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Dynamic dune restoration: Site-specific variability in sediment transport and soil response following notch creation

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ABSTRACT

Coastal sand dunes are dynamic systems that provide critical ecosystem services, yet decades of stabilisation have led to widespread loss of bare sand habitats and associated biodiversity. Restoration efforts increasingly focus on re-establishing dune mobility through interventions such as foredune notch creation, which can enhance inland sand transport. However, the effectiveness of these interventions remains poorly understood, and cross-site comparisons are rare. This study evaluates changes in sediment dynamics and soil characteristics following notch interventions across multiple dune systems in Wales. Sand flux was monitored using sand-rain collectors along intervention and control transects at 50 m, 100 m, and 200 m inland, and soil properties (bulk density, organic matter, calcite, and pH) were measured before and after intervention. Results indicate strong site-specific variability in sediment response. At Aberffraw, sand flux increased by over +200 g m^{-2} day^{-1} at 50 m, while Merthyr Mawr showed more localised increases (+30 g m^{-2} day^{-1}), and minimal changes were observed at Kenfig and Pembrey (<10 g m^{-2} day^{-1}). Across all sites, a generalised linear mixed model indicated an approximately fivefold increase in sand flux at intervention transects relative to controls. Soil responses were more limited, with modest but statistically detectable changes, including a 29% reduction in organic matter (OR ≈ 0.71) and small increases in calcite content. These findings demonstrate that foredune notching can enhance aeolian sediment transport but resulting soil changes are modest and highly site dependent. The study highlights that intervention effectiveness is governed by interactions among wind regime, sediment supply, and system configuration, emphasising the need for site-specific, process-based approaches to dune restoration.

1. Introduction

Coastal sand dunes are dynamic landforms that provide critical ecosystem services, including coastal protection, biodiversity support, and cultural functions (e.g., Rodriguez-Revelo et al., 2018; Everard et al., 2010). Sand dunes are also attractive landscapes for tourism and recreation (Richardson and Nicholls, 2021). However, people's perceptions of coastal dune systems have changed over time, and so has the focus of their management (Vina et al., 2024). Globally, these systems have undergone profound change over the past century, driven by both natural processes and human interventions. Coastal zones are increasingly shaped by anthropogenic pressures, with recent large-scale analyses showing that human activities account for most observed landscape change, often exceeding 75% of total transformation (Yan et al., 2026). These changes are driven by urban expansion, land reclamation, and intensified marine resource use, fundamentally altering sediment dynamics, vegetation patterns, and coastal geomorphology. Understanding how management interventions operate within such human-dominated systems is therefore critical for assessing restoration effectiveness.

Since the 1950s, widespread stabilisation efforts such as vegetation planting, dune afforestation and reduction in traditional management methods, coupled with atmospheric nitrogen pollution and changing climatic conditions, have led to increased dune stability and vegetation cover (Provoost et al., 2011; Pye et al., 2014; Gao et al., 2020). This has resulted in the loss of open sand habitats, with nearly 95% of bare sand disappearing in northwest Europe (Provoost et al., 2011), although the magnitude and timing of these changes vary considerably between sites

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depending on land use, management, and sediment supply. This shift has triggered ecosystem ageing, soil acidification, and a decline in rare pioneer species that depend on mobile, nutrient-poor substrates (Arens et al., 2013; Schwarz et al., 2019).

In dune systems, vegetation type and height, climate, and soil pH are significant factors in the rate of stabilisation, and subsequent soil development (Jones et al., 2010). Dune soils develop from an accumulation of organic matter, with vegetation cover providing leaf litter and root carbon inputs (Sevink, 1991). The rate of organic matter input is balanced by decomposition rates, which in turn are partly mediated by factors such as soil pH and climate. Once dune surface soils decalcify and the pH drops below 6.5, microbial communities tend to shift towards increasing dominance by fungi and decomposition processes become slower (Kooijman et al., 2020). This leads to faster soil development once soils start to acidify. Climate controls soil development in two ways, by altering plant production and its associated litter input, and by moderating decomposition rates of organic material (Conant et al., 2011). Once an initial organic layer begins to form, the improved water holding capacity can partially alleviate summer drought controls on plant growth, thereby leading to increased plant production (Sevink, 1991). In general, the quantity of soil organic matter tends to increase with vegetation succession (Jones et al., 2008).

Sand transport in coastal dune systems is governed by a combination of aerodynamic processes, vegetation–flow interactions, and spatially variable sediment supply (Bagnold, 1937; Hesp, 2013; Delgado-Fernandez, 2011). Vegetation plays a key role in modifying near-surface airflow, reducing wind velocity and altering turbulence structures, thereby influencing sediment entrainment and deposition patterns (Wolfe and Nickling, 1993; Liu et al., 2025). At the same time, sediment transport is highly sensitive to the spatial organization of the system, with even subtle differences in surface structure, roughness, and connectivity leading to disproportionate changes in transport behaviour (Dai et al., 2020). This sensitivity is further compounded by the complexity of sediment source-to-sink pathways, whereby sediment supply reflects the integration of multiple contributing sources, transport routes, and reworking processes (Bauer et al., 2009; Lin et al., 2024; Bauer et al., 2025). Consequently, dune systems should be understood as spatially heterogeneous and dynamically coupled environments. The ecological consequences of dune stabilisation are increasingly recognised in the context of climate change. Rising sea levels, intensifying storms, and altered sediment budgets threaten coastal resilience, making the restoration of natural dune dynamics a priority for nature-based adaptation strategies (Hesp and Walker, 2013; van IJzendoorn et al., 2021). Mobile dunes act as buffers against extreme events and maintain biodiversity hotspots, yet their restoration requires re-establishing aeolian connectivity between beaches, foredunes, and inland dune slacks (Arens et al., 2013; Ruessink et al., 2018). Recent management approaches in Europe have therefore shifted towards creating self-sustaining dynamic systems through interventions such as vegetation removal, slack excavation, and foredune notch creation (Laporte-Fauret et al., 2021a, 2021b; Nguyen et al., 2022).

Foredune notches are designed to enhance sediment transport inland by creating gaps that allow wind-driven sand movement (Fig. 1). These interventions aim to rejuvenate soils with calcareous beach sand, counteracting long-term acidification and organic matter accumulation. However, the success of notch creation varies widely and depends on factors such as notch geometry, wind regime, beach sediment supply, and vegetation feedbacks (Riksen et al., 2016; Sanromualdo-Collado

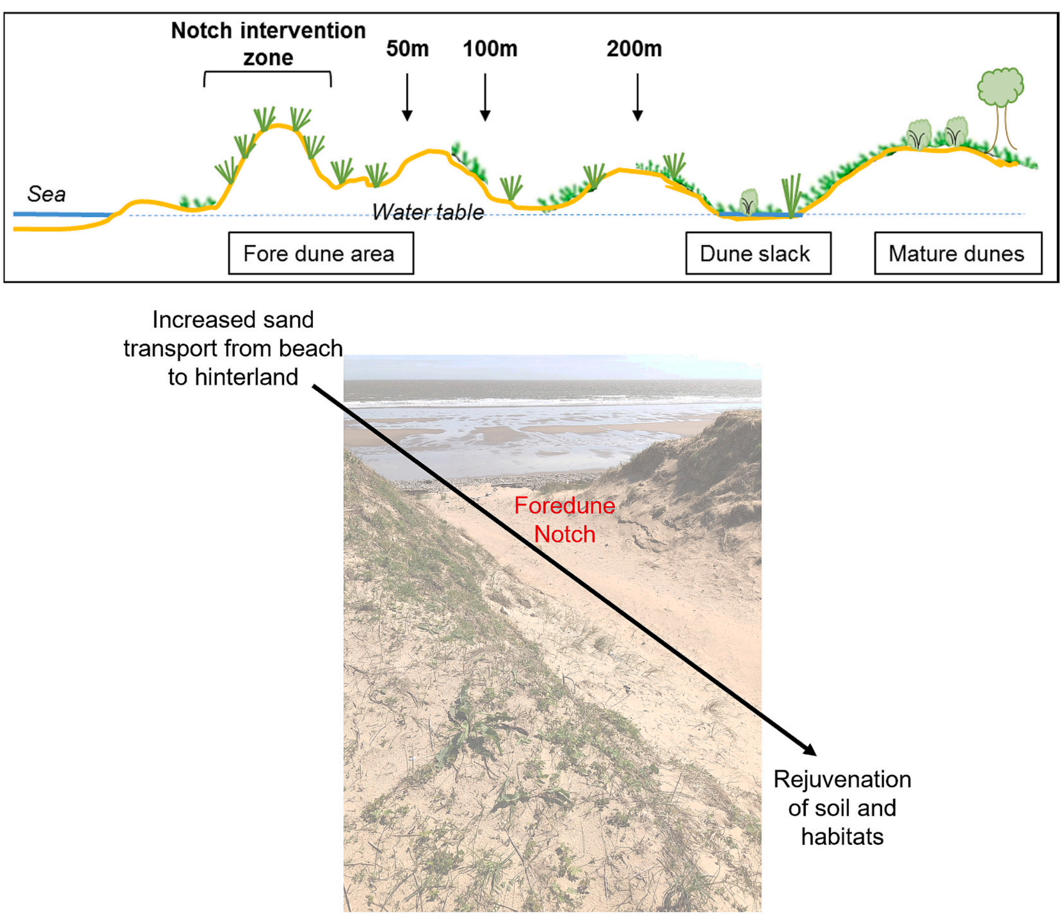

Fig. 1. Conceptual overview of a dune system showing the notch intervention zone and transect locations, alongside an example photograph of a foredune notch taken at Kenfig.

et al., 2022). Despite growing interest in dynamic dune restoration, there remain significant knowledge gaps regarding the mechanistic drivers of notch performance and their long-term ecological outcomes.

