

Article

Impacts of Shelterbelt Configuration on Wind–Sand Fixing Efficiency and Soil Erodibility in a Low-Elevation Arid Basin

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Abstract

Wind erosion poses a serious threat to land stability and agricultural sustainability across global arid and semi-arid zones. This study was conducted in Tuoksun County, China's sole county situated below sea level; its unique low-elevation landform generates distinctive wind–sand movement processes, forming a representative research platform for elucidating shelterbelt functional mechanisms under extreme arid environments. In this work, we systematically monitored wind field characteristics, shelterbelt windbreak performance, and soil wind erodibility and quantitatively analyzed the regulatory effects of different shelterbelt configurations on sand-fixing efficiency and soil anti-wind erosion capacity. The results revealed an obvious decoupling between wind velocity and wind direction frequency within the study area: the maximum wind speed ($\approx 5.5 \text{ m s}^{-1}$) occurred in the NNW direction, whereas the W and WSW directions exhibited the highest wind occurrence frequency. Shelterbelt height showed an extremely significant positive correlation with wind speed reduction efficiency ($r = 0.817^{***}$), while ambient wind speed was significantly negatively correlated with windproof benefit ($r = -0.690^{***}$). Among forest types, F2 and PF achieved significantly higher efficiency and lower wind speeds than F1. Intact shelterbelts reached >85% efficiency, while degraded belts fell below 40%. Soil texture acted as the dominant factor controlling soil erodibility: clay, fine sand, and very fine sand increased soil wind erodibility, while coarse sand and gravel suppressed erodibility. Hierarchical clustering analysis of vertical wind speed profiles confirmed that shelterbelts can substantially reduce near-ground wind velocity; compared with shelterbelt types, spatial position (windward side, leeward side, and central zone) exerted a stronger influence on wind field regulation. This study elucidates the internal correlations among shelterbelt spatial configuration, sand-fixing efficiency, and soil wind erodibility, providing scientific support for the optimization of shelterbelt layout in low-elevation arid ecological regions.

Keywords: shelterbelt configuration; wind–sand fixing efficiency; soil wind erodibility; low-elevation arid region



Academic Editors: Lei Deng and
Hermano Melo Queiroz

Received: 29 May 2026

Revised: 24 June 2026

Accepted: 29 June 2026

Published: 9 September 2026

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1. Introduction

Soil wind erosion is a major environmental and agricultural challenge in arid, semi-arid, and some agricultural regions worldwide, leading to land degradation, loss of fertile topsoil, air pollution, and ecosystem deterioration [1,2]. The susceptibility of soil to wind erosion, termed soil erosivity, is a complex function of intrinsic soil properties and extrinsic environmental factors [3,4]. Key intrinsic factors include soil texture (particularly the

content of erodible fractions < 0.84 mm), aggregate size distribution (ASD), aggregate stability, organic matter (OM) content, moisture content, the presence of surface crusts or rock fragments [5–8], wind characteristics (velocity, duration, shear stress) and surface conditions such as vegetation cover and roughness [9–11]. Among these, soil texture and ASD are recognized as fundamental determinants of erodibility, as they directly influence the availability of particles susceptible to entrainment by wind forces [12,13].

