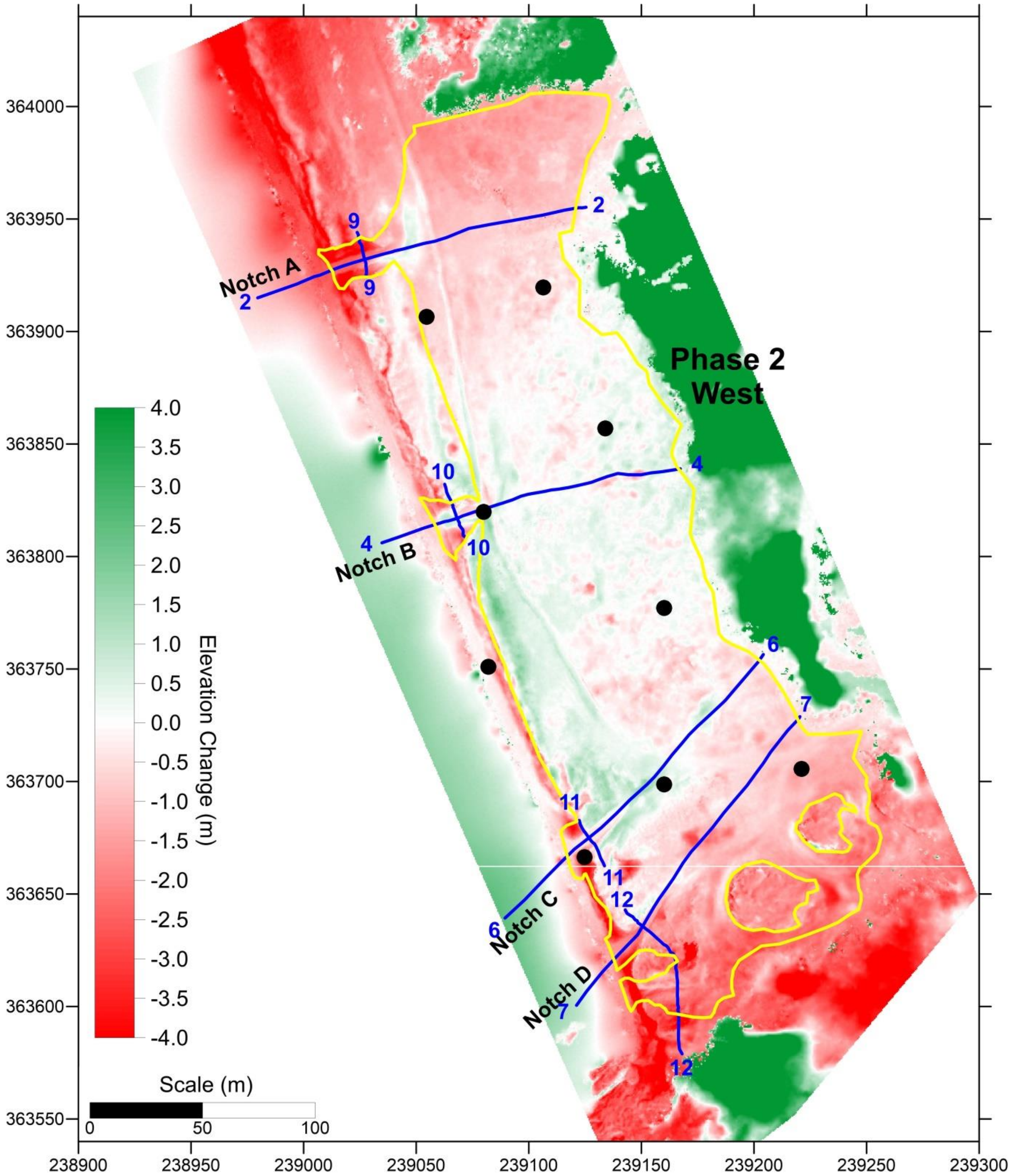


Figure 68. Difference in elevation between 2014 aerial LiDAR survey and 2016 UAV survey DEMs. The 2016 UAV DEM is unreliable beyond the limits of the works areas. The calibration points used by the survey company to correct the elevations are shown as black dots

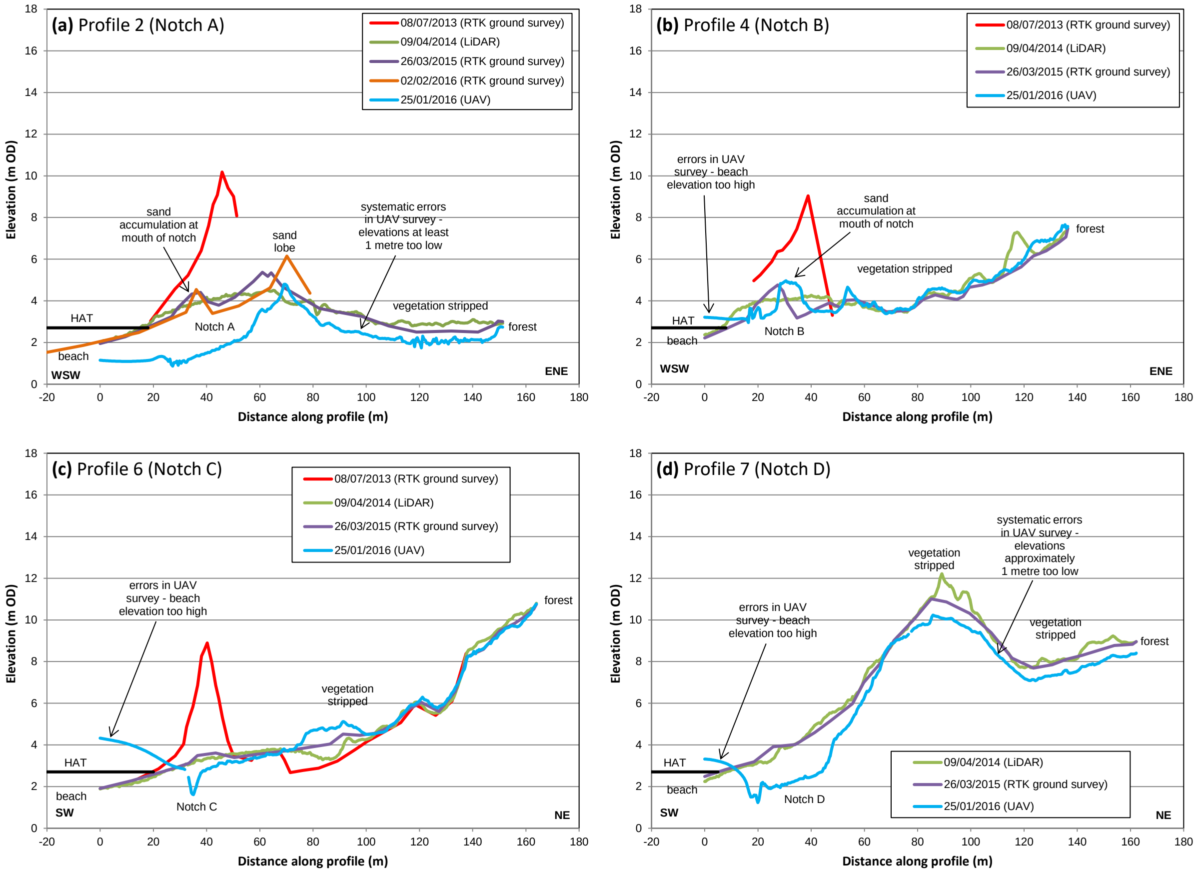


Figure 69. Topographic profiles along the axes of the notches in the Phase 2 West area of Newborough (at Traeth Penrhos). Where possible, elevations pre-works are shown from the ground RTK survey on 08/07/2013. Post-works elevations are shown for the aerial LiDAR survey flown 09/04/2014, the subsequent ground RTK survey on 26/03/2015, and UAV survey on 25/01/2016. The level of HAT (at 2.7 m OD) is also shown. Note that the 2016 UAV survey contains significant systematic errors at the northern and southern limits of the site (Profiles 2 and 7), and at the western and eastern limits (evident by exaggerated beach levels on all profiles)

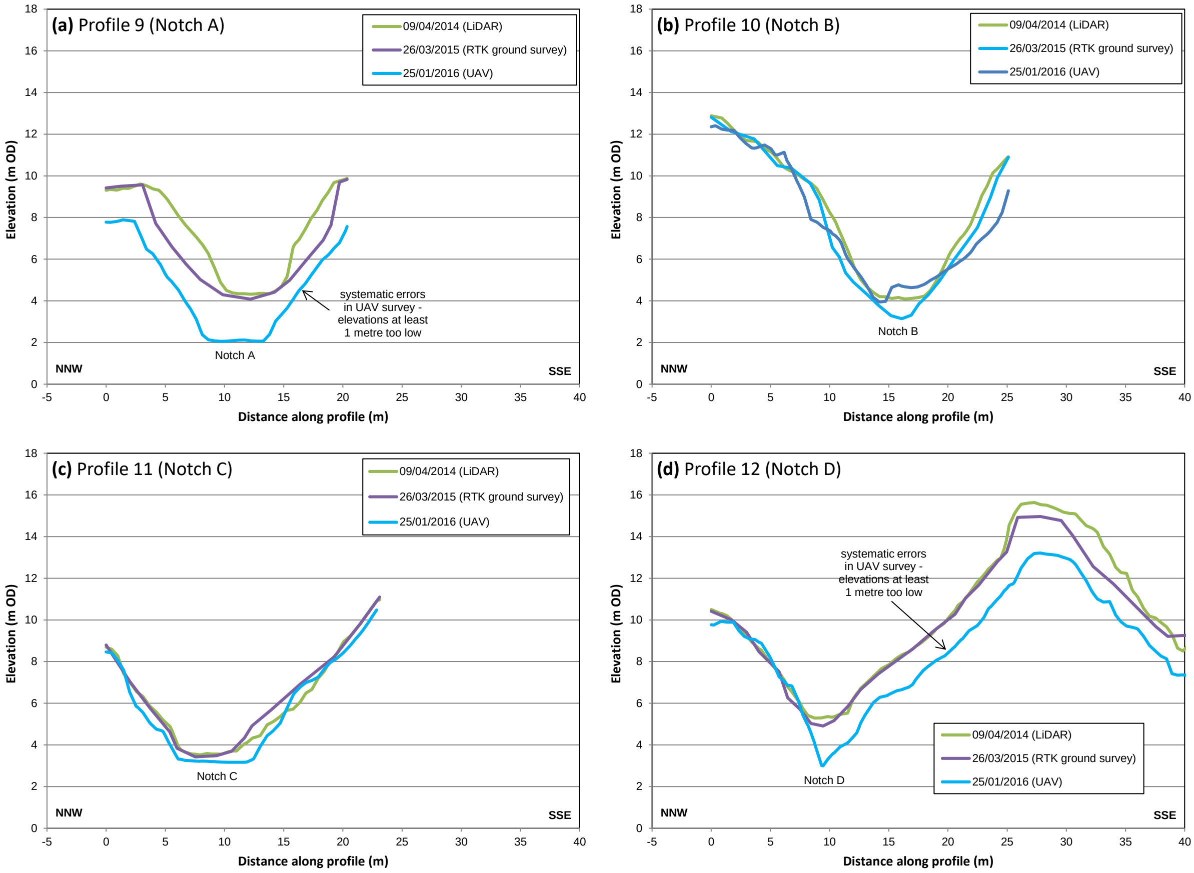


Figure 70. Topographic profiles across notches in the Phase 2 West area of Newborough (at Traeth Penrhos). Post-works elevations are shown for the aerial LiDAR survey flown 09/04/2014, the subsequent ground RTK survey on 26/03/2015, and UAV survey on 25/01/2016. Note that the 2016 UAV survey data are at least 1 metre too low on Profiles 9 and 12 due to a greater distance from the control points which were located in the centre of the site