We addressed these gaps by monitoring changes in sediment flux, particle characteristics, and soil properties following notch interventions across multiple Welsh dune systems. At each site, we monitored a control transect without a notch and conducted pre-intervention and post-intervention monitoring for at least one year in each period to control for other factors influencing sand deposition. By linking physical processes to soil chemistry, this study aims to evaluate the effectiveness of foredune notches in enhancing aeolian sand transport and reversing soil acidification. We hypothesise that notch creation enhances inland sediment flux, with the potential to increase sediment supply to dune systems and initiate changes in surface soil conditions that would benefit early-successional species.

2. Methods

2.1. Site descriptions

Soil and sand-rain monitoring was established at five dune systems in Wales: Tywyn Aberffraw and Newborough in North Wales, and Kenfig, Merthyr Mawr, and Pembrey Burrows in South Wales (Fig. 2). However, the planned notch creation was not implemented at Newborough and only pre-intervention sand-rain data were collected there. Accordingly, Newborough is included only as a background site for comparison of baseline conditions across systems and was excluded from analyses of intervention effects.

2.1.1. Dune systems

The sand plain and dunes at Tywyn Aberffraw extend approximately 2.5 km inland. The western end of the beach comprises a triangular area of active dunes (around 250 m wide), which widens to about 1 km at the eastern end. The remainder of the area consists of sand plain and fixed dunes (May, 2003). The site was formerly grazed by sheep and, following a period without livestock after the 2001 Foot-and-Mouth outbreak, is now grazed by cattle and a fluctuating rabbit population. Additional disturbance arises from recreational use. The dunes at Tywyn Aberffraw are important for rare bryophytes and vascular plants such as early sand grass (*Mibora minima*).

Kenfig contains bare foredunes (approximately 4 ha, representing 0.5% of the total area; Pye et al., 2014), alongside more extensive areas of semi-fixed dunes dominated by marram and red fescue, and fixed dunes characterised by red fescue and lady's bedstraw (JNCC, 1990), as well as several important dune slack areas. The site is used for recreation and is partly managed for livestock grazing. Extensive remobilisation and rejuvenation work, including slack scraping and mowing to enhance habitat conditions for Fen orchid (*Liparis loeselii*), has been carried out over the past 5–10 years.

The Merthyr Mawr dune system includes transgressive (migratory) climbing dunes that extend inland, reaching heights of over 80 m in places. The area of bare sand has declined from approximately 39% in 1940 to 3.5% in 2009 (Pye and Blott, 2017). The site is open for recreation and is also grazed in parts by cattle and rabbits.

Newborough is an extensive and exposed dune system approximately 2 km wide. Around half of the dune system was planted with conifer woodland between 1949 and 1969, and despite retaining a mix of active and stable dunes, only about 6% of bare sand remained in 1991 (Jones et al., 2008; May, 2003). Dune crests typically reach around 10 m in height, although some are taller. The site has been grazed since the late 1980s by cattle and by ponies, as well as rabbits. A detailed account of the grazing history is provided in Plassmann et al. (2010). The dunes are extensively vegetated, although considerable remobilisation work in dune slacks has been undertaken in the last ten years. The planned notching for this study was unfortunately not implemented at Newborough, and no post-intervention monitoring was conducted. Data from this site were therefore used only for background comparison and were excluded from analyses of intervention effects.

Pembrey Burrows forms part of the Pembrey Coast dune system which contains a mixture of embryonic, semi-fixed, and fixed dunes extending approximately 10 km in length and up to 3 km in width. The northern part of the site is used for military training, although large areas are also open for recreation and some are managed for cattle grazing.

2.1.2. Wind data

Wind data were obtained from the Ogimet meteorological database, which provides archived hourly observations from World Meteorological Organization (WMO) surface stations. Three stations were selected based on proximity and exposure characteristics relevant to the study dune systems: Valley (WMO 03302; 53.250°N, −4.533°E; 10 m a.s.l.), Pembrey Sands (WMO 03605; 51.700°N, −4.367°E; 3 m a.s.l.), and St Athan (WMO 03716; 51.400°N, −3.433°E; 50 m a.s.l.). Valley was used as the representative wind record for the northern sites Aberffraw and Newborough, as it is a coastal location within 20 km of those two sites. Data from Pembrey Sands was used for Pembrey, and St Athan for the more easterly dune systems Merthyr Mawr and Kenfig. For each station, all available hourly observations covering the full duration of the study period were downloaded and subsequently divided into pre-intervention and post-intervention subsets according to the intervention date. Percentages were normalised within each panel.

To relate observed wind conditions to potential sand movement from the beach into the dune system, wind direction and speed data from the representative meteorological stations were used to characterise aeolian transport potential along each transect. The selected stations provide the nearest high-quality wind data, but local dune-toe winds may differ because of topographic and roughness effects and should therefore be interpreted as providing process context rather than direct site measurements. A threshold wind speed of 5 m s^{-1} was used as an approximate indicator of transport-effective conditions. Field observations indicate that aeolian transport and dune-forming processes can occur at wind speeds greater than or equal to 5–6 m s^{-1} when surface sediments are sufficiently dry (Nield et al., 2010; Liu et al., 2015), although the exact threshold varies with moisture and surface conditions (Bauer et al., 2009). Accordingly, wind roses were used to identify both (i) the proportion of winds exceeding the 5 m s^{-1} transport threshold and (ii) the directional alignment of those transport-effective winds with respect to the transects.

2.2. Field sampling

Pre-intervention baseline soil samples (June 2019) were taken along a transect starting at approximately 50 m distance inland from the scheduled dune re-profiling work at each site, and then at two further points (100 and 200 m) moving inland and along the prevailing wind direction and along a control transect. The intervention transects are labelled e.g., A1 and control samples are labelled e.g., AC. For each of the three sample points along each transect, a surface soil sample was taken using metal bulk density sampling rings of diameter 8 cm and depth 5 cm. Post-intervention soil sampling was conducted in May 2023 at the same distances along both the intervention and control transects, resulting in six soil samples per site for each sampling period.

After taking the initial soil samples a sand-rain collector designed to capture wind-blown sand (following designs in Goossens et al., 2000; Riksen et al., 2016) was installed at each of the three sample points along each transect. The sand-rain monitoring device consisted of a plant pot (diameter (top) 29.5 cm, depth 24 cm) inserted into the sand at ground level, with a sample bag liner and marble sieve top. The sample bag liners were adapted from rubble sacks and cut down to fit the pot size with three holes cut at the base to allow drainage. The drainage holes were covered with cotton material and held in place with cloth tape, to ensure no sand loss from the bag while allowing water to drain