Extensive research has quantified the relationships between soil properties and erodibility parameters. Studies have shown that soils with higher clay and silt content, larger mean weight diameter (MWD) of aggregates, and greater organic carbon (OC) content generally exhibit lower wind erosion rates (WERs) [14,15]. Conversely, sandy soils with a high proportion of fine sand particles (e.g., 0.1–0.2 mm) are highly erodible [16]. Soil moisture significantly increases the threshold friction velocity required to initiate particle movement, thereby reducing erodibility, with critical moisture levels varying by soil texture [17,18]. Furthermore, the application of soil amendments, such as clay or the formation of biological soil crusts, can enhance aggregate stability and surface cohesion, effectively diminishing soil loss [19]. These findings underscore the critical role of managing soil physicochemical properties to mitigate wind erosion. In agricultural landscapes, shelterbelts (or windbreaks) are a widely adopted and effective ecological engineering measure for wind erosion control [20,21]. Their primary mechanism is aerodynamic: by disrupting airflow, shelterbelts reduce wind speed and shear stress on the leeward side, thereby decreasing the capacity of the wind to detach and transport soil particles [22–24]. The sheltering efficiency is influenced by the structure of the shelterbelt, including its height, porosity, optical porosity, and arrangement (single or multiple rows) [25,26]. Computational Fluid Dynamics (CFD) simulations and wind tunnel experiments have been instrumental in optimizing these design parameters to maximize the protected zone [27]. Beyond the immediate aerodynamic sheltering, a growing body of evidence suggests that shelterbelts induce significant changes in the soil environment of the adjacent farmland, which may lead to a sustained reduction in soil erodibility. Long-term studies indicate that shelterbelts alter soil erosion and deposition patterns, leading to the redistribution of soil particles and nutrients along transects perpendicular to the belt [28,29]. Typically, finer particles (silt and clay) and associated nutrients tend to deposit at greater distances from the shelterbelt, while coarser materials may accumulate closer to it [30]. This spatial sorting modifies the soil texture—a key erodibility factor—within the field. Moreover, the microclimate created by shelterbelts (e.g., reduced evaporation, modified temperature) can affect soil moisture regimes and organic matter dynamics [31]. The accumulation of litter and organic inputs from the shelterbelt vegetation itself can enhance soil organic carbon and aggregate stability in nearby soils [32,33]. These physicochemical improvements could potentially lower the intrinsic erodibility of the soil, meaning the soil itself becomes more resistant to wind forces even when the direct aerodynamic shelter is less effective (e.g., during periods of canopy dormancy or under extremely high winds). Accordingly, understanding the relationship between shelterbelt structure and its functional outcomes is a prerequisite for evidence-based design and management of agroforestry systems in both temperate and arid contexts [34,35].

However, a critical knowledge gap persists. While the aerodynamic effects of shelterbelts and the general principles of soil erodibility are well-studied in isolation, the explicit causal linkages between the long-term, shelterbelt-induced modifications of key soil physicochemical properties (e.g., texture, aggregate stability, organic carbon) and the consequent reduction in intrinsic soil wind erodibility remain inadequately quantified and mechanistically understood. Most studies treat shelterbelt effects on soil and on wind erosion as parallel outcomes rather than as an interconnected cause-and-effect chain [36]. It is unclear

to what extent the observed reduction in wind erosion within shelterbelt-protected fields is attributable solely to the instantaneous wind speed reduction versus a lasting improvement in the soil's inherent resistance to erosion.

As China's only county with large areas near and below sea level, Toksun County exhibits a unique low-lying basin topography surrounded by mountains, leading to extreme aridity, frequent strong winds, and distinctive near-surface wind–sand transport processes that differ markedly from ordinary arid regions. Such a special geomorphic setting raises two key scientific questions: (1) How do near-sea-level terrain conditions reshape wind regime characteristics and the vertical distribution of wind speed profiles in shelterbelt systems? (2) What are the relative contributions of shelterbelt type, vertical vegetation structure, and positional effects (windward vs. leeward/center) to windbreak efficiency and sand fixation in this unique low-elevation windy environment?

Clarifying these mechanisms is urgently needed to improve wind erosion prediction and ecological restoration in similar below-sea-level arid basins. This study therefore investigated wind regimes, shelterbelt performance, soil erodibility, and wind speed clustering patterns in Toksun County, aiming to reveal the coupled effects of topography, vegetation structure, and shelterbelt configuration on wind field modification. The objectives are to clarify the coupling relationships among wind regimes, shelterbelt structure, and soil erodibility and to identify key factors dominating windbreak effectiveness. The findings are expected to provide a scientific basis for optimizing shelterbelt design, improving wind erosion control strategies, and supporting ecological restoration in similar extremely arid low-elevation ecosystems worldwide.