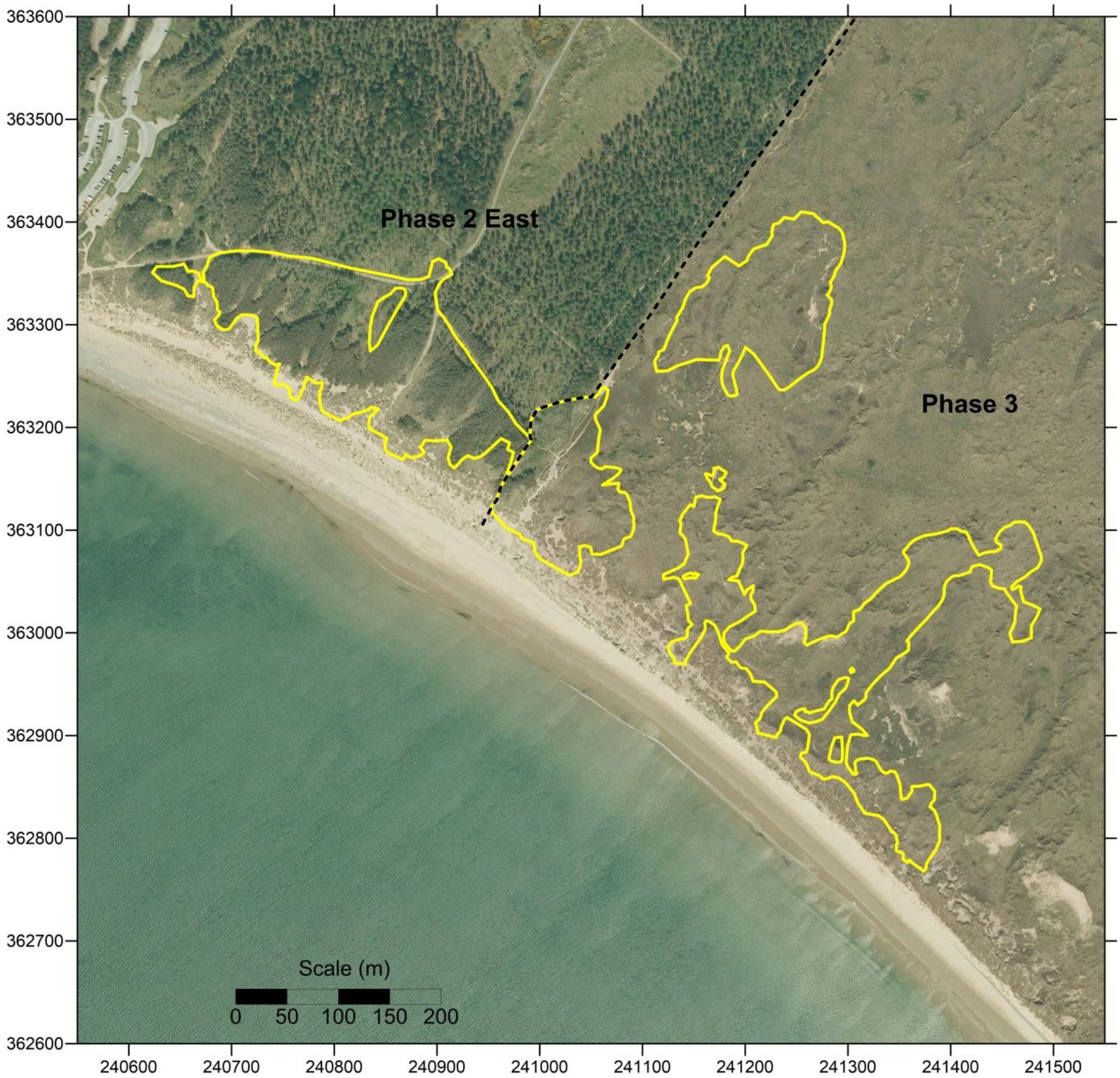


Figure 71. Pre-works aerial photograph flown 11 May 2009, showing boundaries of the Newborough Phase 2 East and Phase 3 rejuvenation trial areas (separated with the dashed black line). The yellow lines indicate the bare sand (vegetation stripping and sand ridges and heaps) created in December 2014 to March 2015, as surveyed on 25-27 March 2015 by ground RTK-GPS survey

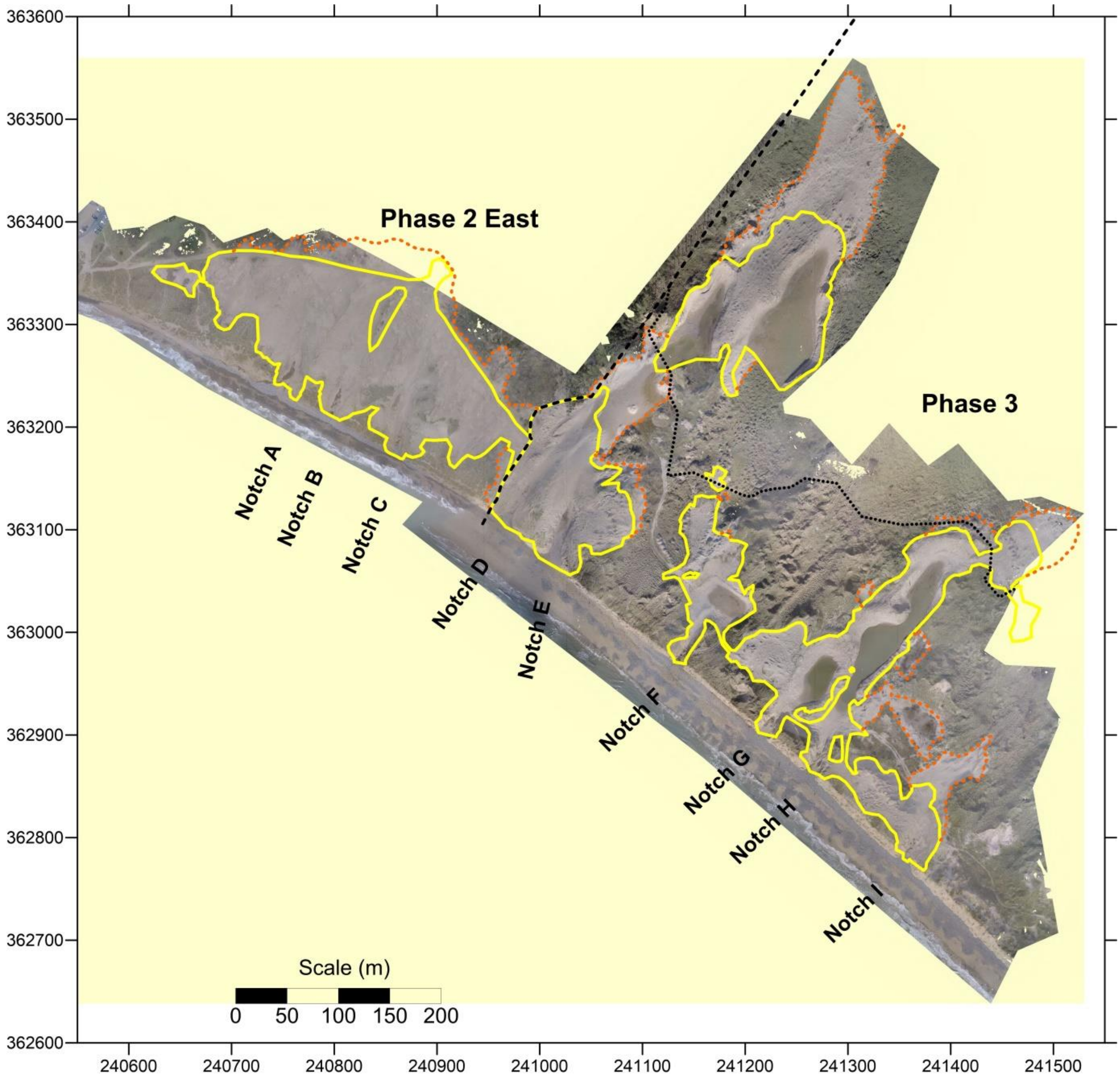


Figure 72. UAV aerial imagery flown January 2016 showing the extent of bare sand on the Phase 2 East and Phase 3 rejuvenation works at Newborough, undertaken December 2014 to March 2015. The yellow lines indicate the bare sand areas created in December 2014 to March 2015, the orange dashed lines the areas of blown sand outside the works areas by January 2016 (note that some areas are estimated due to incomplete UAV coverage)

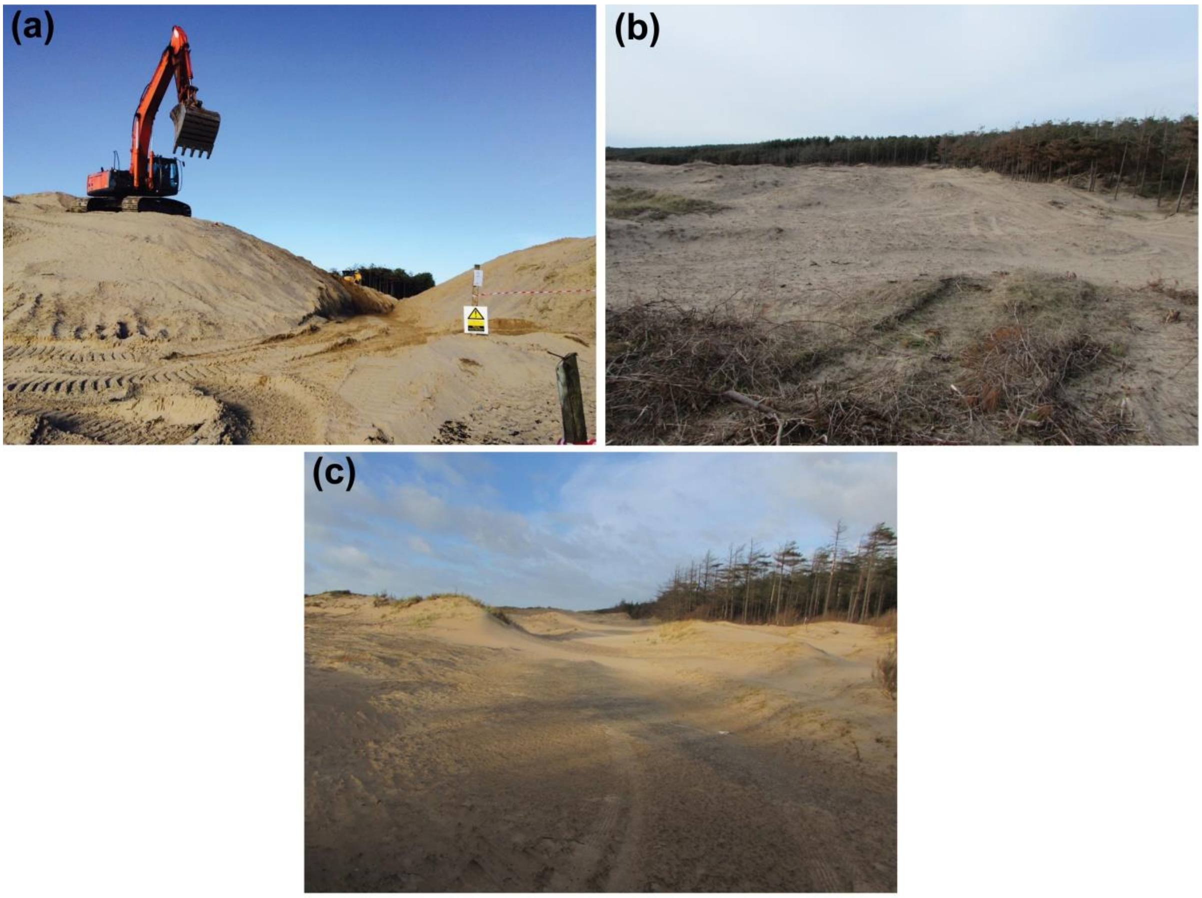


Figure 73. Ground photographs of Newborough Phase 2 East: (a) During the rejuvenation works February 2015; (b) February 2015; (c) February 2016

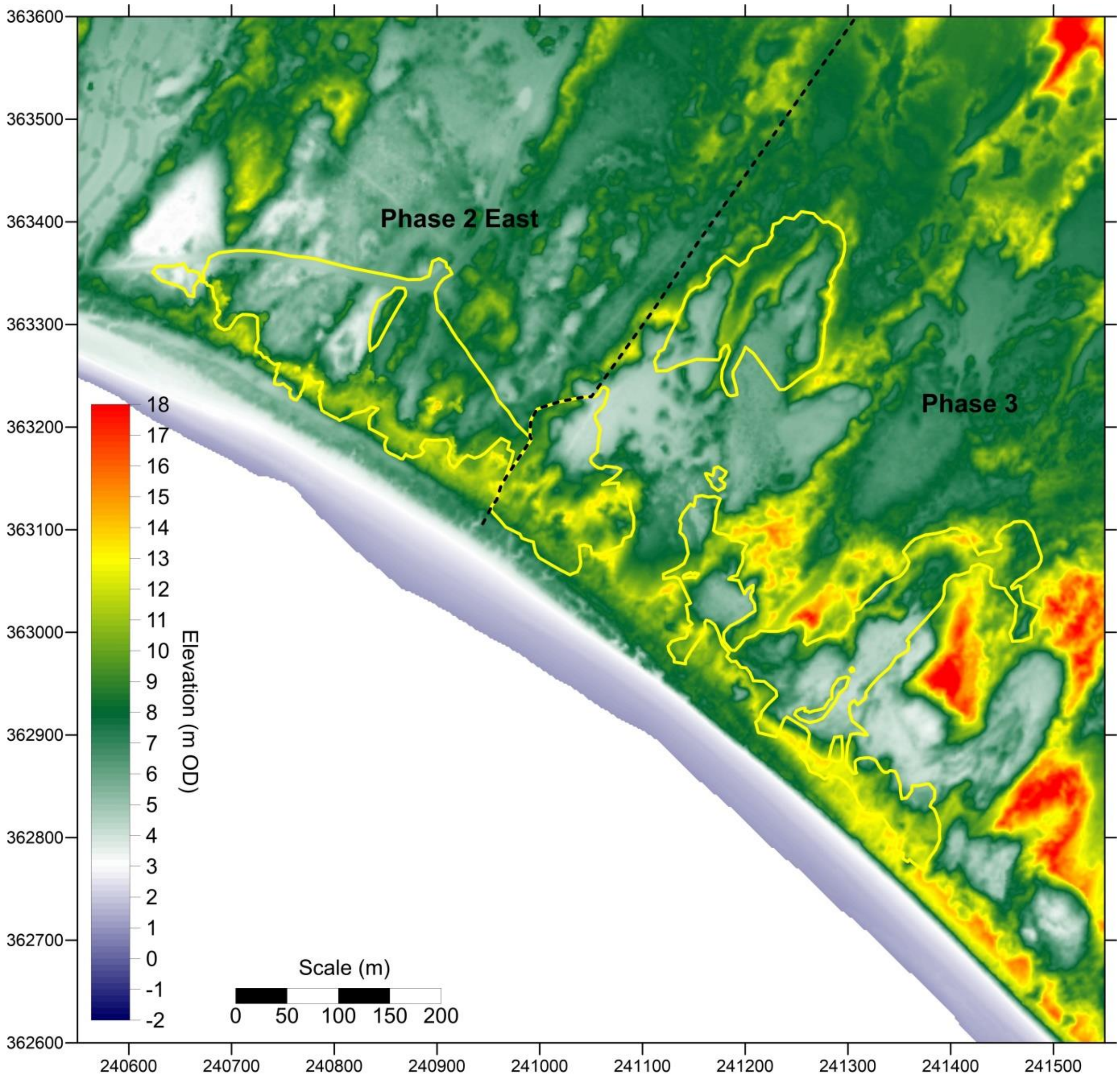


Figure 74. Filtered DEM of Newborough Phase 2 East and Phase 3 areas, based on an aerial LiDAR survey on 12 May 2009, before the rejuvenation works