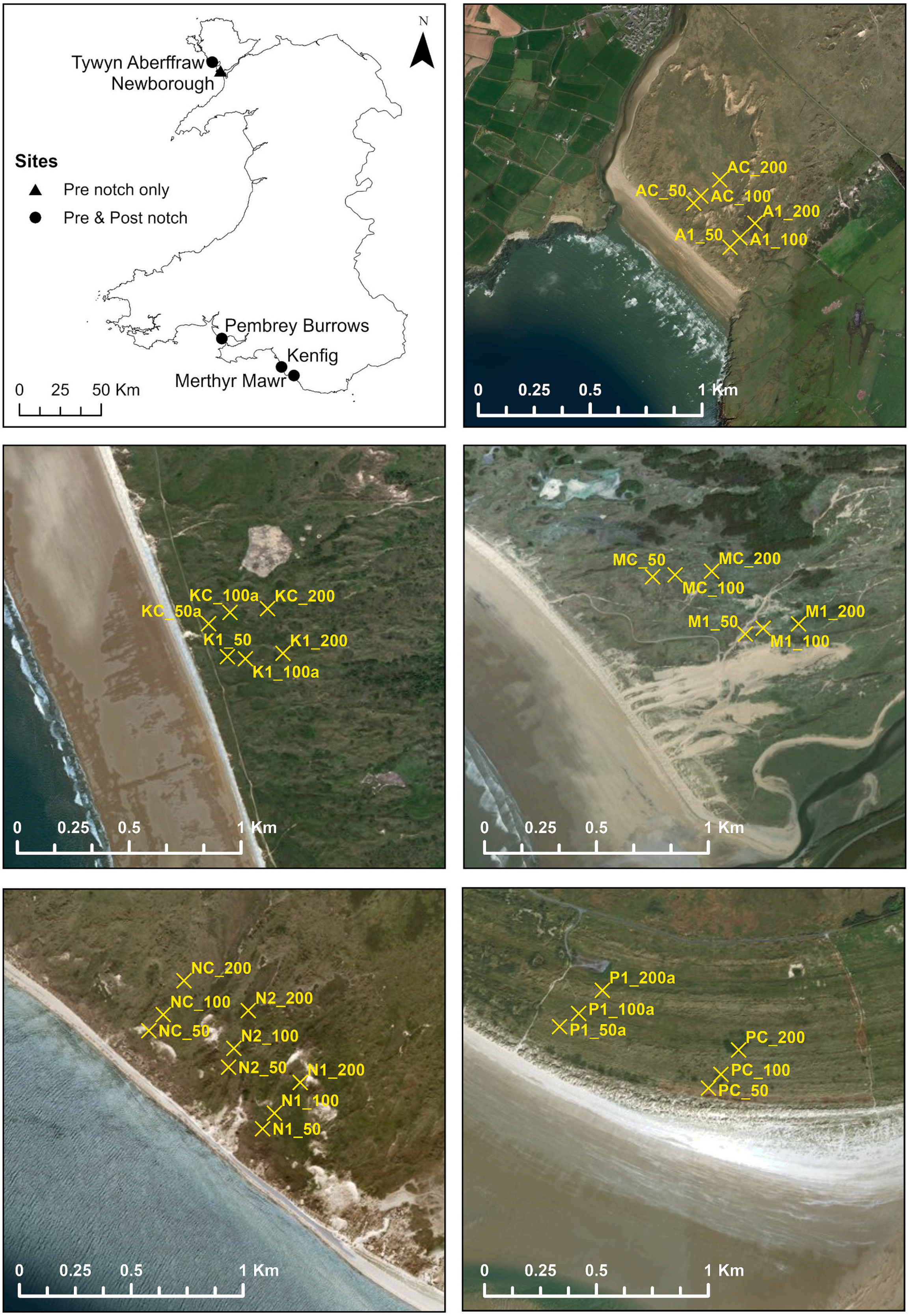

Fig. 2. Study site locations and transect layouts: (a) site locations on the Isle of Anglesey and in South Wales, UK; (b) Aberffraw; (c) Kenfig; (d) Merthyr Mawr; (e) Newborough; and (f) Pembrey. Background imagery courtesy of Esri World Imagery (Wayback 2019-05-15) and data providers.

out. The marble sieve filter consisted of a circular plastic sieve (diameter 29 cm, mesh size 1 cm) with two layers of round glass marbles (14 mm diameter). This filtered large particles and stopped sand from being blown out of the collector. A wire mesh with green matting (50 cm × 50 cm, mesh size 1 cm, secured with tent pegs) was placed over the marble filter to protect the collector from damage. The green matting provided a uniform area immediately surrounding the collector and reduced sand falling in from external edges. In addition, at Pembrey Burrows a cage (53 cm × 53 cm × 53 cm, mesh size 7.4 cm) was placed around each sand-rain collector to protect from damage by livestock.

On each collection date, sample bags were carefully removed and secured with an elastic band positioned to exclude sand deposited from the outer edges of the collectors. Bags were collected and replaced at three-month intervals from installation until the final post-intervention sampling in September 2023. Each trap was sampled six times during the pre-intervention period. Post-intervention monitoring continued for at least one year at each site, although the number of sampling intervals varied with the timing of the intervention works (Supplementary S1); for example, traps were sampled four times post-intervention at Aberffraw and ten times at Pembrey.

At some sites, unplanned disturbances altered the original sampling context. At Pembrey, multiple small notches were created, changing the distance between some transect points and the nearest notch relative to the initial design. Some transect locations at Pembrey were also influenced by pre-existing sea buckthorn scrapes, where fragile colonising vegetation was subsequently disturbed by grazing cattle, and a comparable unplanned scrape affected part of the Kenfig site. In addition, occasional disturbance to sand-rain collectors by livestock or other external factors was identified during field visits. These samples were excluded from the primary analysis as they do not represent aeolian transport under the parameters of the experimental design.

2.3. Laboratory analysis

2.3.1. Soil samples

The weight of soil per sample volume was calculated using the dimensions of the bulk density (BD) sampling ring (πr^2 x height in cm) and the weight of soil dried at 25 °C for 14 days, de-agglomerated and sieved through a 2 mm sieve. Subsamples of 20 g were subjected to thermogravimetric analysis (TGA, mass loss observed during the increase in furnace temperature) using a LECO TGA701 instrument. After first obtaining the soil moisture content by heating at 105 °C for 3.5 h (until constant weight) the instrument was then heated at 375 °C for 15 h and the percentage loss was recorded. The percentage calcite ($CaCO_3$) was determined following the Loss on ignition (LOI) analyses. The sample was further heated to 650 °C for 2 h (LECO TGA701) to remove any remaining non-calcite soil components, before then being heated to 1000 °C for 2 h to decompose calcite, and the weight of calcite was determined by difference. The pH was determined using a Corning 220 pH meter, VWR combination electrode 662–1805, to measure the 'pH de-ionised' (10 g soil in 25 ml de-ionised water).

2.3.2. Sand-rain analysis

Sample bags were cut immediately below the elastic band tie and were then air dried. The dried contents were sieved with a 500 μm mesh (Riksen et al., 2016) and weighed. For each sieved sample the sedimentation flux deposition was calculated from the weight of sieved sample/sample area (0.066 m^2) and total sampling time (days), expressed as g m^{-2} day^{-1}.

Particle size classes were determined with a laser diffraction particle size analyser (Beckman Coulter LS 13320). Organic matter was removed from a 0.5 g subsample by addition of H_2O_2 (hydrogen peroxide) and multiple heating cycles and then 5 ml of 5% Calgon solution was added. Following a thorough shaking of the samples they were transferred to the particle size analyser. Sediment was classified into 38 classes between 0 and 2000 μm. Analysis of the percentage $CaCO_3$ was conducted on the same selection of samples.

2.4. Statistical analysis

Sand flux data were analysed using two complementary approaches. First, site- and distance-specific difference-in-differences (DiD) contrasts were computed as $(\text{Post–Pre})_{\text{Intervention}} - (\text{Post–Pre})_{\text{Control}}$ to provide descriptive effect sizes controlling for baseline differences and system-wide temporal change. Approximate 95% confidence intervals were derived from pooled standard errors of the four contributing group means, assuming independence between groups. Because flux was measured repeatedly at fixed trap locations over multiple collection intervals, these confidence intervals should be interpreted as descriptive rather than inferentially rigorous; the propagated standard errors reflect variation across sampling occasions and trap locations within each Site × Distance × Treatment × Period cell rather than independent spatial replication alone.

Second, a generalised linear mixed model (GLMM) was fitted to the flux data using a Tweedie distribution with log link to accommodate continuous, right-skewed, strictly positive flux values. Fixed effects included period (Pre/Post), treatment (Control/Intervention), distance from the dune toe as a continuous covariate (m), and their interactions, with site included as a fixed effect. A random intercept was specified for transect to account for repeated sampling at fixed trap locations. Coefficients were exponentiated to report multiplicative effect sizes (ratios of mean flux) with 95% confidence intervals and Wald tests. Models were fitted using the glmmTMB package. Sand flux collectors were sampled at unequal intervals across sites due to variation in intervention timing; the number of post-intervention collection periods ranged from four at Aberffraw to ten at Pembrey, and this imbalance is reflected in the site-level contribution to the mixed-model estimates. Counts of excluded observations associated with disturbance or altered sampling context are provided in Supplementary Table S1.1.

For soil properties, linear mixed-effects models (LMMs) were fitted separately to each response variable using lmerTest. Bulk density and pH were modelled assuming Gaussian errors. Percentages $CaCO_3$ and LOI were analysed as proportional responses: values were linearly rescaled to (0.005, 0.995) prior to logit transformation to avoid boundary values, and LMMs were then fitted on the logit scale; exponentiated coefficients are reported as odds ratios. Fixed effects included period × treatment × distance, with distance treated as a within-transect repeated factor with three levels (50, 100, and 200 m). Transect was specified as a random intercept and represents the unit of replication.