2. Materials and Methods

2.1. Study Area

The study was conducted in the southern suburban area of Toksun County (87°14'05"–89°11'08" E, 41°21'14"–43°18'11" N), located in the eastern part of Xinjiang Uygur Autonomous Region, China. Tuokexun County lies at the southern foot of the Tianshan Mountains and the western edge of the Turpan Basin. The terrain is characterized by mountains on three sides, with higher elevations in the north and lower elevations in the east. The elevation descends from approximately 0 m at the county center to –125 m at the lowest point in the east [37]. The region has a typical arid continental climate (Figure 1). From 2008 to 2016, the mean annual temperature ranged from 14.8 to 16.4 °C, the annual precipitation from 3.1 to 15.8 mm, the annual potential evapotranspiration from 2995.9 to 3431 mm, and the number of strong wind days (wind speed > Beaufort scale 6) from 49 to 80 days [38]. The study area is predominantly affected by northwesterly winds, which represent the most frequent damaging wind direction and the primary driver of wind erosion and elevated evaporative demand in this region.

The dominant vegetation species in the experimental area include Euphrates poplar (*Populus euphratica*), Chinese tamarisk (*Tamarix chinensis*), Saxaul (*Haloxylon ammodendron*), Siberian elm (*Ulmus pumila*), Annual bluegrass (*Poa annua*), Common reed (*Phragmites australis*), and Camelthorn (*Alhagi sparsifolia*). Soils in the oasis area are primarily Fluvo-aquic soils, irrigated cultivated soils, and irrigated warped soils, with some arenosols. The cultivated soils are generally characterized by low fertility, with an average organic matter content of 1.72%, total nitrogen of 0.076%, total phosphorus of 0.064%, and high salinity, with saline-alkali land accounting for about 36% of the cultivated area [32,33].

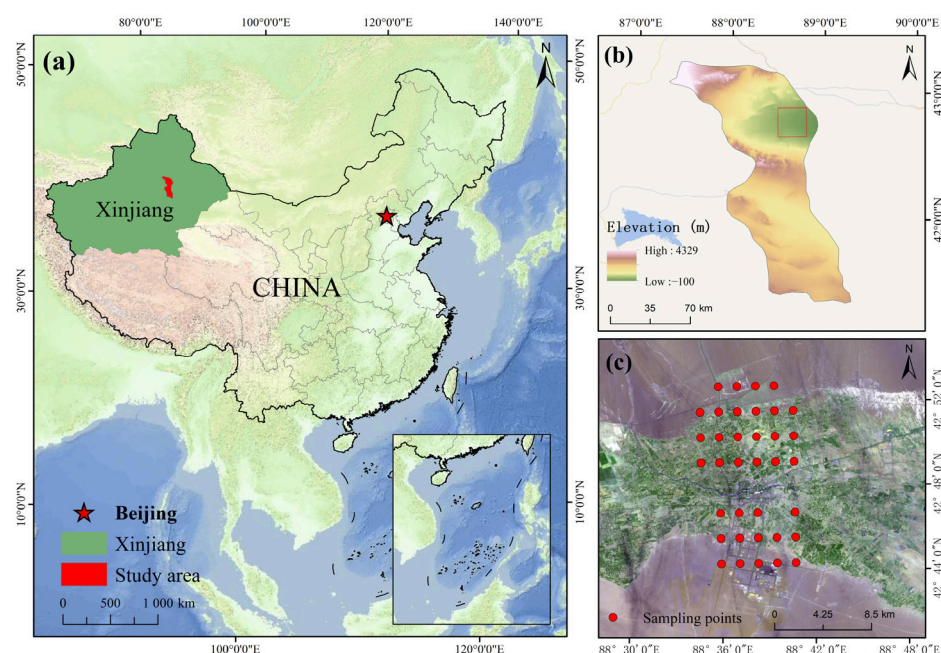


Figure 1. Study area. Notes: Location and geographic characteristics of the study area: (a) elevation map of the study area; (b) distribution of sampling points within the study area; (c) satellite imagery of the study area.