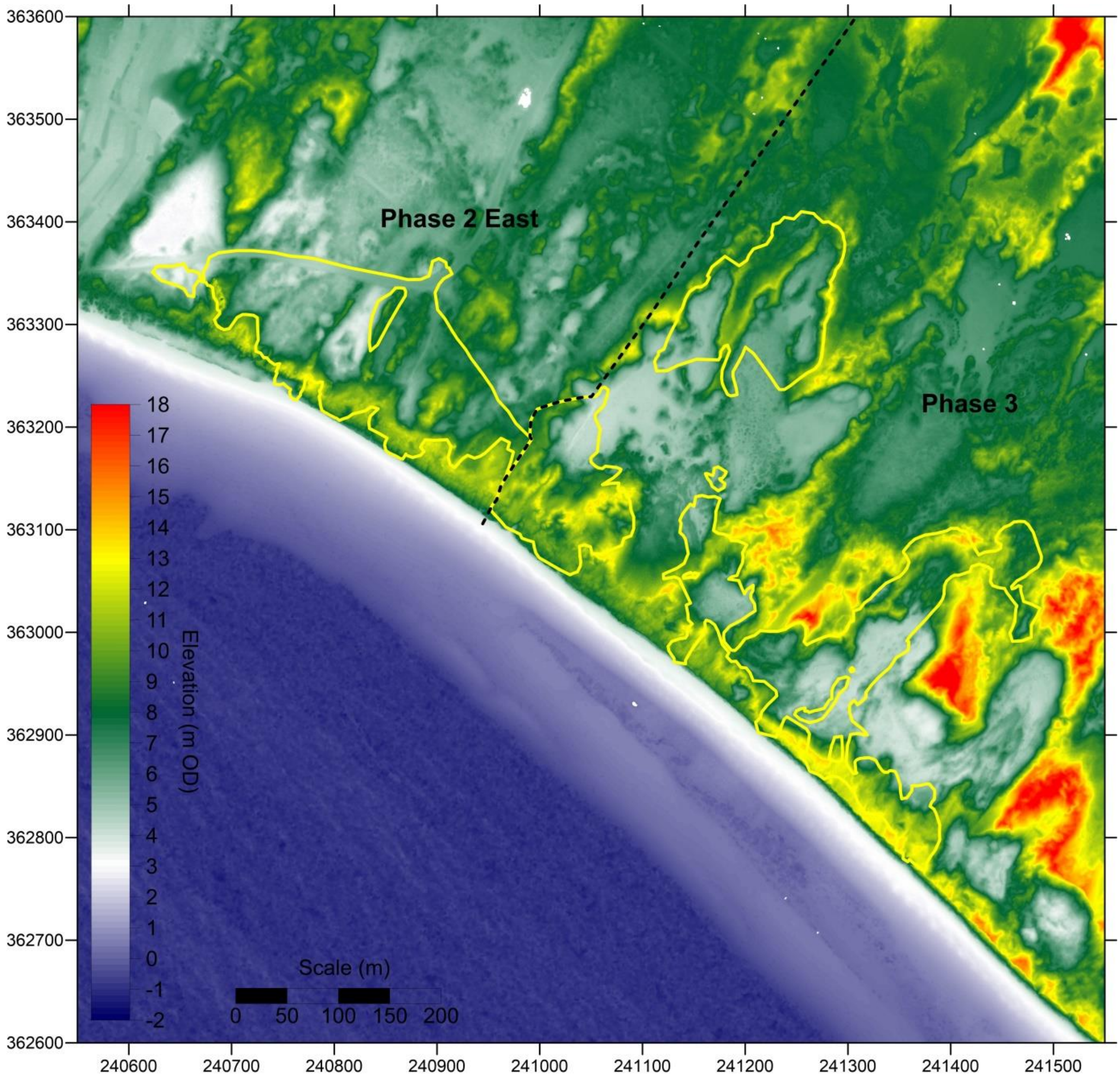


Figure 75. Unfiltered DEM of Newborough Phase 2 East and Phase 3 areas, based on an aerial LiDAR survey on 9 April 2014, before the rejuvenation works

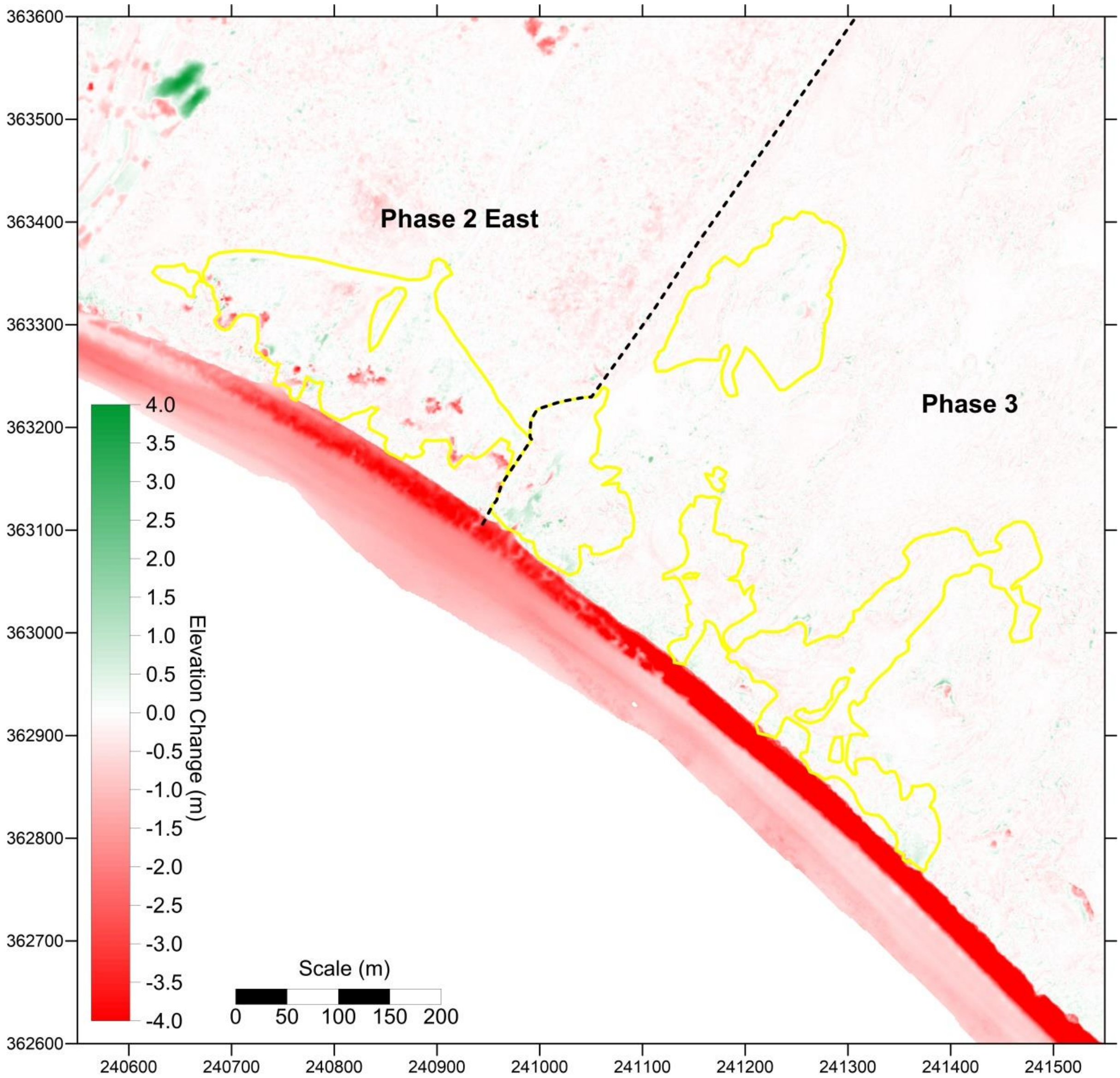


Figure 76. Difference in elevation between 2009 and 2014 aerial LiDAR DEMS. Very little sediment from frontal dune erosion appears to have moved inland to the dunefield

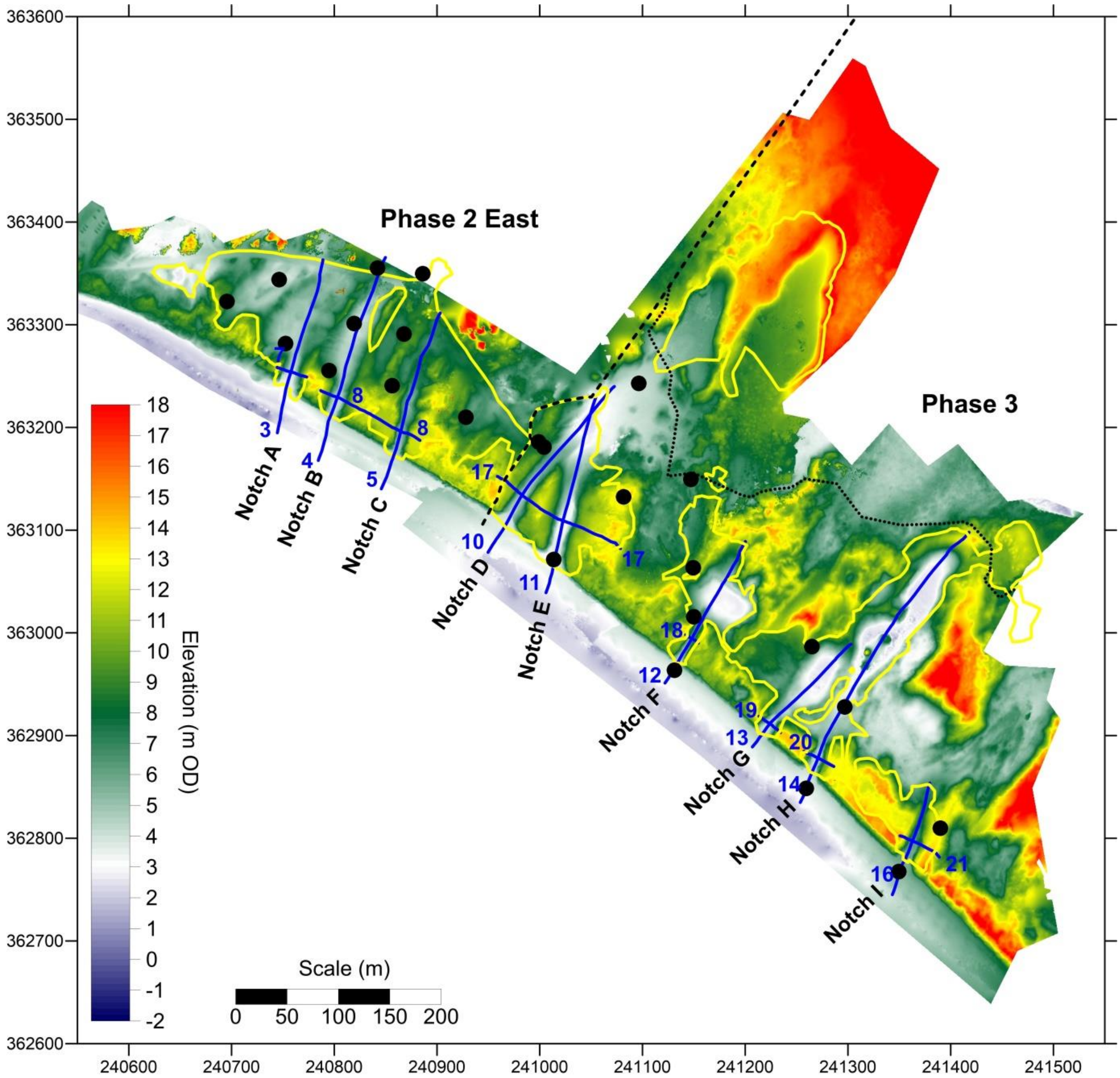


Figure 77. DEM of Newborough Warren Phase 2 and 3 areas, based a UAV survey in January 2016, after the rejuvenation works. The calibration points used by the survey company to correct the elevations are shown as black dots