Soil sampling comprised a single intervention transect and a single control transect per site, each sampled at three distances and two time points. Mixed-model results for soil properties should therefore be interpreted as indicative of trends rather than as inferentially robust estimates, given the absence of within-site spatial replication at the transect level. Confidence intervals and *p*-values for the soil models should consequently be interpreted with caution.

Model adequacy was assessed using simulation-based residual diagnostics (DHARMa), including tests for dispersion, zero inflation, and residual uniformity; no substantial deviations from model assumptions were detected. Newborough was excluded from DiD and mixed-model analyses because no notch intervention was implemented and no post-intervention data were available.

3. Results

3.1. Sand flux

Table 1 presents summary statistics for daily sand flux across sites, periods, and treatments based on the cleaned dataset used in the analyses (a more detailed data table is included in Supplementary Table S1.2). These descriptive data provide context for the patterns shown in Fig. 3 and for the site- and distance-specific DiD contrasts

Table 1
Summary statistics for daily sand flux calculated across distances and multiple sampling periods.

Site	Period	Treatment	n	Mean ± SD ($g\ m^{-2}\ day^{-1}$)	Median [IQR] ($g\ m^{-2}\ day^{-1}$)
Aberffraw	Pre	Control	18	2.5 ± 2.7	1.9 [0.8–3.0]
Aberffraw	Pre	Intervention	17	16.3 ± 28.0	6.0 [2.9–12.6]
Aberffraw	Post	Control	11	1.6 ± 1.2	1.3 [0.8–2.0]
Aberffraw	Post	Intervention	10	148.2 ± 154.5	80.5 [13.3–273.9]
Kenfig	Pre	Control	16	2.9 ± 5.3	0.9 [0.4–2.7]
Kenfig	Pre	Intervention	18	0.2 ± 0.1	0.2 [0.1–0.3]
Kenfig	Post	Control	18	3.2 ± 4.4	1.0 [0.4–4.0]
Kenfig	Post	Intervention	15	0.4 ± 0.4	0.2 [0.1–0.7]
Merthyr Mawr	Pre	Control	18	0.6 ± 0.9	0.3 [0.1–0.5]
Merthyr Mawr	Pre	Intervention	18	5.2 ± 5.1	2.9 [1.6–7.2]
Merthyr Mawr	Post	Control	20	0.6 ± 1.7	0.2 [0.1–0.3]
Merthyr Mawr	Post	Intervention	20	13.1 ± 24.9	2.4 [1.4–11.6]
Newborough*	Pre	Control	18	38.8 ± 53.3	20.1 [7.2–42.7]
Newborough*	Pre	Intervention	36	52.9 ± 66.4	26.2 [7.8–74.2]
Pembrey	Pre	Control	17	9.0 ± 5.6	9.0 [4.3–13.3]
Pembrey	Pre	Intervention	16	9.9 ± 10.7	7.6 [4.0–11.9]
Pembrey	Post	Control	19	5.4 ± 4.5	3.7 [2.6–7.0]
Pembrey	Post	Intervention	26	7.1 ± 8.2	3.9 [1.6–9.2]

* Newborough contributed pre-intervention background data only and was excluded from intervention-effect models. All values are based on the cleaned dataset used in statistical analysis. Mean ± SD and median [interquartile range] are shown to summarise central tendency and variability.

reported. Sand flux differed substantially among sites. Mean post-intervention flux at the intervention transects was 148.2 $g\ m^{-2}\ day^{-1}$ at Aberffraw, 0.4 $g\ m^{-2}\ day^{-1}$ at Kenfig, 13.1 $g\ m^{-2}\ day^{-1}$ at Merthyr Mawr, and 7.1 $g\ m^{-2}\ day^{-1}$ at Pembrey. The DiD metric represents the intervention-attributable change from pre- to post-intervention after subtracting any background change observed in the controls. The DiD analysis confirms strong site-specific variability in intervention effectiveness. Aberffraw exhibited the largest positive effects, with an estimated increase of over +200 $g\ m^{-2}\ day^{-1}$ at 50 m and + 190 $g\ m^{-2}\ day^{-1}$ at 100 m, far exceeding changes observed in controls. At Merthyr Mawr, the effect was moderate at 50 m (+31 $g\ m^{-2}\ day^{-1}$) but diminished inland. Kenfig showed negligible or negative effects at 50 m and only small gains at 100 m. Pembrey displayed minimal intervention impact, with slight positive changes at 200 m.

When analysed across all sites, the mixed-model analysis provided clear evidence that the notching intervention increased aeolian sand transport, with several interaction terms indicating treatment-specific changes over time and distance. The Tweedie GLMM showed that fluxes were substantially higher at intervention sites in the post-intervention period, with treatment increasing sand flux by a factor of five relative to controls (Estimate = 1.61, $p = 0.017$). Importantly, the significant period × treatment term (Estimate = −1.56, $p = 0.002$) indicated that this treatment effect was absent before the intervention and emerged only afterwards. Flux declined strongly with increasing distance from the dune toe (Estimate = −0.0115, $p < 0.001$), yet the near-significant three-way interaction (period × treatment × distance; Estimate = 0.0069, $p = 0.057$) suggests that the inland decline became slightly shallower at intervention sites following the intervention. Site-level differences were also evident, with Newborough exhibiting substantially higher fluxes and Kenfig and Merthyr Mawr lower fluxes relative to the reference site (Aberffraw).

3.2. Particle characteristics of blown deposits

Particle size distributions of the deposits collected from traps along each transect at 50 m, 100 m, and 200 m before and after intervention are shown in Fig. 4. The y-axis indicates the percentage of the total sample within each particle-size bin. Control and intervention particle-size distributions at each site were broadly similar. Particle-size distributions differed more strongly between sites, with some sites containing coarser material than others. Although all distributions showed bimodal patterns with primary peaks between approximately 100 and 300 μm, temporal comparisons suggested a tendency towards finer particles post-intervention at A1, KC, and K1, particularly at 50 m. Other sites, however, showed minimal differences between pre- and post-intervention periods. Distance effects were also inconsistent. For example, at KC and MC, distributions at 200 m had broader or shifted peaks relative to closer distances, whereas at AC and A1, finer fractions were more pronounced at 50 m.

Across all transects, $CaCO_3$ displayed relatively low and spatially heterogeneous values, with no consistent directional change with distance from the beach (Supplementary S2). While minor fluctuations occurred at individual distances along some transects, there was no clear or systematic increase or decrease attributable to the intervention.

3.3. Soil surface characteristics

Across all soil transects, the descriptive patterns in BD, $CaCO_3$, LOI and pH generally showed modest spatial variability and limited pre- to post-intervention differences when examined visually. Control sites remained largely stable across time, whereas intervention sites exhibited slightly greater variability, but without strong directional trends in the raw data. However, mixed-model analyses revealed early but statistically detectable shifts at intervention transects.

Calcite concentrations in the soil remained low across most transects, particularly at control sites, which showed minimal temporal change (Fig. 5). Some intervention sites, notably A1, K1, and M1, displayed higher $CaCO_3$ levels, though with only minor changes over time. Despite this, the mixed-model results indicated a significant period × treatment interaction, with intervention plots showing elevated calcite levels relative to controls. At 50 m, the odds ratio for $CaCO_3$ proportion was 1.34 (95% CI: 1.02–1.76, $p = 0.037$), indicating subtle but measurable enrichment of calcite material. At Aberffraw, this enrichment was particularly pronounced at 100 m.

Organic matter content exhibited the highest spatial heterogeneity among the measured soil properties (Fig. 6). Control sites consistently showed low LOI (<10%), while several intervention sites displayed considerably higher values pre-intervention compared to post-intervention. The mixed model output demonstrated a significant decline in LOI at intervention sites relative to controls (OR = 0.71, 95% CI: 0.55–0.91, $p = 0.008$). Spatially, patterns varied by site.

Bulk density remained broadly consistent across control sites. Intervention transects however displayed greater site-specific variation (Fig. 7). Modest increases were visible along the transects at A1, M1 and P1, but the changes were not spatially uniform nor followed a trend with distance. Mixed-model analysis confirmed a small but statistically significant increase in BD under intervention conditions (estimate = +0.15 g m-3, 95% CI: 0.04–0.26, $p = 0.011$). At Aberffraw, these increases were most pronounced at 100 m, coinciding with calcite enrichment and LOI decline.

Soil pH remained relatively stable, with minimal temporal or spatial variation. No significant trend was detected by the mixed-model analysis (Supplementary S3). Nonetheless, site-specific deviations occurred, with slight pH increases at the 100 m transect point at Aberffraw post-intervention, whereas pH at Merthyr Mawr decreased slightly across the transect. This indicates that pH responses, where present, were subtle and context dependent.