2.2. Experimental Design and Shelterbelt Configurations

Based on the existing shelterbelt structures in the southern suburbs of Toksun County, three types of shelterbelts with relatively uniform tree age, growth status, and topography were selected. All shelterbelts were oriented north–south, perpendicular to the prevailing northwesterly winds, each covering an area of approximately 940 m × 560 m, with no undergrowth. The configurations were:

Mixed Forest 1 (F1): Dominated by *Populus euphratica*, with a composition of approximately 70% *P. euphratica* and 30% *Tamarix chinensis*. Mixed Forest 2 (F2): Dominated by *Tamarix chinensis*, with a composition of approximately 60% *T. chinensis* and 40% *P. euphratica*. Pure *Haloxylon ammodendron* forest (PF). CK: Bare sandy land (Figure 2, Table 1).

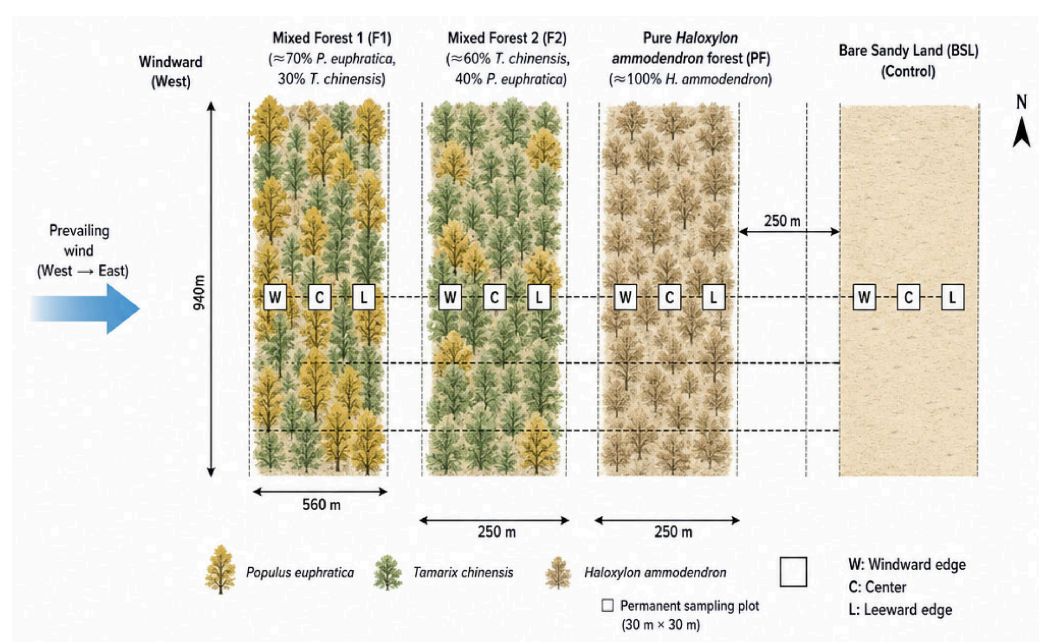


Figure 2. Standard plot setting.

Table 1. Overview of forest land.

Shelterbelt Type	Vegetation Structure	Forest Land Surface Condition
Mixed Forest (F1)	Planting spacing: 2 m × 3.5 m; the average height of <i>Populus euphratica</i> is 2.96 m, with an average crown size of 2.05 m × 1.63 m and a clear bole height of 0.56 m; the average height of <i>Tamarix chinensis</i> is 1.8 m, with an average crown size of 1.76 m × 1.78 m; the plants grow well.	The inter-row surface was bare with weeds distributed, the stand coverage was 17%, and the porosity was 35%.
Mixed Forest (F2)	Planting spacing: 2 m × 3.5 m; the average height of <i>Populus euphratica</i> is 3.08 m, with an average crown size of 1.97 m × 1.76 m and a clear bole height of 0.71 m; the average height of <i>Tamarix chinensis</i> is 1.78 m, with an average crown size of 2.05 m × 1.86 m; the plants grow well.	The inter-row surface was bare with weeds distributed, the stand coverage was 21%, and the porosity was 38%.
<i>Haloxydon ammodendron</i> forest (PF)	Planting spacing: 1.5 m × 3.5 m; the average height is 2.72 m, with an average crown size of 1.0 m × 0.9 m; the plants grow well.	The inter-row surface was bare without weeds, the stand coverage was 13%, and the porosity was 32%.
CK	None.	—