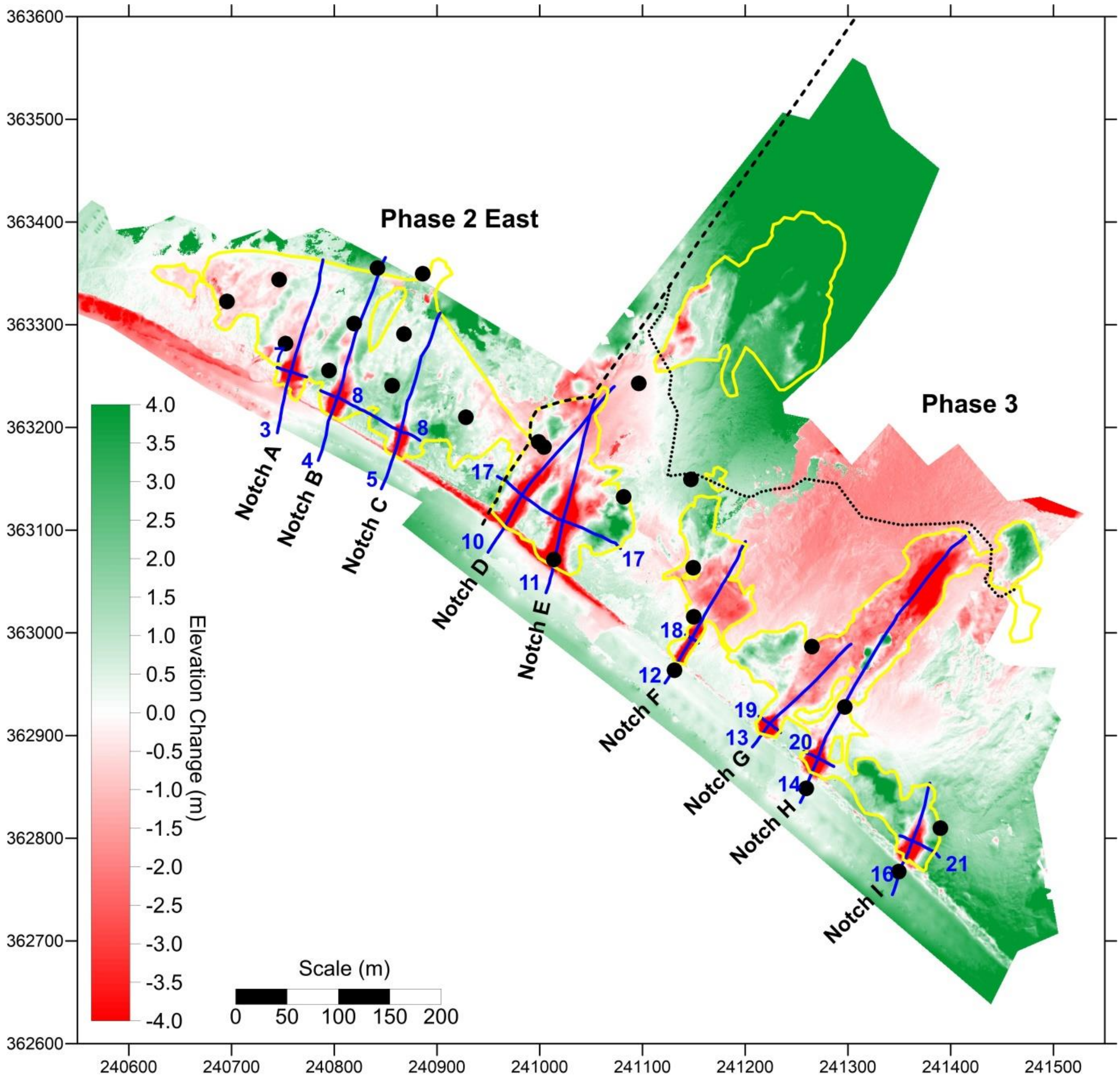


Figure 78. Difference in elevation between 2014 aerial LiDAR survey and 2016 UAV DEMs. The 2016 UAV DEM is unreliable beyond the limits of the works areas (in particular to the north of Phase 3, leading to apparent accretion of well-vegetated dunes), and the 'step' in elevation running SW-NE through the Phase 3 area. The calibration points used by the survey company to correct the elevations are shown as black dots

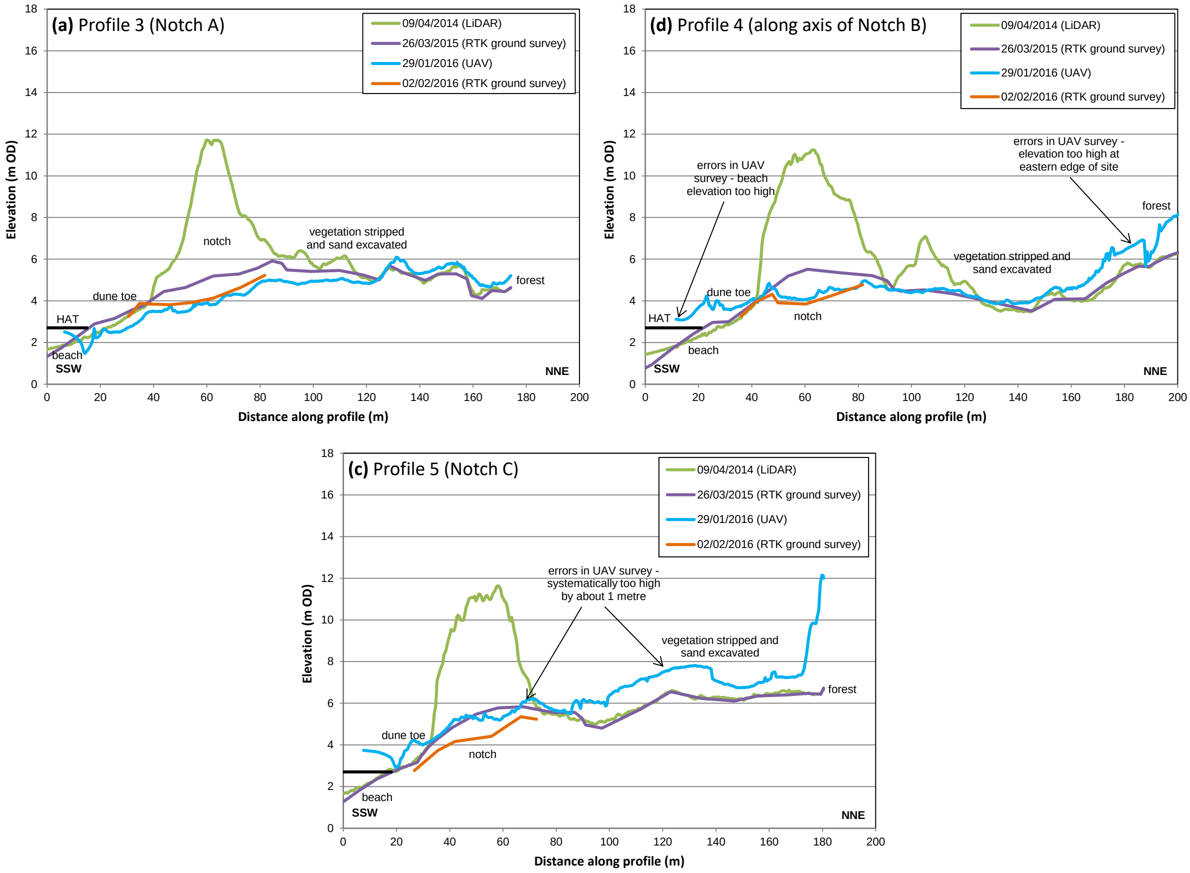


Figure 79. Topographic profiles along the axes of the notches in the Newborough Phase 2 East area. Elevations pre-works are shown from the aerial LiDAR survey flown 09/04/2014. Elevations post-works are shown from the subsequent ground RTK surveys on 26/03/2015 and 02/02/2016, and the UAV survey on 29/01/2016. The level of HAT (at 2.7 m OD) is also shown. Note that the 2016 UAV survey contains significant systematic errors, especially at the western and eastern limits of the site, these areas being furthest from the control points

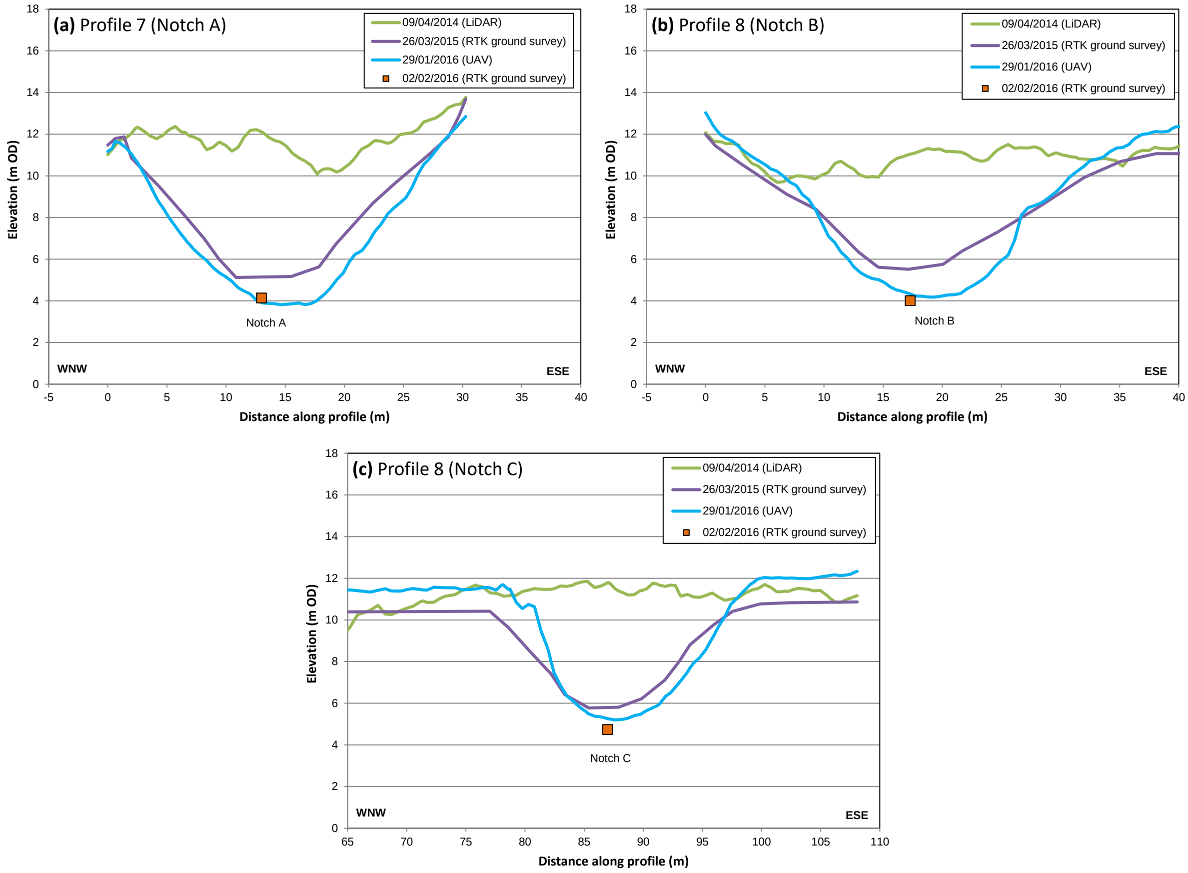


Figure 80. Topographic profiles across the notches in the Newborough Phase 2 East area. Elevations pre-works are shown from the aerial LiDAR survey flown 09/04/2014. Elevations post-works are shown from the subsequent ground RTK survey on 26/03/2015 and the UAV survey on 29/01/2016. Cross-profiles were not measured during the ground RTK survey on 02/02/2016, but the position and elevation at which the axial profile crosses the cross-profile is indicated with an orange square

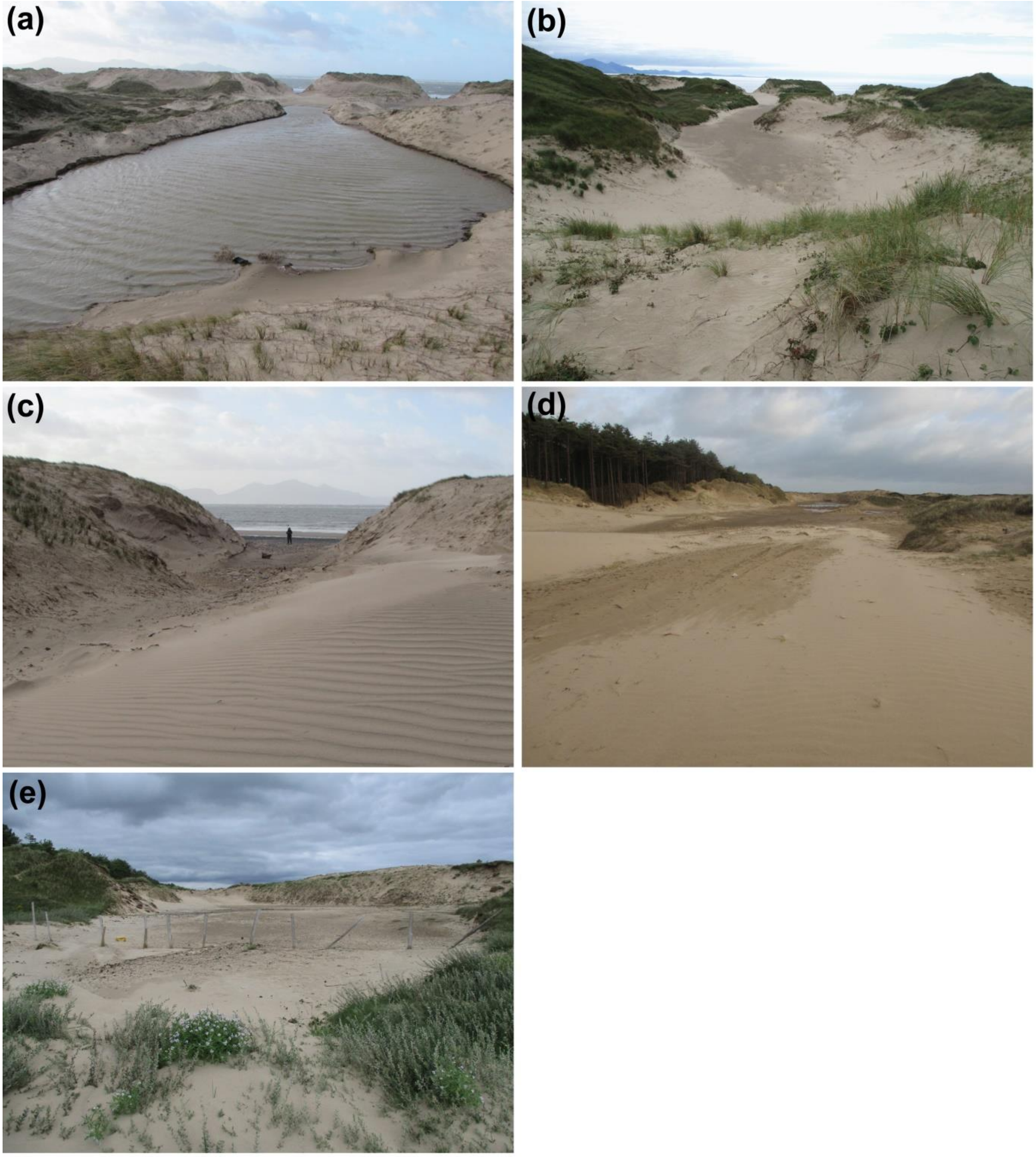


Figure 81. Ground photographs of Newborough Phase 3: (a) February 2016; (b) August 2016; (c) February 2016; (d) March 2015; (e) August 2016