3.4. Wind analysis

Wind direction and speed data were summarised as wind roses,

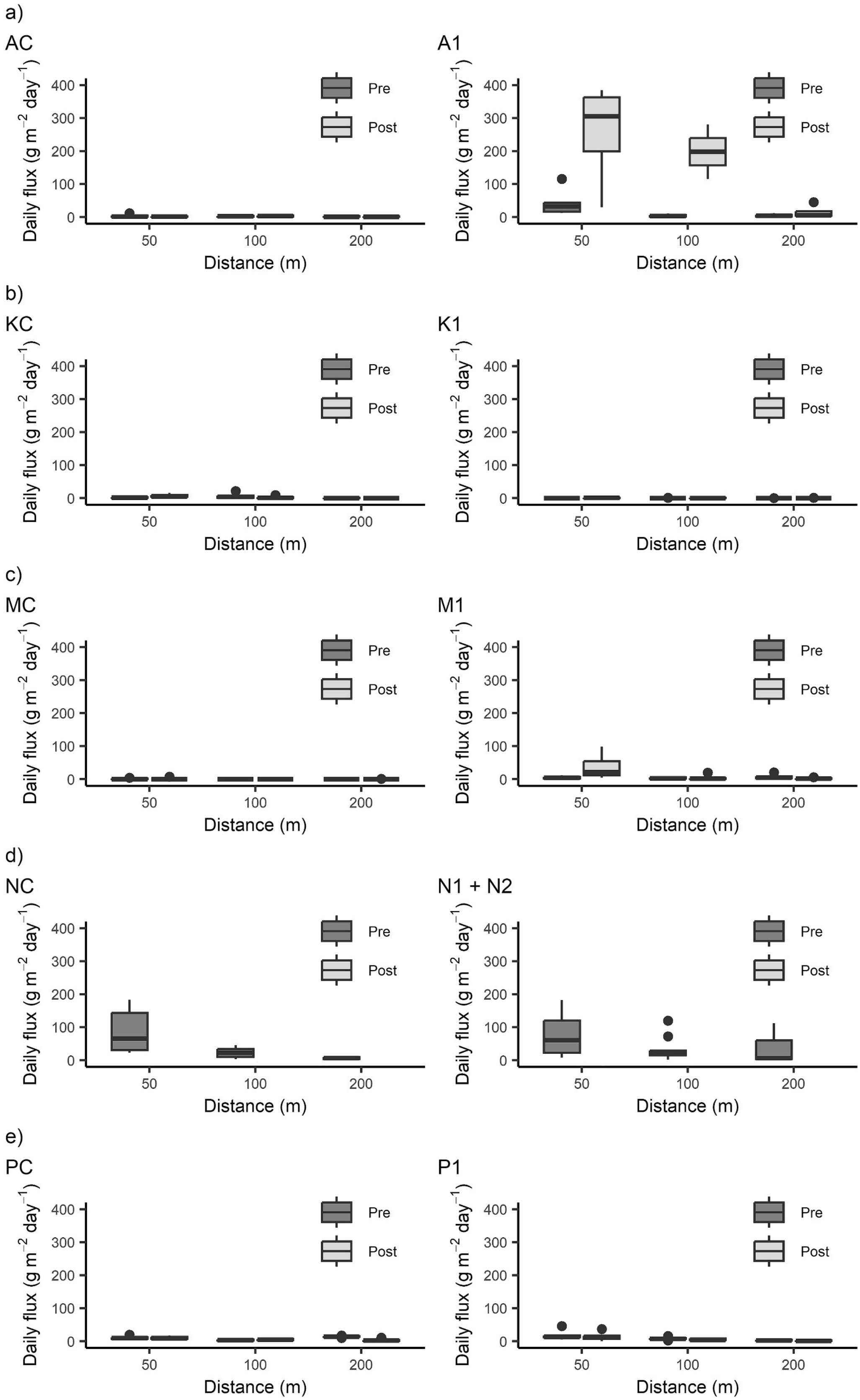

Fig. 3. Boxplot of daily sand flux coloured by pre- and post-intervention period and grouped by control and intervention transects for each site. No post-intervention data were collected at Newborough, and pre-intervention data from the two planned notch transects (N1 and N2) were pooled.

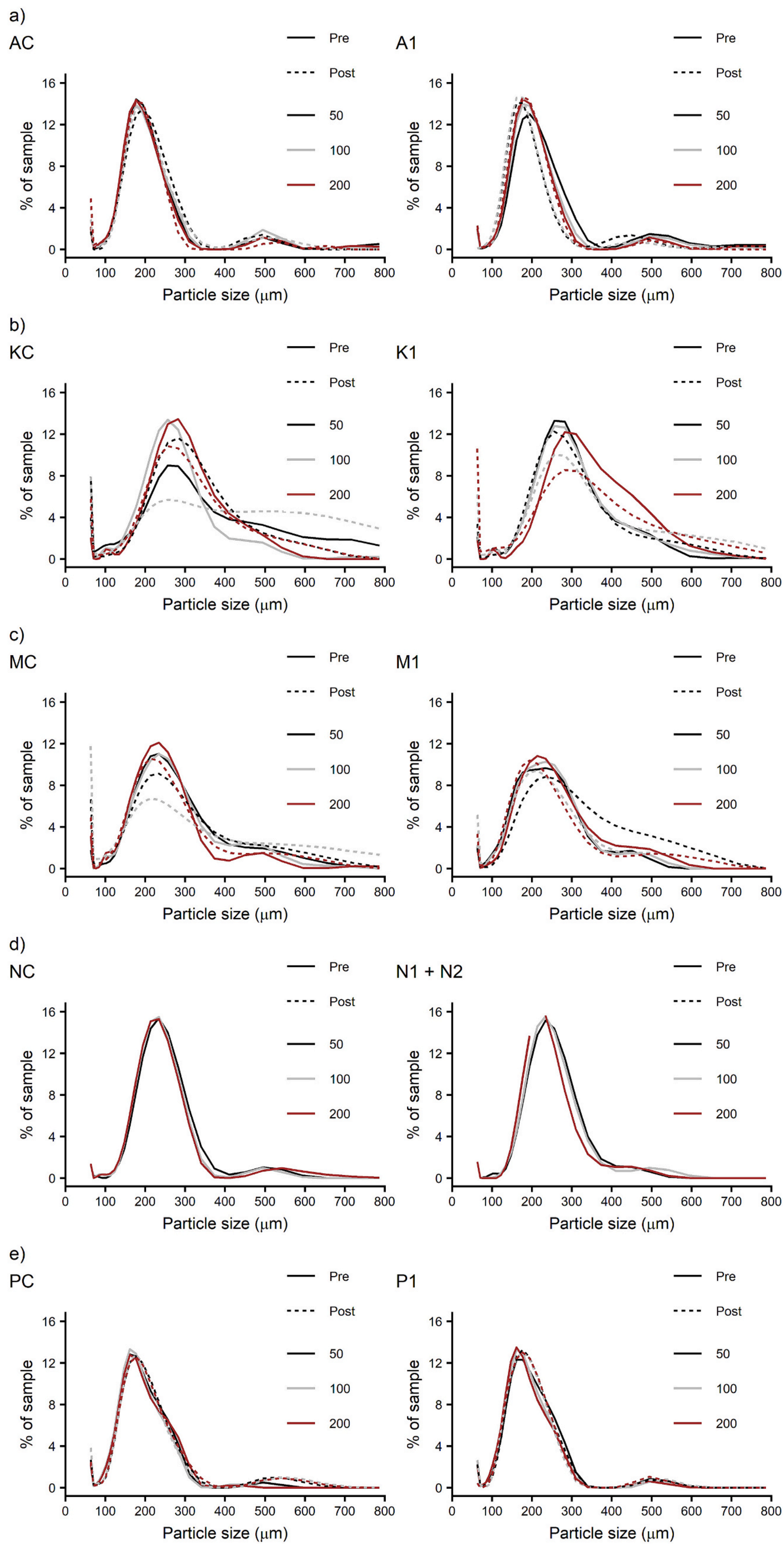

Fig. 4. Particle size distributions of sand deposits collected at three transect distances (black = 50 m, grey = 100 m, red = 200 m) during the pre-intervention (solid lines) and post-intervention (dashed lines) periods. No post-intervention data were collected at Newborough.