A bare sandy land (BSL), located 250 m to the right (east) of the shelterbelt complex and free of surface crust, served as the control site. The distance between any two experimental sites (shelterbelts and BSL) was 250 m to ensure independence.

Within each shelterbelt type, three permanent sampling plots (30 m × 30 m each) were established along the prevailing wind direction (west–east): one at the windward forest edge, one at the center site, and one at the leeward forest edge. Similarly, three plots were established in the BSL. This resulted in a total of 12 plots (3 shelterbelt types × 3 positions + 3 BSL plots). A complete tree inventory was conducted in each shelterbelt plot in March 2025.

2.3. Measurement of Aerodynamic Efficiency

Wind Regime Monitoring: A small automatic weather station (AWS-008, Jinan, Shandong, China) was installed in the BSL, 250 m north of the shelterbelts, to monitor the background wind regime from January 2022 to December 2025. Wind speed and direction were recorded at 10-min intervals.

Wind Profile and Shelter Efficiency: Field experiments were conducted from mid-March to mid-May in 2022 to 2025. For individual tree effects, wind profiles were measured at distances of 2H (H = tree height) and 1H upwind and 1H, 2H, and 3H downwind of single *P. euphratica*, *T. chinensis*, and *H. ammodendron* trees, as well as in the BSL. For shelterbelt effects, portable wind profile instruments were deployed simultaneously at the W, C, and L positions within each shelterbelt type and in the BSL. Wind speeds were measured at heights of 10, 50, 80, 120, 160, 200, 240, and 300 cm above ground. Measurements were taken for 1-h periods, with a sampling interval of 2 s and a recording interval of 30 s. Total observation time under strong wind conditions exceeded 8 h per site.

Shelter efficiency (SE, E_z %) at height z was calculated as:

$$E_z = \frac{U_{CK} - U_z}{U_{CK}} \times 100\% \quad (1)$$

where E_z is the wind erosion control efficiency (%) at height Z (m). U_{CK} is the mean wind speed at height Z (m) in the bare sandy land (control plot). U_Z is the mean wind speed at height Z (m) in the forest stand.

The calculation method for sand retention efficiency [39] is expressed as follows:

$$E = \frac{Q_{CK} - Q}{Q_{CK}} \times 100\% \quad (2)$$

where E is sand retention efficiency (%) and Q_{CK} is sediment discharge of the control plot (g).

Q is the sediment discharge of the forest stand (g). The calculation method for sediment transport flux is expressed as follows:

$$Q_t = \frac{Q}{S \times t} \quad (3)$$

where Q_t is the sediment transport flux ($\text{g} \cdot \text{cm}^{-2} \cdot \text{min}^{-1}$), Q is the sediment discharge (g), S is the sand collection area (cm^2), and t is the collection duration (min).

The calculation method for erodible particle content (EF) [28] is given by the following formula:

$$EF = \frac{W_{<0.84}}{T} \times 100\% \quad (4)$$

where EF represents soil erodibility fraction, $W_{<0.84}$ is the mass of soil particles with diameter less than 0.84 mm, and T is the total mass of the sieved soil. Roughness refers to the height at which the near-surface wind velocity is zero, reflecting the resistance of the ground surface to air flow.