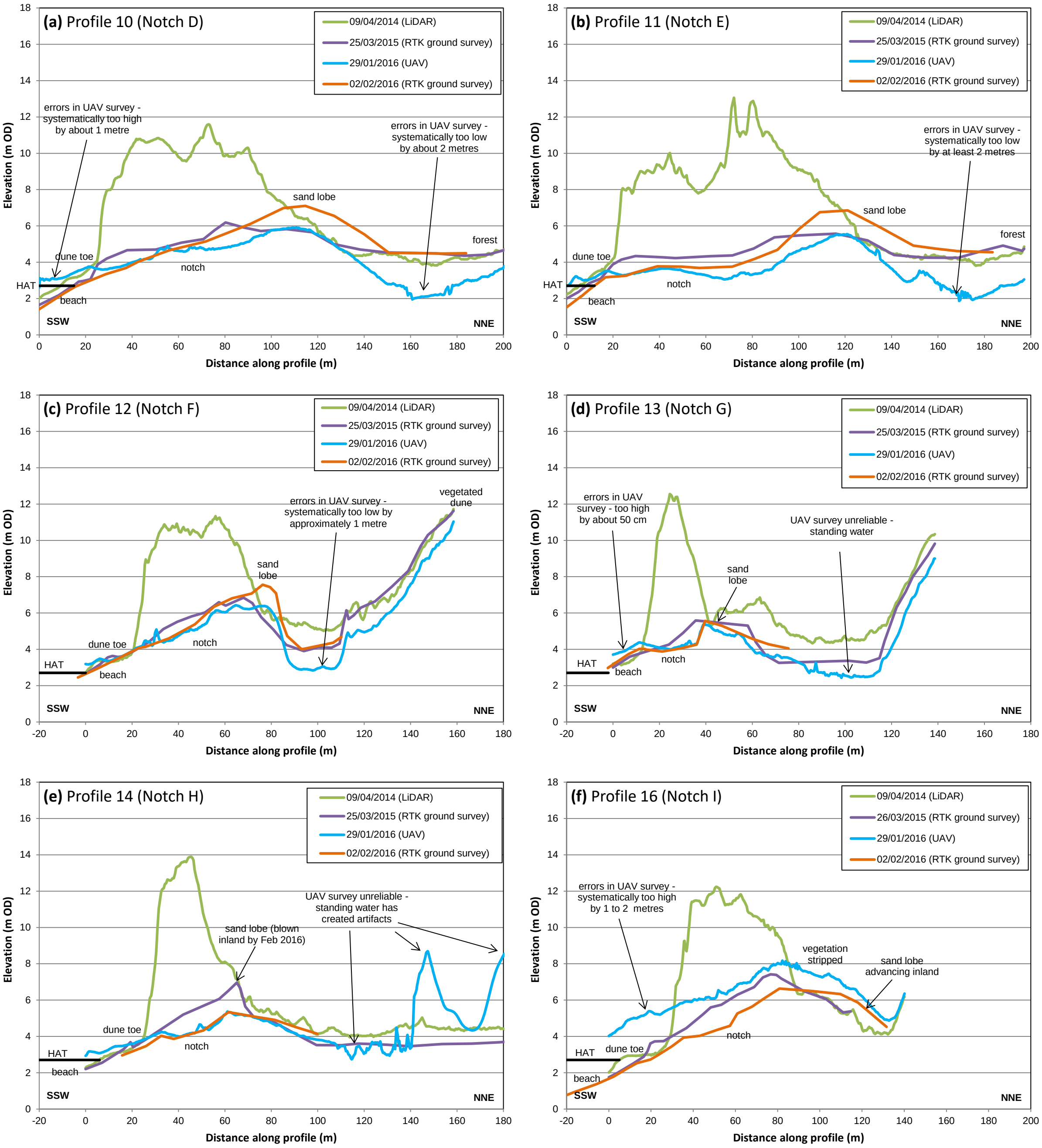


Figure 82. Topographic profiles along the axes of the notches in the Phase 3 area at Newborough Warren. Elevations pre-works are shown from the aerial LiDAR survey flown 09/04/2014. Elevations post-works are shown from the subsequent ground RTK surveys on 26/03/2015 and 02/02/2016, and the UAV survey on 29/01/2016. The level of HAT (at 2.7 m OD) is also shown. Note that the 2016 UAV survey contains significant systematic errors, especially at the western and eastern limits of the site, and for the southern limit at Profile 16 (Notch I), these areas being furthest from the control points. Also, the UAV survey contains significant artefacts for standing water areas, such as on Profile 14

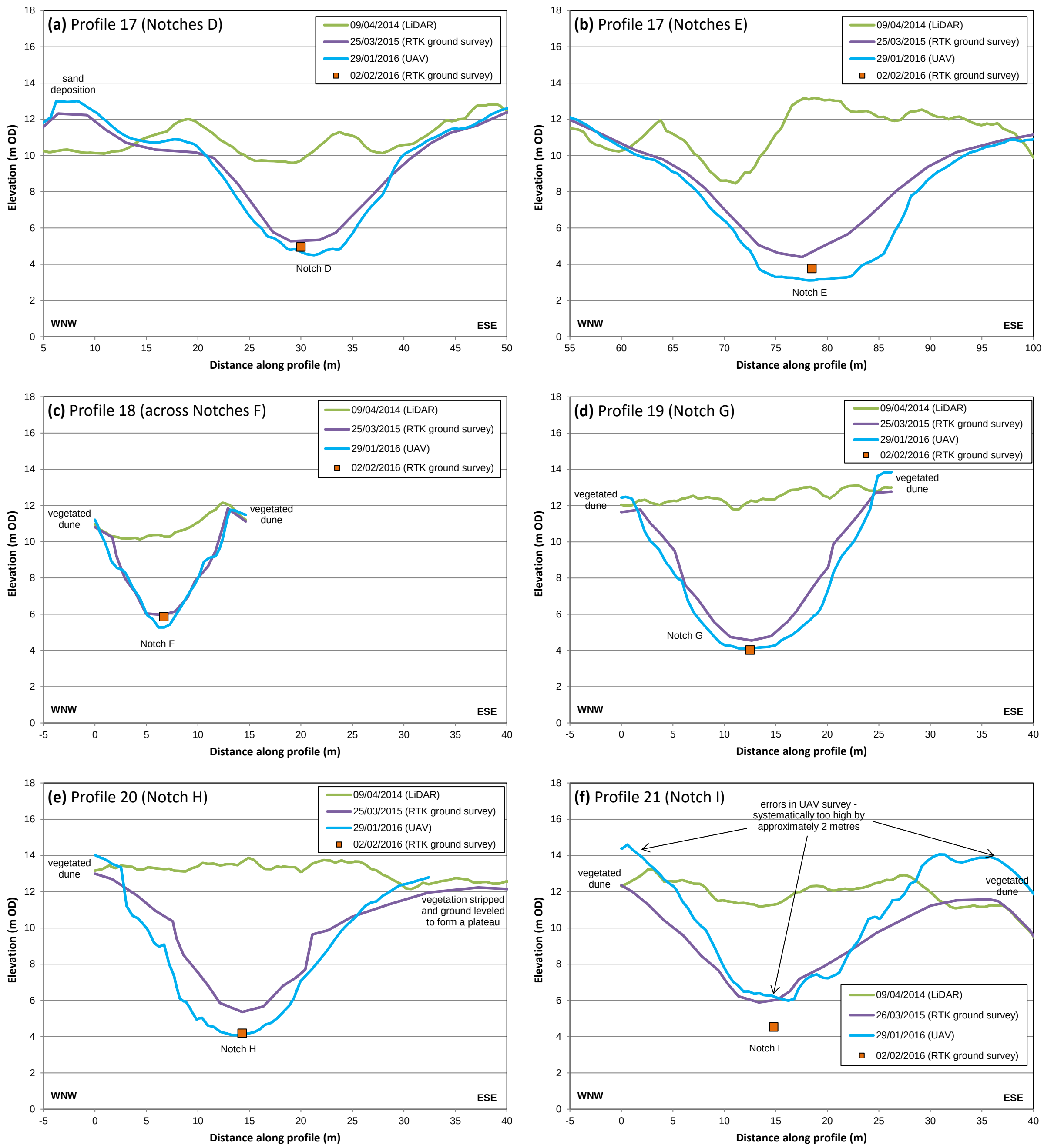


Figure 83. Topographic profiles across the notches in the Newborough Phase 3 area. Elevations pre-works are shown from the aerial LiDAR survey flown 09/04/2014. Elevations post-works are shown from the subsequent ground RTK survey on 26/03/2015 and the UAV survey on 29/01/2016. Cross-profiles were not measured during the ground RTK survey on 02/02/2016, but the position and elevation at which the axial profile crosses the cross-profile is indicated with an orange square. Note that the 2016 UAV survey contains significant systematic errors at Profile 16 (Notch I), this area being furthest from the control points

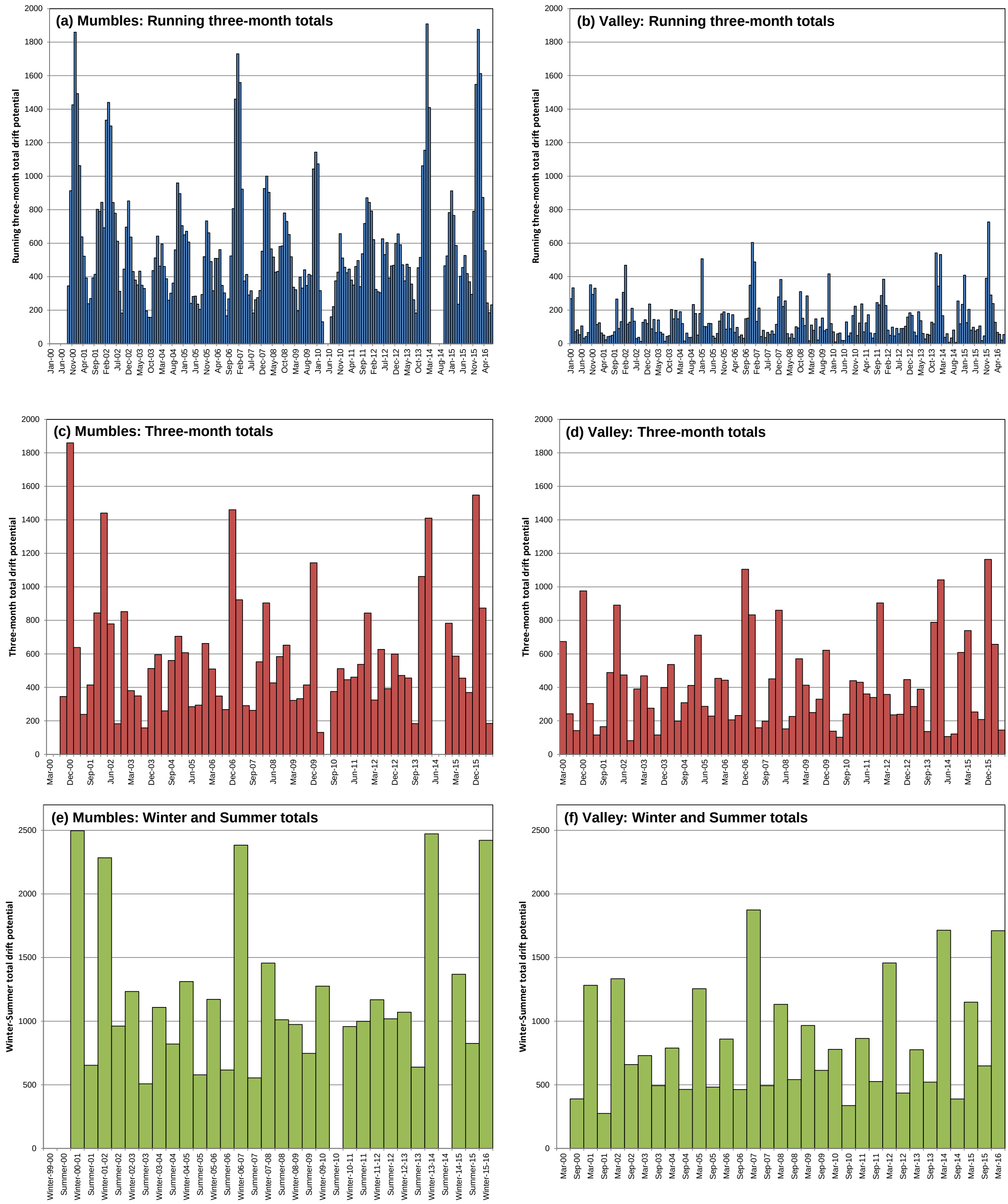


Figure 84. Temporal variation in aeolian sand drift potential (in vector units, VU) between January 2000 and July 2016, based on wind records for Mumbles Head (the closest meteorological station to Kenfig and Merthyr Mawr) and Valley (the closest meteorological station to Newborough Warren), calculated using the Fryberger and Dean (1979) equation: (a and b) running three-month totals; (c and d) three month totals; (e and f) six month winter (October to March) and summer (April to September) totals