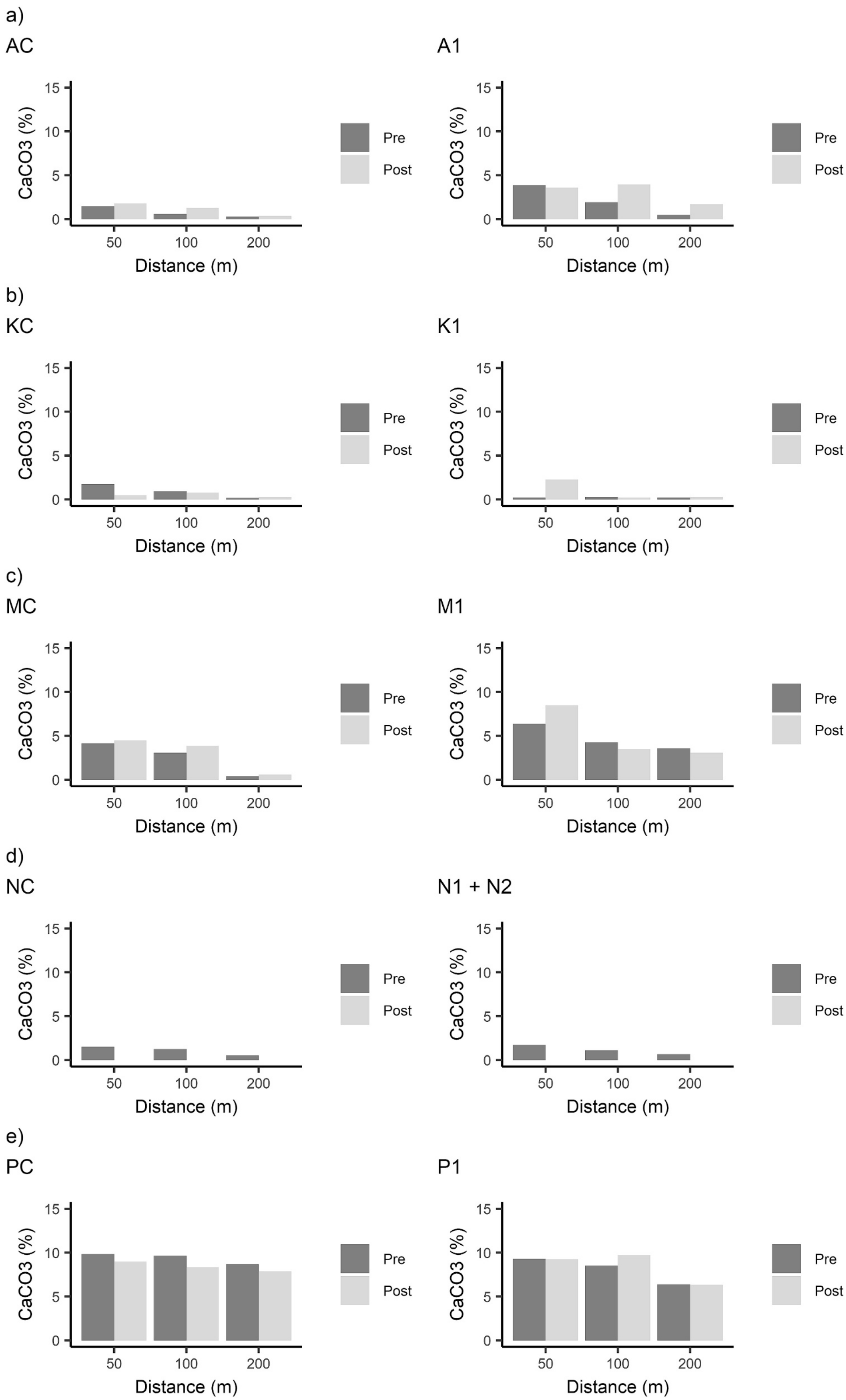

Fig. 5. Calcite ($CaCO_3$) content of soil samples collected along the control (C) and intervention (1) transects. No post-intervention data were collected at Newborough.

stratified by pre- and post-intervention period for each site (Fig. 8). The wind roses showed distinct site-specific directional regimes, with south-westerly dominance at Aberffraw, a bidirectional regime at Pembrey, and predominantly westerly to west-south-westerly winds at Merthyr Mawr and Kenfig. Wind direction and speed distributions were broadly similar between pre- and post-intervention periods at all sites. As no on-site meteorological stations were available, data from the nearest coastal stations were used as proxies.

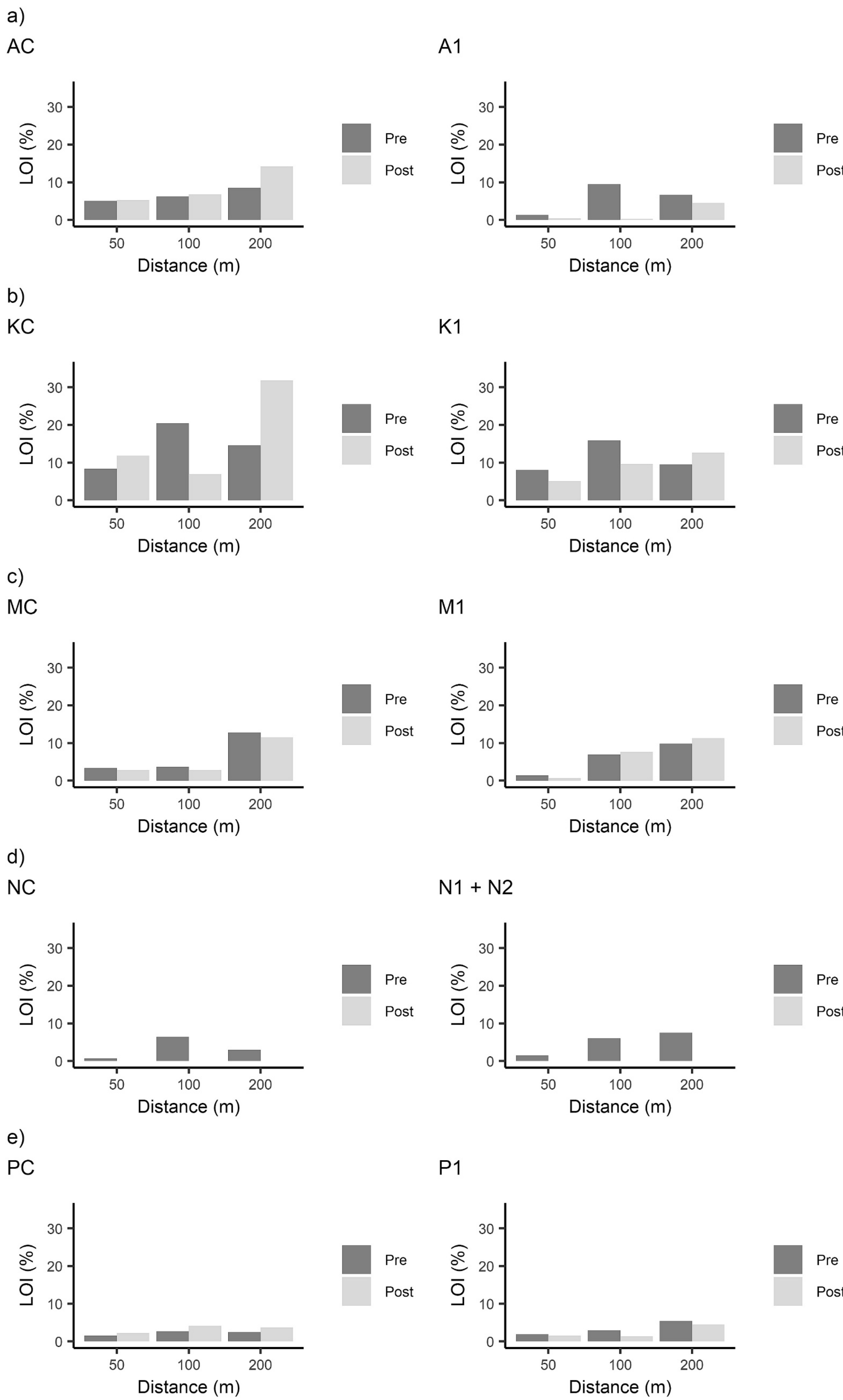

Fig. 6. Organic (LOI) content of soil samples collected along the control (C) and intervention (1) transects. No post-intervention data were collected at Newborough.