The calculation method for roughness is as follows:

$$\lg z_0 = \frac{\lg u_2 - \lg u_1 \times \frac{u_2}{u_1}}{1 - \frac{u_2}{u_1}} \quad (5)$$

where Z_0 is the surface roughness, and u_1 and u_2 are the wind speeds at two arbitrarily selected different heights at the same moment, respectively.

Strong wind and strong wind day [40]: In this study, according to the regulations of the China Meteorological Administration (<https://www.cma.gov.cn/en/index.html>) (accessed on 31 December 2025), wind with a wind force greater than Beaufort scale 6 is defined as strong wind, and a day on which wind above Beaufort scale 6 occurs is defined as a strong wind day.

The calculation method for strong wind frequency is as follows:

$$W = \frac{D}{d} \quad (6)$$

where W is the strong wind frequency (%), D is the number of days with wind speed > 12 m/s during the total observation period, and d is the total number of observation days. Sand-driving wind frequency [41] refers to the number of days with wind speed exceeding the threshold wind velocity for sand transport within the total observation days.

$$M = \frac{F}{f} \quad (7)$$

where M is the sand-driving wind frequency (%), F is the number of days with wind speed exceeding the threshold wind velocity for sand transport during the total observation period, and f is the total number of observation days.

2.4. Soil Sampling and Analysis

Soil samples were collected from late April to mid-May 2025. In each of the 12 plots, five sampling points were arranged in an “S” pattern. Surface soil (0–20 cm depth) was collected from each point and thoroughly mixed to form one composite sample per plot. This resulted in 36 composite samples (12 plots $\times$ 3 replicates, though the text mentions 27 shelterbelt + 9 BSL = 36 total, aligning with 3 reps per plot).

The following soil physicochemical properties were analyzed using standard methods [33,42,43]:

Determination of soil moisture: The oven-drying method was used to determine the water content. First, the sealed soil samples were brought back to the laboratory and weighed immediately, then dried in an oven for 24 h, and finally weighed again. The soil water content was calculated according to the difference between the two weights.

Determination of soil organic matter: The potassium dichromate method was used to determine soil organic matter [39].

Determination of soil bulk density: The ring knife method was used to determine soil bulk density.

Determination of soil mechanical texture: The soil particle size distribution was determined using a Mastersizer 2000 laser particle size analyzer (Malvern, Worcestershire, UK) (January 2022 to December 2025), which is widely used in soil science research due to its high precision, wide measurement range (0.02–2000 μm), and excellent repeatability. This instrument has been extensively validated and applied in numerous studies on forest soil characterization [39]. The particle size was classified according to the United States Department of Agriculture (USDA) (<https://www.usda.gov>) (accessed on 31 December 2025) system, which is one of the most internationally recognized and widely adopted soil classification frameworks, facilitating comparison with the existing literature. The particle size classes included: gravel (>2 mm), very coarse sand (1–2 mm), coarse sand (0.5–1 mm), medium sand (0.25–0.5 mm), fine sand (0.1–0.25 mm), very fine sand (0.05–0.1 mm), and silt/clay (<0.05 mm). The soil texture of each forest stand was determined using the coordinate method based on the USDA soil texture triangle diagram.

Determination of soil erodibility index (EF) by the flat sieving method: 500 g of soil was selected from each forest land and bare sandy land for the flat sieving experiment. The flat sieve was divided into eight grades: >2 mm, 1–2 mm, 0.85–1 mm, 0.5–0.85 mm, 0.25–0.5 mm, 0.1–0.25 mm, 0.05–0.1 mm, and <0.05 mm. The sieving time was 15 min, and 5 repeated experiments were carried out to improve the accuracy.

Determination of total nitrogen (N), phosphorus (P), potassium (K), available N, P, and K in soil: The total nitrogen in the soil was determined by the Kjeldahl method; the total phosphorus in the soil was determined by the molybdenum–antimony anti-spectrophotometric method; the alkaline hydrolysis nitrogen in the soil was determined by the alkaline hydrolysis diffusion method; the available phosphorus in the soil was determined by the molybdenum–antimony anti-spectrophotometric method; the available potassium in the soil was determined by the ammonium acetate flame photometry method.