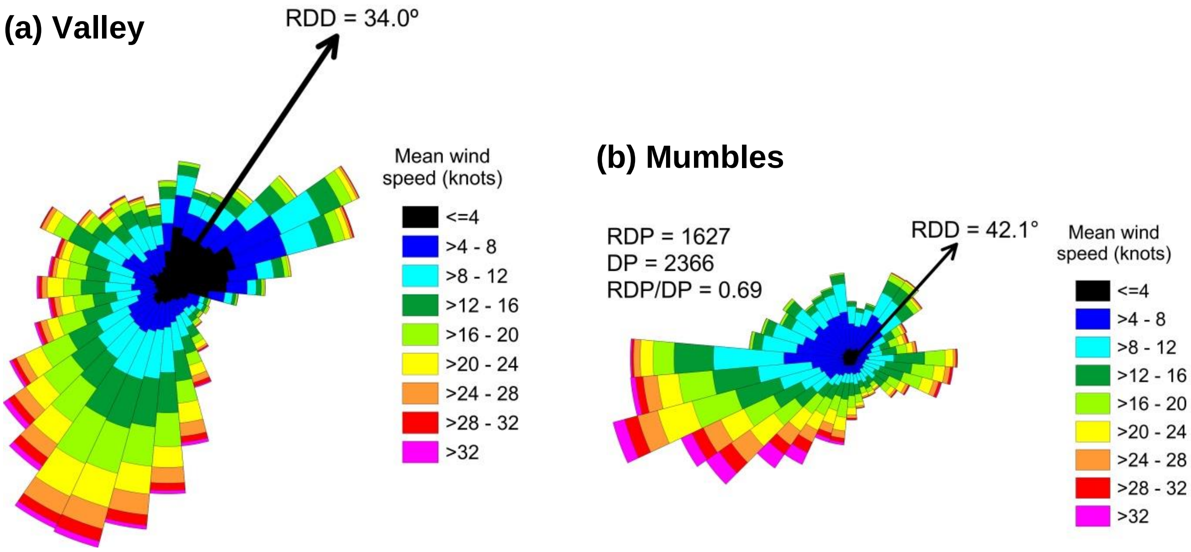


Figure 85. Wind roses for Valley (1957-2015) and Mumbles (2000-2015), also showing resultant aeolian sand drift direction (RDD) calculated for winds >11 knots using a modified version of Fryberger & Dean's (1979) method

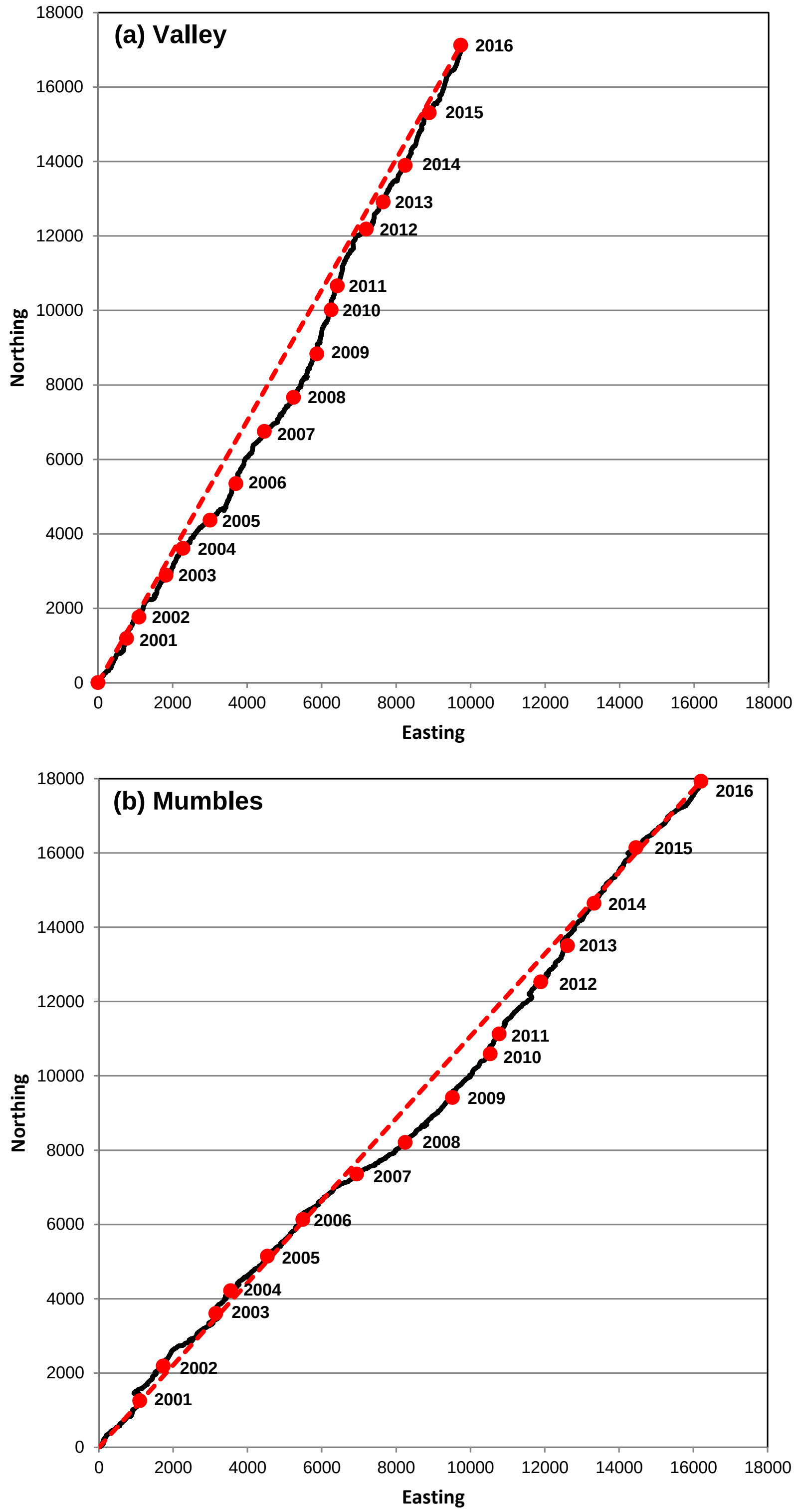


Figure 86. Cumulative sand transport vectors for Valley and Mumbles, calculated for the period 2000-2015 inclusive, for all winds >11 knots. The value on 1st January each year is shown with a red dot. Note trend towards more easterly transport (i.e. strong westerly and northwesterly winds relative to southerly and southwesterly winds) at Valley between 2004 and 2011, and at Mumbles between 2007 and 2013. There has been a return to greater influence of strong southwesterly winds at Valley since 2011 and at Mumbles since late 2012.

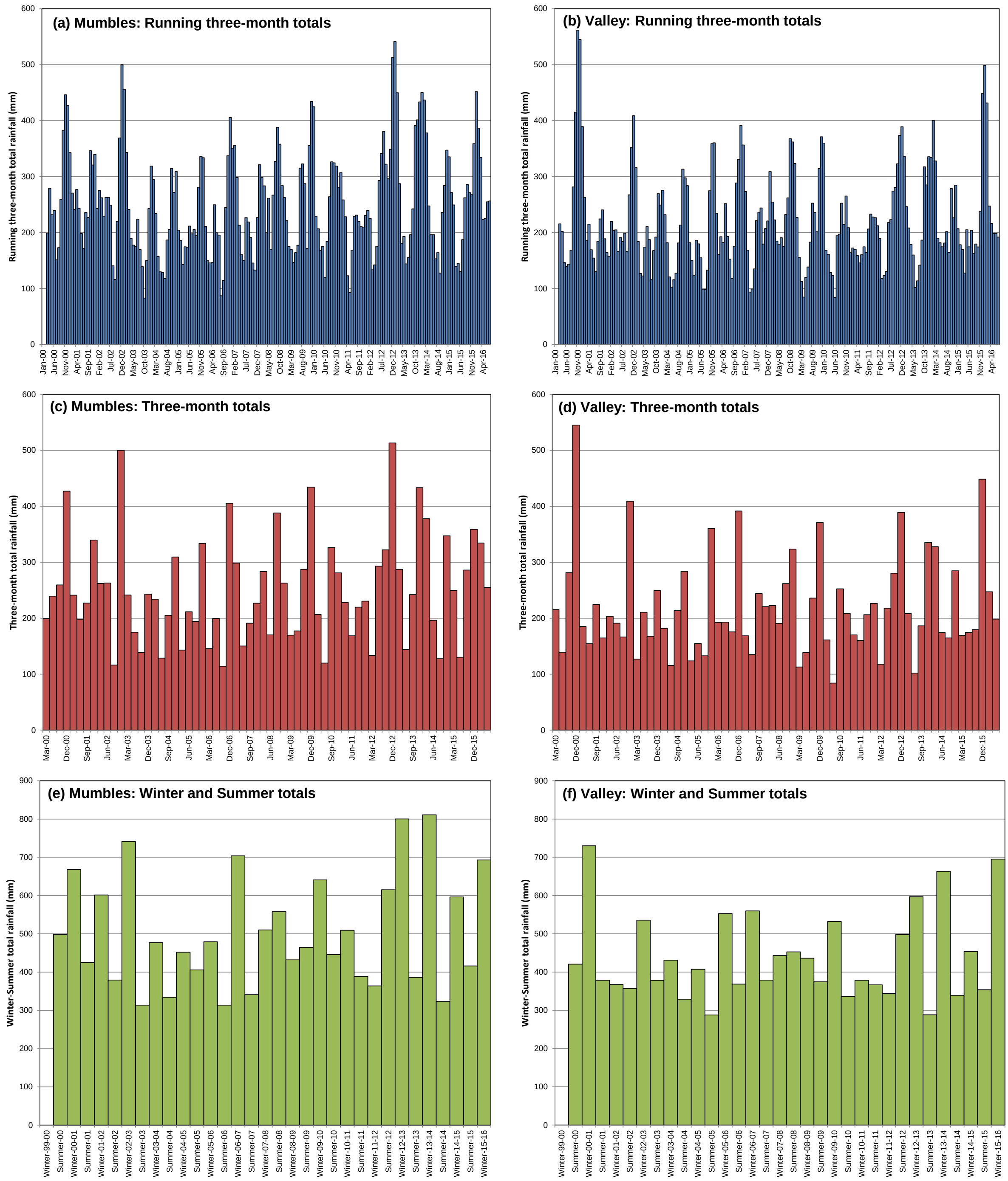


Figure 87. Temporal variation in rainfall between January 2000 and July 2016 at Mumbles Head (the closest meteorological station to Kenfig and Merthyr Mawr) and Valley (the closest meteorological station to Newborough Warren): (a and b) running three-month total ; (c and d) three month totals; (e and f) winter (October to March) and summer (April to September) totals. Note that although the winters of 2013-14 and 2015-16 had higher than average aeolian transport potential they were also much wetter than average

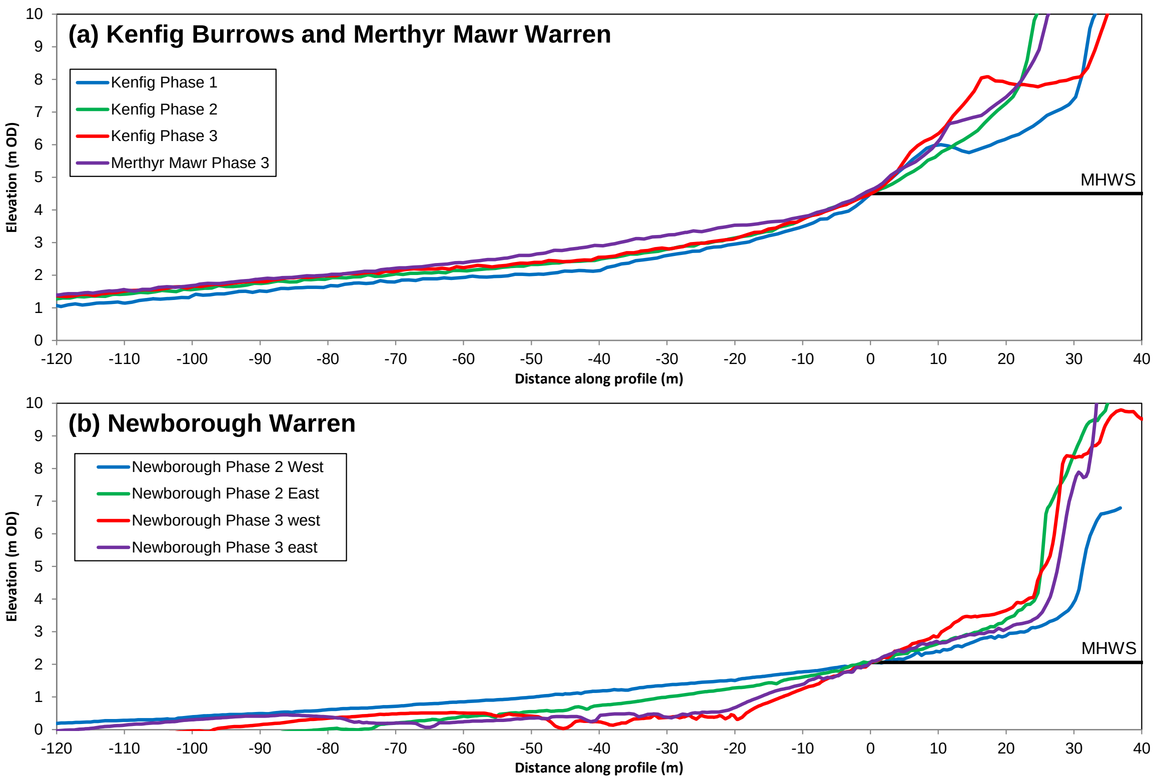


Figure 88. Comparison of topographic profiles across the beach at (a) Kenfig Burrows and Merthyr Mawr Warren and (b) Newborough. Elevations taken from LiDAR surveys in 2014 and 2015. The horizontal red lines indicate the levels of MHWS and MLWS.