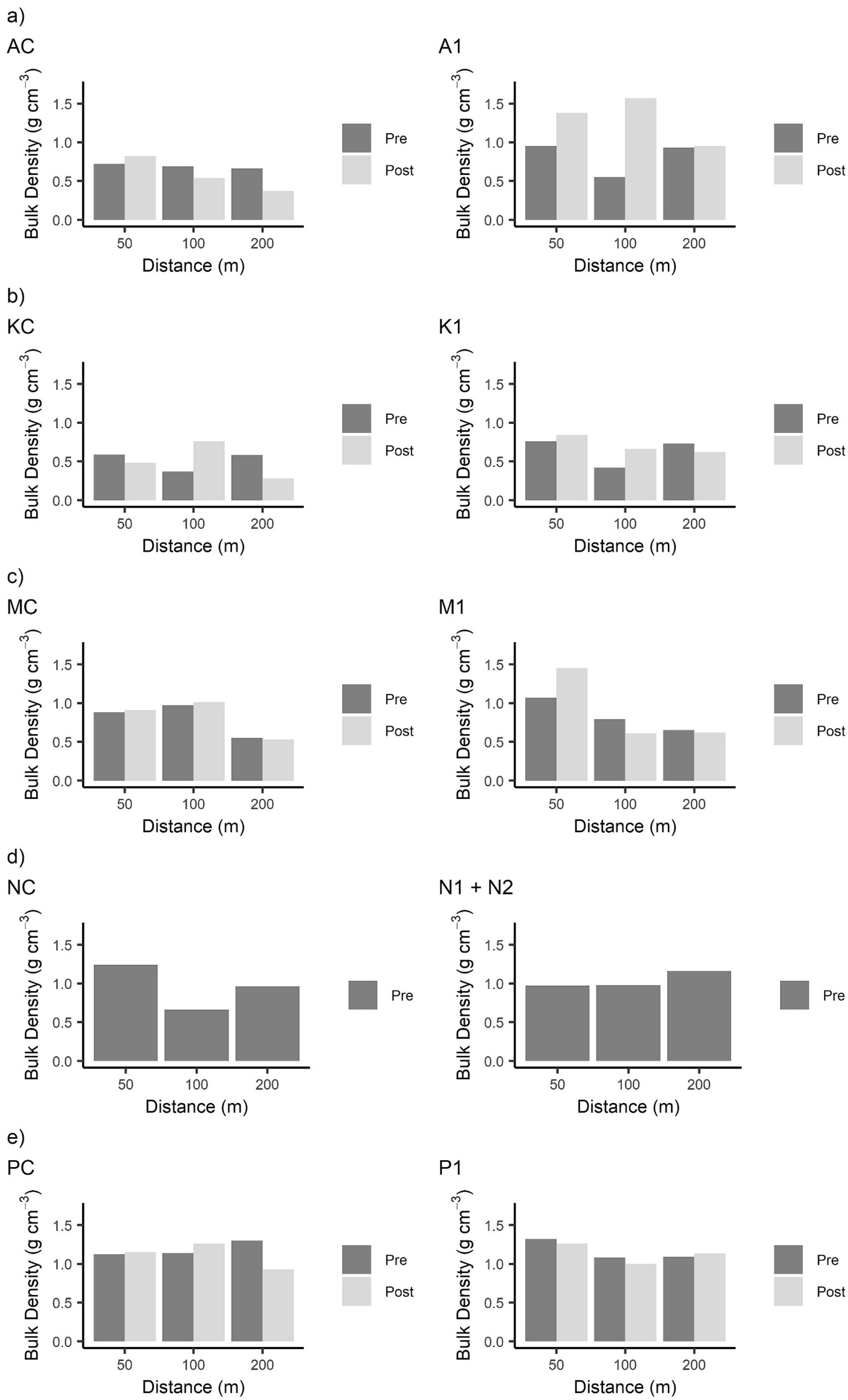

Fig. 7. Bulk density (BD) of soil samples collected along the control (C) and intervention (1) transects. No post-intervention data were collected at Newborough.

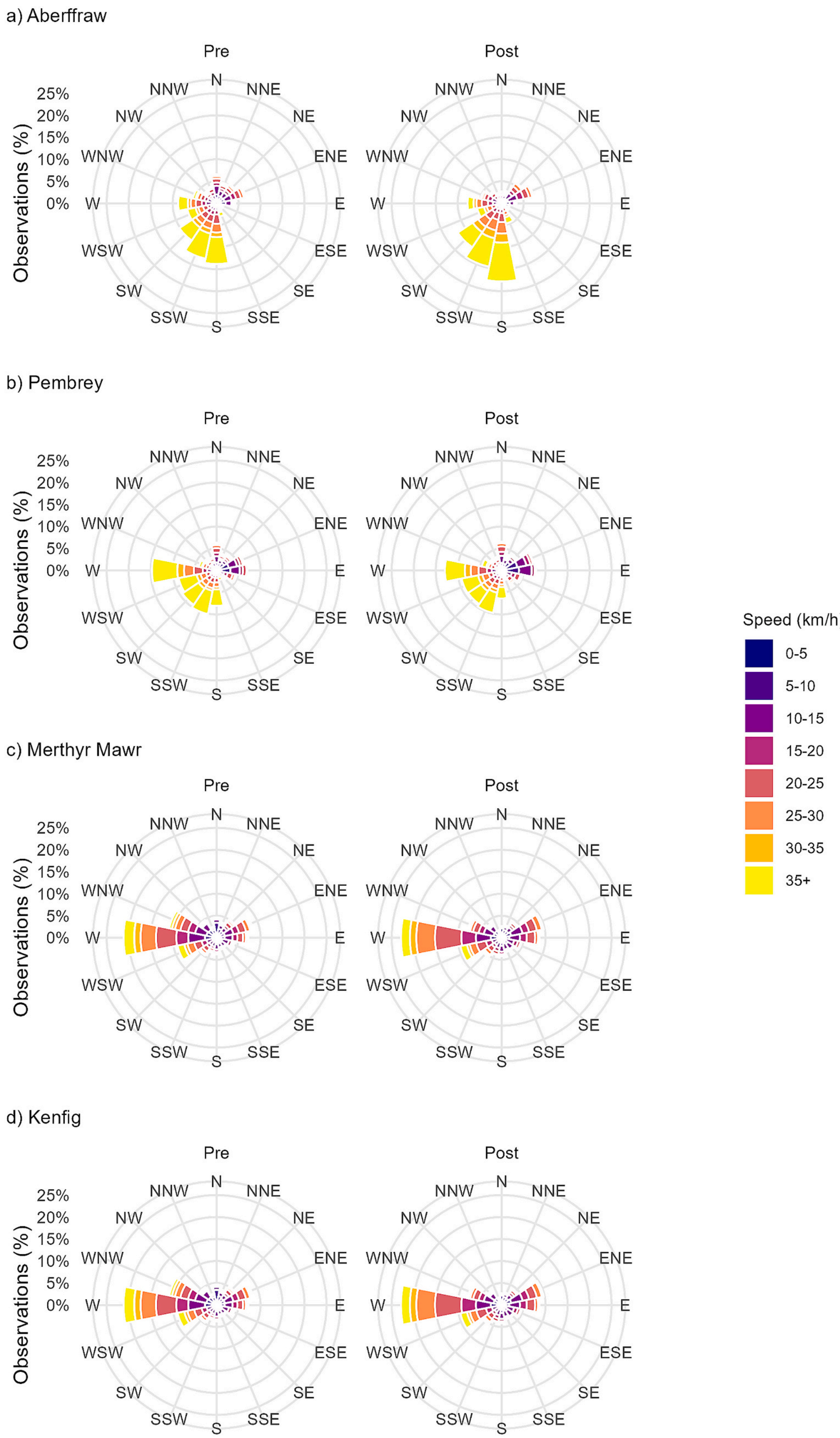

Fig. 8. Wind roses for the pre- and post-intervention periods at the meteorological stations used to represent each dune system: (a) Aberffraw (Valley station; intervention date: 30 September 2022), (b) Pembrey (Pembrey Sands station; intervention date: 28 February 2021), (c) Merthyr Mawr (St Athan station; intervention date: 31 October 2021), and (d) Kenfig (St Athan station; intervention date: 31 January 2022).

4. Discussion

4.1. Site-specific responses to foredune notching

Foredune notches are designed to create pathways for wind-driven transport of calcite-rich beach sand into the dune hinterland (Riksen et al., 2016; Ruessink et al., 2018). We anticipated that these interventions would increase sediment flux, particularly near the dune toe, with diminishing effects inland, and generate measurable changes in soil properties through deposition of calcareous sand.

Our results show that responses to notching were highly site-specific. Aberffraw exhibited substantial increases in aeolian transport (e.g. increases exceeding $+200$ g m^{-2} day^{-1} at 50 m), while Merthyr Mawr showed more localised effects confined to the area closest to the notch ($\approx +30$ g m^{-2} day^{-1} at 50 m). In contrast, Kenfig and Pembrey displayed minimal responses (typically <10 g m^{-2} day^{-1}), indicating that notch creation alone is insufficient to drive widespread dune reactivation under all conditions. Across sites, mean post-intervention intervention-transect fluxes ranged from 0.4 g m^{-2} day^{-1} at Kenfig to 148.2 g m^{-2} day^{-1} at Aberffraw, with intermediate values of 13.1 g m^{-2} day^{-1} at Merthyr Mawr and 7.1 g m^{-2} day^{-1} at Pembrey, highlighting the magnitude of inter-site variability.

Pre-intervention differences in sand flux largely persisted following intervention, indicating that the effects of notching were superimposed on existing system dynamics rather than overriding them. Sites with higher transport rates prior to intervention, such as Aberffraw, continued to show stronger responses, while sites with limited sediment supply or lower wind energy exhibited constrained change. This reinforces the need for both baseline data and control transects when evaluating restoration effectiveness.

Soil data indicate modest changes consistent with the early stages of mineral sand input and surface soil modification. At Aberffraw, increased calcium calcite, reduced organic matter (OR $\approx$ 0.71), and slightly higher bulk density are consistent with the deposition of mineral-rich beach sand onto older organic surfaces. At Merthyr Mawr, patchier changes suggest more spatially heterogeneous sediment deposition, while at Kenfig, limited change reflects restricted beach–dune connectivity and low sediment supply. However, the magnitude of these changes was relatively small and spatially variable, indicating that while sediment inputs are detectable, longer-term monitoring is required to determine whether these shifts translate into sustained soil and ecological recovery.

4.2. Process controls on aeolian transport and dune response

Differences in response among sites reflect interactions between wind regime, sediment availability, and system morphology. Wind direction and speed relative to dune orientation strongly influence transport potential, but sediment supply from the beach often acts as a limiting factor (Bauer et al., 2009; Delgado-Fernandez, 2011; Bauer et al., 2025). Sites with a higher proportion of transport-effective winds aligned with dune orientation (e.g. Aberffraw) corresponded to the largest observed increases in sand flux, highlighting the importance of directional wind forcing. At sites where sediment supply is restricted, such as Kenfig, however, even favourable wind conditions may not translate into significant inland transport.

More generally, these findings highlight the importance of treating dune systems as spatially heterogeneous sediment transport systems rather than uniform environments. Vegetation–flow interactions, surface roughness, and microtopography all influence local transport dynamics (Wolfe and Nickling, 1993; Liu et al., 2025), while sediment pathways integrate multiple source areas and transport processes (Kok et al., 2012; Lin et al., 2024). Particle size distributions were broadly similar between control and intervention transects, indicating a common sediment source, with a tendency for finer fractions to dominate at greater distances in line with expected aeolian sorting processes. As a result, relatively small differences in system configuration can lead to disproportionately large differences in transport behaviour.

The wind-rose analysis supports this interpretation. At Aberffraw, the prevailing wind was strongly south-westerly, directly onshore relative to the south-west-facing dune front, and this pattern remained consistent between pre- and post-intervention periods (Fig. 8). At Pembrey, the wind regime showed a bidirectional signature typical of the Bristol Channel corridor, with dominant south-westerly onshore winds and a secondary east-north-easterly component; the stronger wind speeds recorded there likely reflect the exposed position on Carmarthen Bay. The modest increase in the easterly component post-intervention at Pembrey is more likely to reflect seasonal differences in the composition of the two periods than a genuine shift in wind climate, given the early intervention date. At Merthyr Mawr and Kenfig, prevailing westerly and west-south-westerly winds were broadly alongshore relative to the south-facing dune fronts, meaning that the geomorphologically effective onshore component represents only a subset of total wind energy recorded at the station. Taken together, the broad stability of wind direction and speed distributions across periods suggests that differences in observed sediment and soil responses are unlikely to be explained by systematic changes in regional wind climate alone.

4.3. Implications for restoration design and system connectivity

These patterns are consistent with broader coastal morphodynamic theory, which emphasises that landform behaviour emerges from the interaction of multiple environmental controls rather than single parameters (Scott et al., 2011). They also help explain variability observed across European dune restoration studies. Reported outcomes range from substantial inland transport distances (e.g. hundreds of metres; Ruessink et al., 2018) to highly localised effects (Riksen et al., 2016), reflecting differences in wind climate, sediment availability, and system morphology.

In addition, the regulatory effects of intervention design and biotic feedbacks are likely to be important. Notch geometry, orientation, and surrounding vegetation structure can influence airflow and sediment capture efficiency, while rapid vegetation recovery or notch infilling may reduce effectiveness over time. These interactions highlight that notching represents a local modification to flow pathways rather than a direct control on sediment supply, and its success therefore depends on wider system connectivity.

At the process level, transport responses depend not only on wind forcing but also on modifiers such as surface moisture and roughness, and grain size of the source material, which influence entrainment thresholds (Lamy et al., 2024; Nield et al., 2010; Bauer et al., 2009). At the system scale, sediment supply and sediment-routing connectivity determine whether increased transport potential results in sustained inland sediment delivery (Bauer et al., 2009; Davidson-Arnott and Bauer, 2021). Where sediment supply is limited or pathways are disrupted, responses are often spatially constrained and transient.

Differences among studies are also influenced by scale. Short-term, localised monitoring may capture immediate transport responses to interventions, whereas longer-term observations reveal more heterogeneous and scale-dependent behaviour, including vegetation recovery, sediment redistribution, and morphological adjustment. Recent work emphasises the importance of linking plot-scale process observations with landscape-scale monitoring to better understand coastal dune dynamics and inform management (Martín-Gallego et al., 2025).

4.4. Limitations and implications for future monitoring

These findings should be interpreted in the context of several sampling and analytical limitations. For sand flux, some observations were excluded where disturbance, altered local context, or collector damage meant that samples no longer represented the intended comparison of aeolian deposition under consistent field conditions; counts of excluded observations are reported in Supplementary Table S1. Although these exclusions improve the internal consistency of the analytical dataset, they may also reduce the influence of episodic or highly localised transport events that contribute to natural variability. In addition, post-intervention sampling duration differed among sites because interventions were implemented at different times, resulting in an unbalanced monitoring design in which some sites contributed more post-intervention observations than others.

Interpretation of the soil analyses also requires caution. Soil sampling comprised a single intervention transect and a single control transect per site, each sampled at three distances and two time points, which provides only limited replication at the transect level. The mixed-model results therefore identify patterns consistent with early soil change, but they should be regarded as indicative rather than inferentially conclusive. More generally, confidence intervals and *p*-values for the soil models are likely to overstate precision under this level of replication. Even so, the overall conclusions are strengthened by the consistency of the main site-level patterns across descriptive contrasts, mixed-model estimates, and independent process indicators including wind regime and calcite enrichment.

Taken together, these findings indicate that variability in intervention outcomes is not anomalous but reflects predictable differences in environmental forcing, sediment supply, and system configuration. Quantitatively, the observed increase in sand flux at intervention sites demonstrates that notching can substantially enhance transport under favourable conditions, but that this effect is not consistently expressed across sites.

For management, this implies that foredune notching alone is unlikely to guarantee sustained dune mobility. Effective restoration requires site-specific assessment of wind conditions, sediment budgets, and morphological connectivity, and may need to be combined with complementary measures such as vegetation management or sediment nourishment.

More broadly, coastal dune systems provide critical ecosystem services, including coastal protection, resilience to extreme events, and regulation of sediment budgets. Maintaining these functions under climate change depends on sustaining sediment mobility and connectivity across the beach–dune system (Delgado-Fernandez and Davidson-Arnott, 2011; Davidson-Arnott and Bauer, 2021; Martín-Gallego et al., 2026). Integrating field-based process understanding with spatial monitoring approaches offers a pathway towards more adaptive, evidence-based management of these dynamic systems.

5. Conclusion

This study demonstrates that foredune notching can enhance aeolian sediment transport and initiate soil rejuvenation processes, but that its effectiveness is strongly site dependent. While clear increases in sand flux and, modest, early associated changes in soil properties were observed at sites with favourable wind regimes and sufficient sediment supply, responses at other sites were limited or spatially constrained. These findings indicate that intervention outcomes are governed by the interaction of wind forcing, sediment availability, and system configuration, rather than by the intervention itself.

The results highlight that reactivating dune dynamics through localised measures such as notching does not guarantee sustained geomorphic or ecological change. Instead, successful restoration requires an integrated understanding of sediment pathways, beach–dune connectivity, and landscape-scale controls. This reinforces the need for site-specific assessment and adaptive management strategies that account for variability in environmental conditions and system constraints.

From a broader perspective, maintaining sediment mobility is essential for sustaining the ecological function and coastal protection role of dune systems under climate change. By linking process-based field observations with system-scale interpretation, this study contributes to a growing body of evidence that effective dune restoration depends on restoring not just local disturbance, but the wider connectivity and dynamics of coastal systems. Future work should focus on longer-term monitoring and the integration of geomorphological, ecological, and climatic drivers to better predict the persistence and resilience of restoration outcomes.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work the authors used Microsoft Copilot in order to improve the consistency of the language across multiple international authors. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

CRediT authorship contribution statement

Maud A.J. van Soest: Writing – original draft, Visualization, Validation, Project administration, Methodology, Formal analysis, Data curation. **Amanda J. Holder:** Writing – original draft, Resources, Methodology. **Michele Brentegani:** Formal analysis. **Alice Fitch:** Writing – original draft, Visualization, Data curation. **Laurence Jones:** Writing – original draft, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoleng.2026.108113.

Data availability

Data will be made available on request.

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