Figure 89. Ground photographs of Dune H, located in the southeast part of Newborough Warren, taken early August 2016; (a) deflation area, looking towards Llanddwyn island, (b) depositional area, view towards Morfa Dinlle

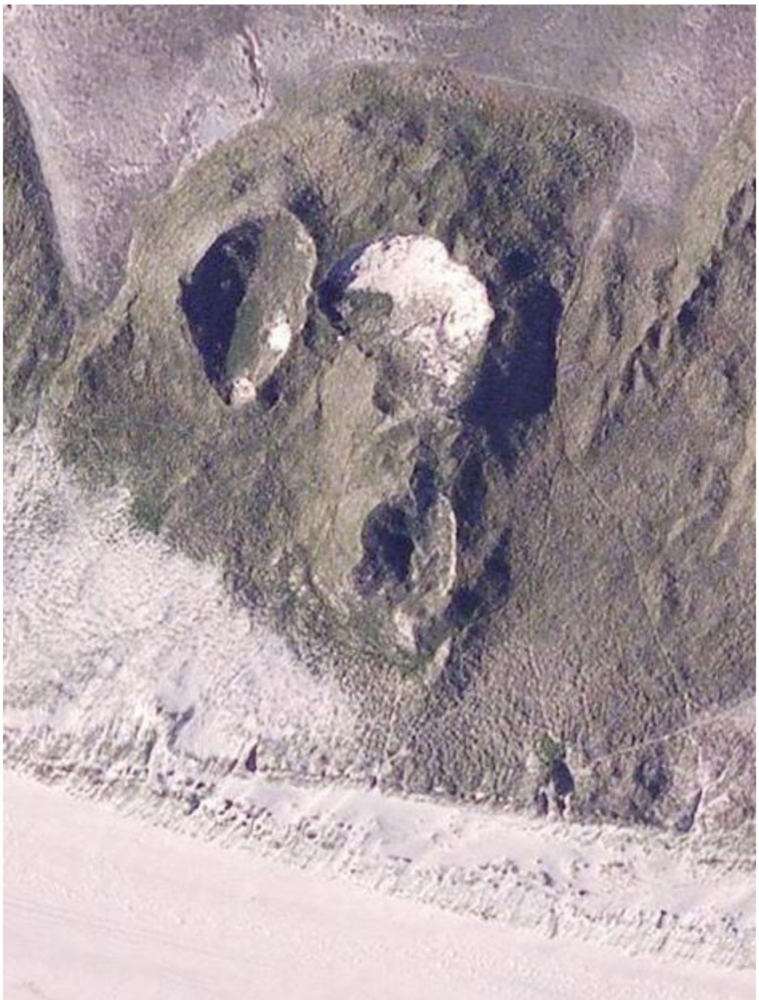


Figure 90. Aerial photograph of partially vegetated saucer blowout dunes NW Abermenai, taken 2011 (source: Bing Maps). Note also the extensive bare sand within and adjacent to the zone of recent frontal dune progradation

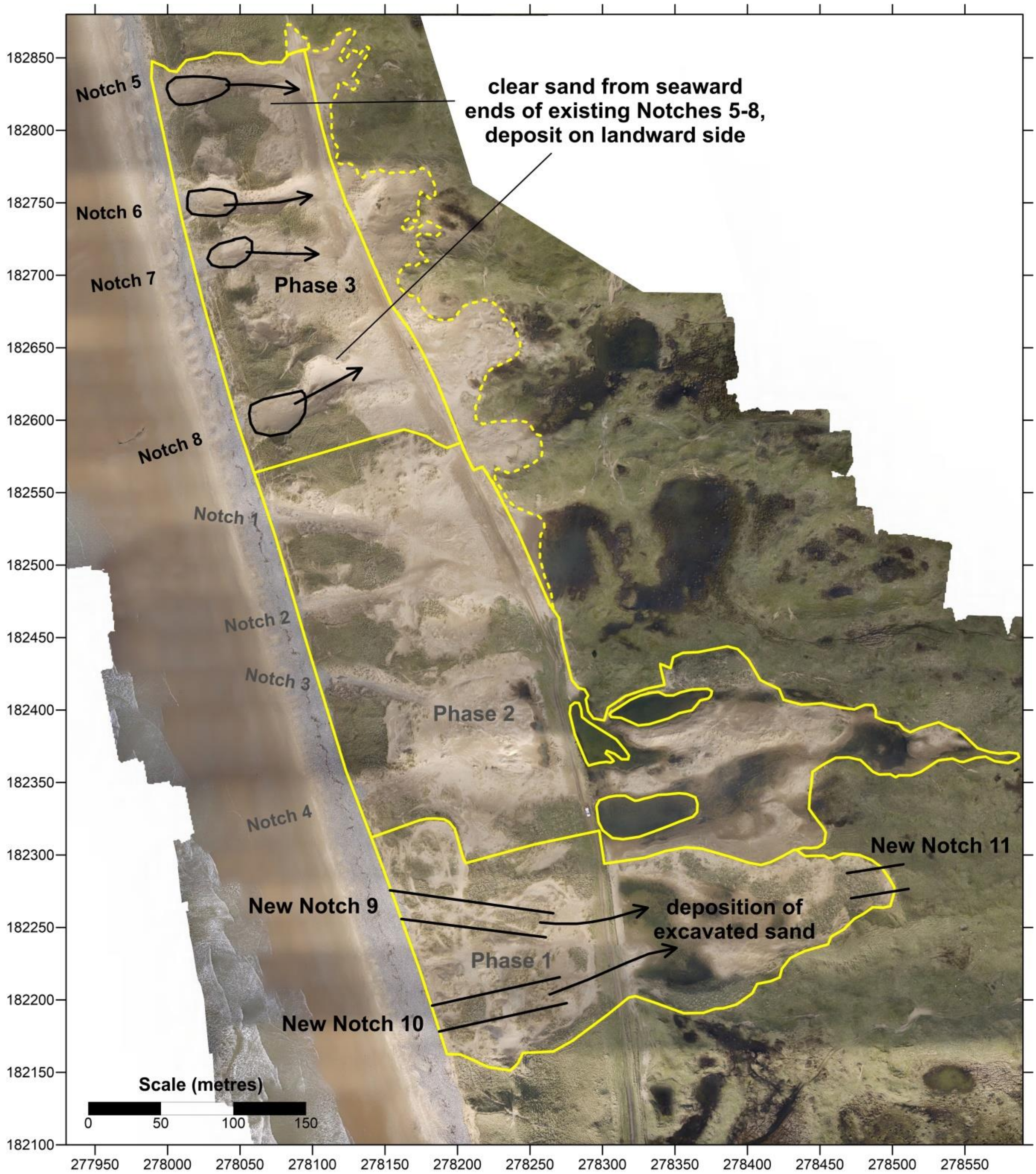


Figure 91. Proposals for further intervention works at Kenfig Burrows: (A) creation of two notches through the frontal dunes within the Phase 1 West area, with translocation of sand to the east side of the haul road (Phase 1 East area); (B) creation of a 3 m deep, 10 m wide notch in the crest of the parabolic dune in the Phase 1 East area; (C) removal of sand obstructing the mouth so the Phase 3 notches and deposition on the west side of the haul road behind the notches.

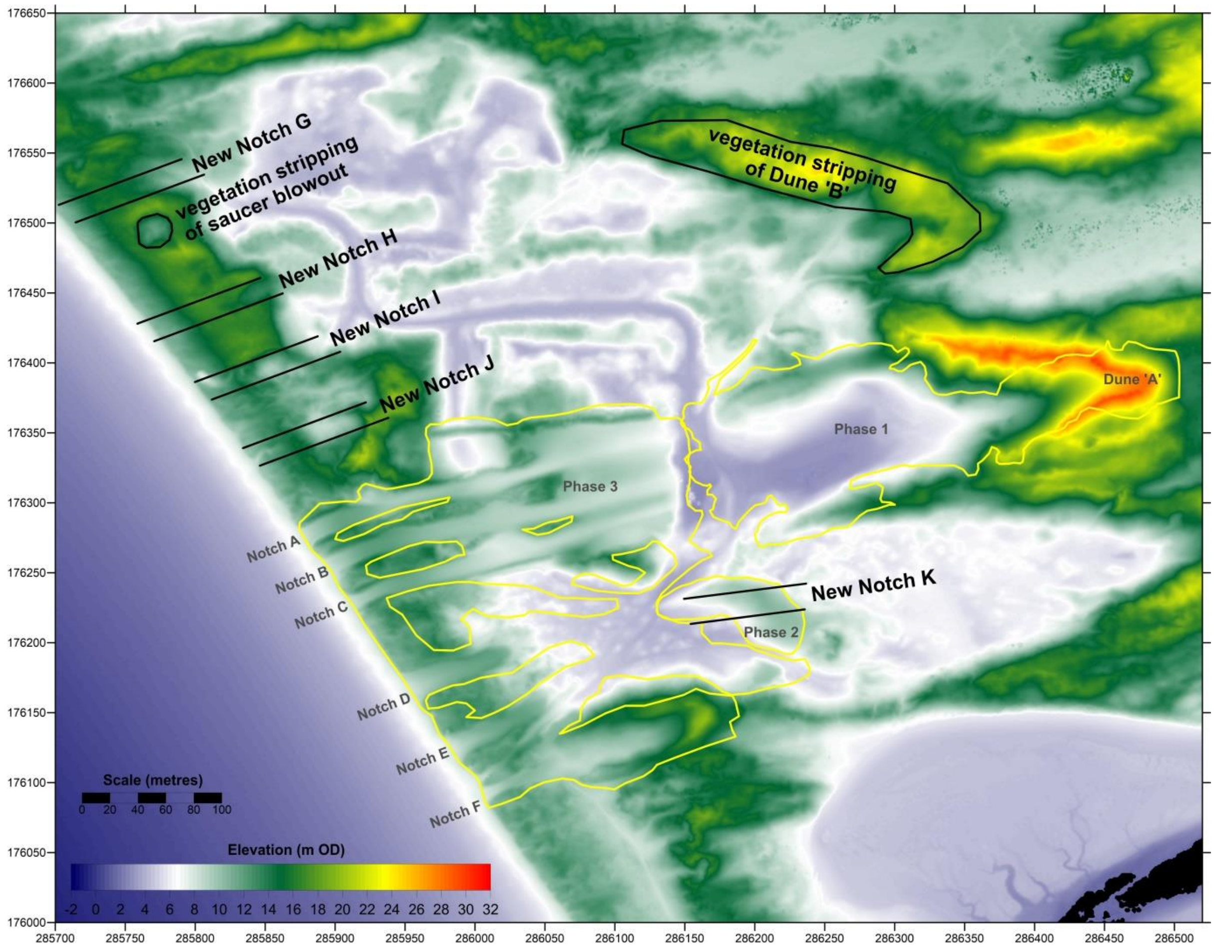


Figure 92. Proposals for further intervention works at Merthyr Mawr: (A) creation of four new notches in the frontal dune to the north of the Phase 3 notches; (B) turf stripping on the windward slope, crest and upper leeward slope of Dune 'B' identified in Pye & Blott (2011b); (C) creation of a notch through the middle of the artificial dune constructed in Phase 2. As an option the four new notches could be given a trapezoidal plan form to focus wind flow in the horizontal as well as vertical direction

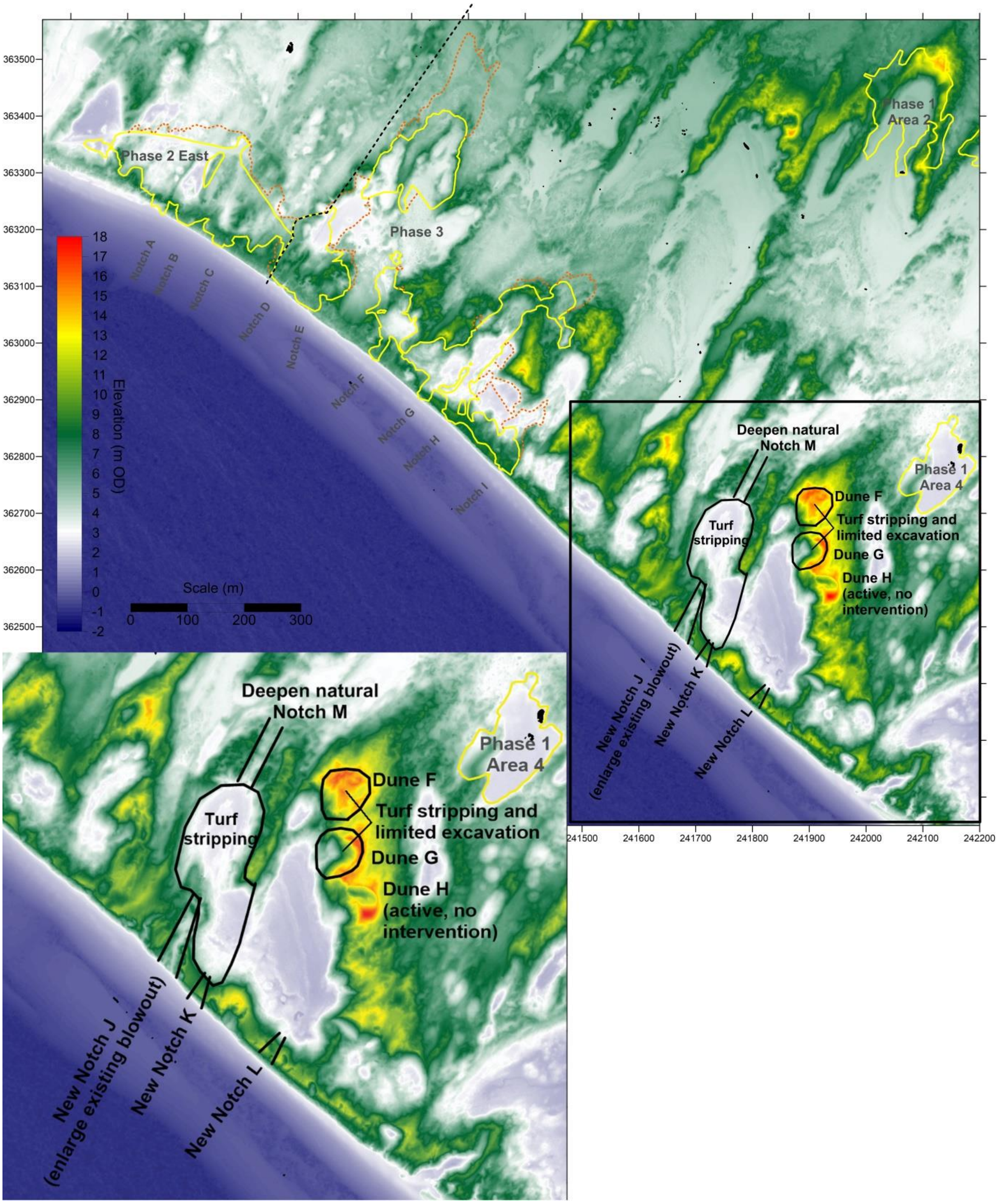


Figure 93. Proposals for further intervention works at Newborough Warren: (A) creation of three additional notches in the fontal dunes to the east of the Phase 3 notches, each notch having a trapezoidal plan form and relatively steep seaward gradient to focus wind flow in both horizontal an d vertical dimensions; (B) turf stripping of the dune deflation corridor inland of notches J and K; (C) enlargement of existing natural notch M' (D) turf stripping and localised sand excavation to enhance wind turbulence and sand movement in the semi-stabilised sub-dunes F and G; sub-dune H is currently active and requires no intervention

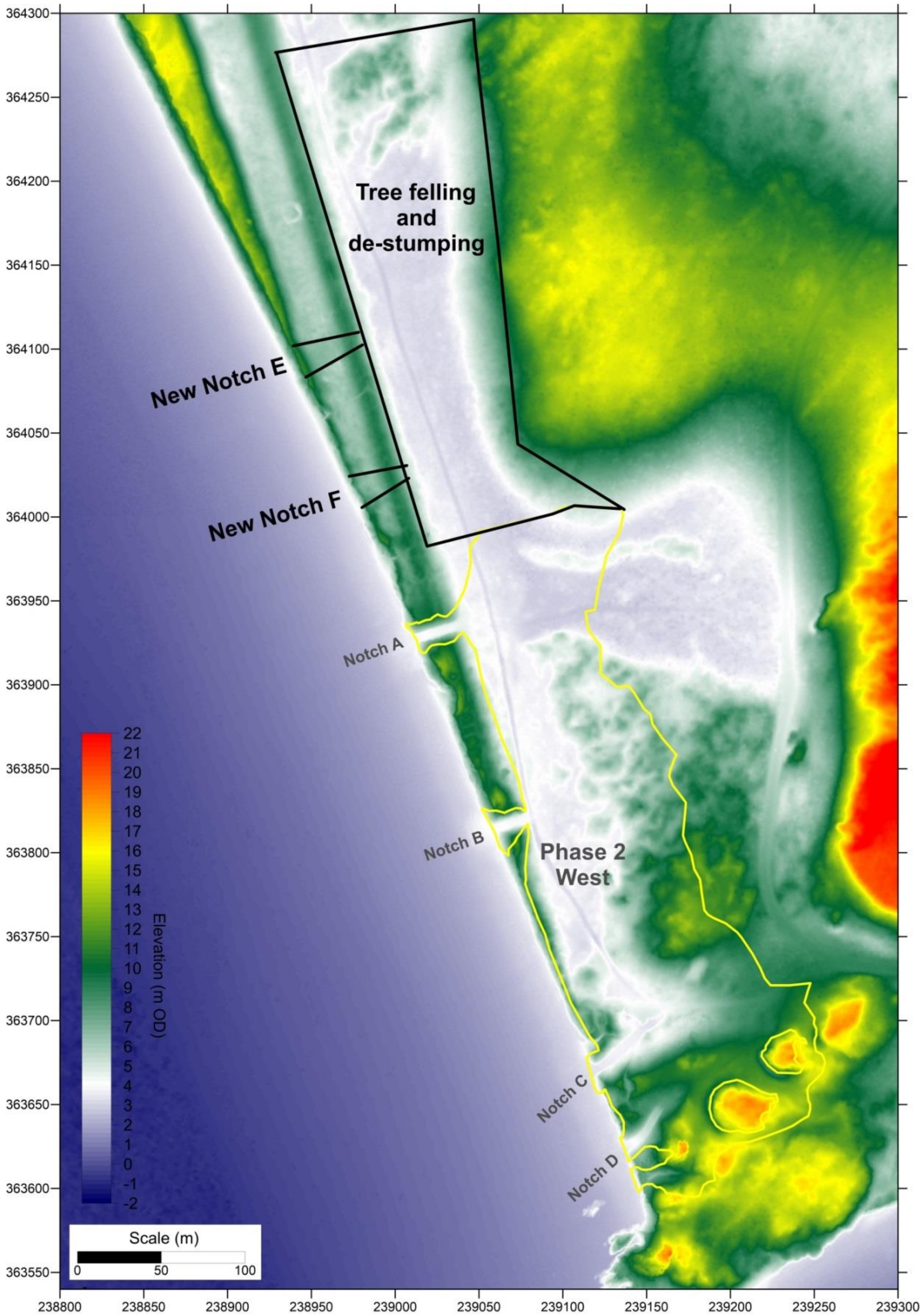


Figure 94. Proposals for further intervention works at Newborough Forest (Traeth Penrhos): (A) tree felling and de-stumping in the degraded frontal dune woodland area to the north of the Phase 2 clearance area; (B) creation of two additional notches in the frontal dune to link the beach with the additional forest clearance area, each notch having a trapezoidal plan form and relatively steep seaward gradient to focus wind flow in both the horizontal and vertical dimensions

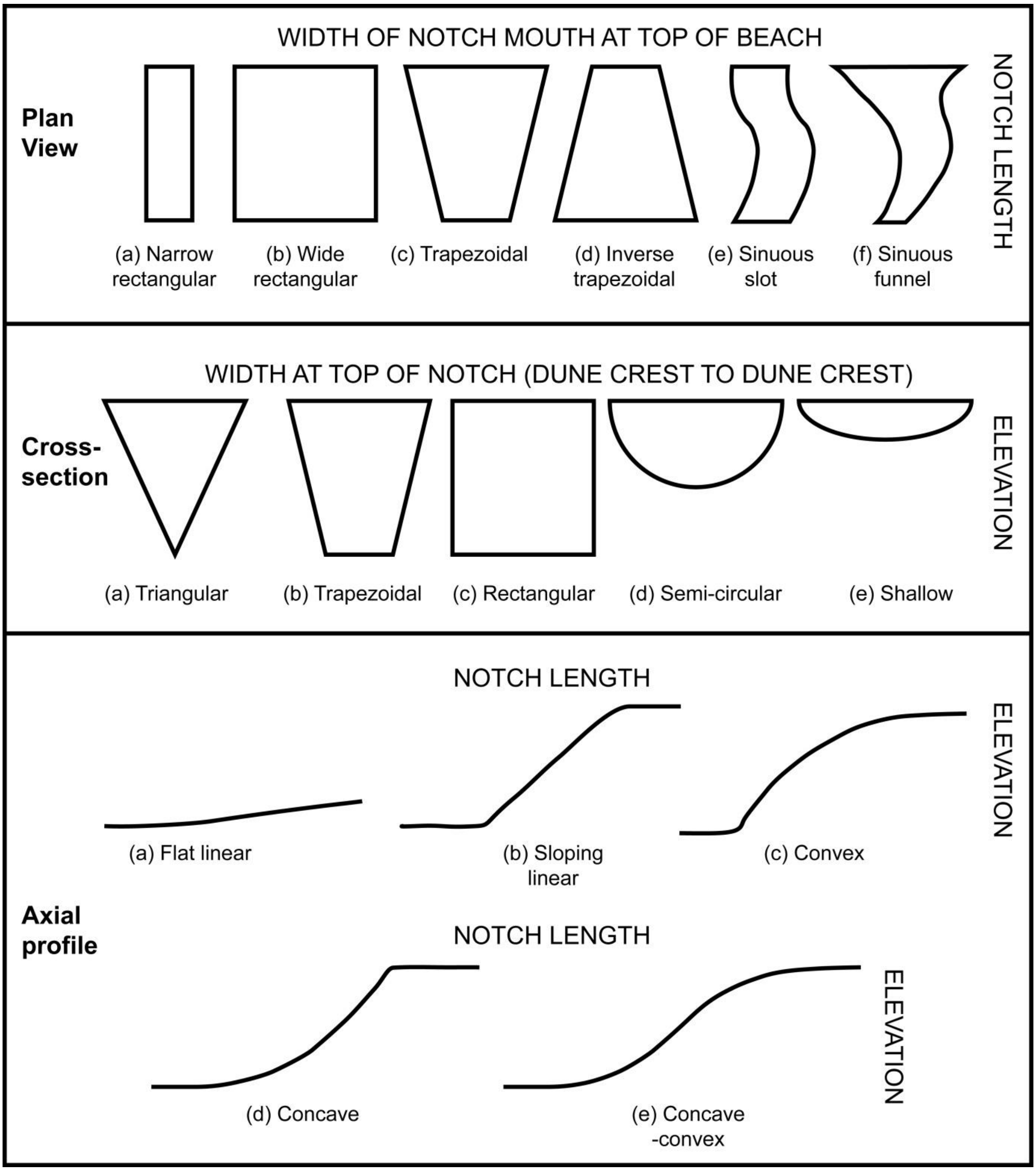


Figure 95. Conceptual diagram of different notch morphology, in terms of plan view, cross-section, and long section

Data Archive Appendix

Data outputs associated with this project are archived in [NRW to enter relevant corporate store and / or reference numbers] on server–based storage at Natural Resources Wales.

The data archive contains:

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

[B] Corrected UAV survey data for Merthyr Mawr, 29 February 2016

[C] Corrected UAV survey data for Kenfig Burrows, 02 March 2016

[D] Corrected UAV Survey data for Newborough Phase 1, Phase 2 West, Phase 2 East and Phase 3 areas, January 2016

[E] KPALRTK GPS Survey data, February 2016

[F] Composite LiDAR DEMs for Kenfig, Merthyr Mawr and Newborough (2009, 2014, 2015)

[G] Revised composite UAV DEMs for Kenfig, Merthyr Mawr and Newborough

[H] Shape files of bare sand areas for each survey at Kenfig, Merthyr Mawr and Newborough

[I] Shape files of proposed areas for additional rejuvenation works at Kenfig, Merthyr Mawr and Newborough

Metadata for this project is publicly accessible through Natural Resources Wales' Library Catalogue https://libcat.naturalresources.wales (English Version) and https://catllyfr.cyfoethnaturiol.cymru (Welsh Version) by searching 'Dataset Titles'.
Data outputs associated with this project are archived in project 481, media 1558 on server–based storage at Natural Resources Wales.

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