2.5. Data Analysis

Data processing and graphing were performed using Excel 2010, Origin 2018, and Surfer 2018. Statistical analyses were conducted using SPSS 19.0.

One-way analysis of variance (ANOVA) was used to test for significant differences in soil erodibility indicators (EF, V_t) and soil properties among different shelterbelt configurations and positions. Post hoc comparisons were performed using Tukey’s HSD test.

Pearson correlation analysis was employed to explore the bivariate relationships between soil erodibility indicators (EF , V_t) and soil physicochemical properties (e.g., clay + silt content, SOM, BD).

3. Results

3.1. Wind–Sand Fixing Efficiency of Shelterbelts with Different Configurations

The wind regime of the study area is characterized by distinct directional variations in both wind speed and occurrence frequency, as illustrated by the combined analysis of wind speed distributions and directional frequency patterns (Figure 3). Wind speeds peak sharply in the north–northwest (NNW) direction, reaching approximately 5.5 m/s, followed by the east–northeast (ENE), north (N), and northwest (NW) directions (3.5–4.5 m/s). In contrast, southern-oriented directions (S, SE, SSE, SSW) exhibit the lowest wind speeds, all below 2.5 m/s. The frequency curve reveals distinct occurrence patterns: the west (W) and west–southwest (WSW) directions show the highest occurrence frequencies (120 and 170 times, respectively), while the south–southwest (SSW) direction has the lowest frequency (20 times). A clear negative correlation between wind speed and frequency is observed: the NNW direction features extreme speed but moderate frequency, whereas W/WSW directions combine moderate-to-high speed with peak frequency, representing the dominant wind energy input of the study area (Figure 3).

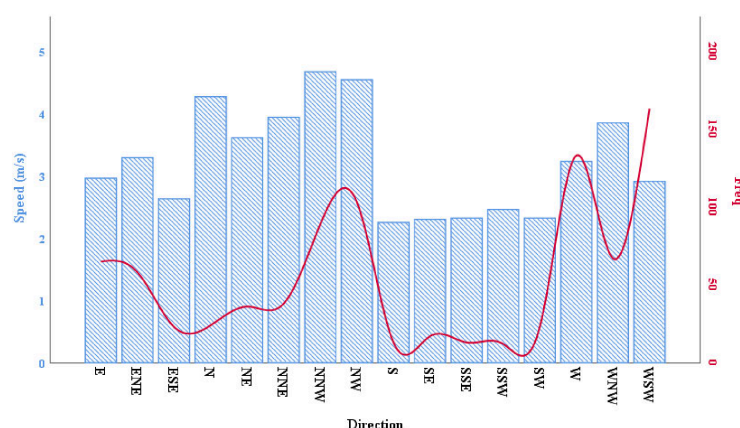


Figure 3. Wind speed and frequency characteristics by direction.

These results indicate that the region is primarily affected by high-energy winds from the W/WSW quadrants and high-speed winds from the N/NNW sectors, while southern directions (S/SSW) constitute weak wind zones with minimal sand transport potential.

The temporal distribution of wind energy and events of erosivity is further quantified via a circular chord diagram (Figure 4), which links seasonal variation to wind speed intensity and the number of days with erosive wind speeds (≥ 12 m/s). Strong winds, defined as those exceeding 10 m/s, are predominantly concentrated in winter and early spring (January–March), as indicated by the thickest chord connections between these months and the highest wind speed ranges. A secondary peak in strong wind activity occurs in late autumn (November–December), while summer months (June–August) exhibit minimal high-wind connections, reflecting a period of low wind energy input. Correspondingly, the radial axis of days with wind speeds ≥ 12 m/s shows that January–March account for the vast majority of erosive wind days (up to ~120 days annually), with late autumn contributing a smaller fraction (Figure 4).

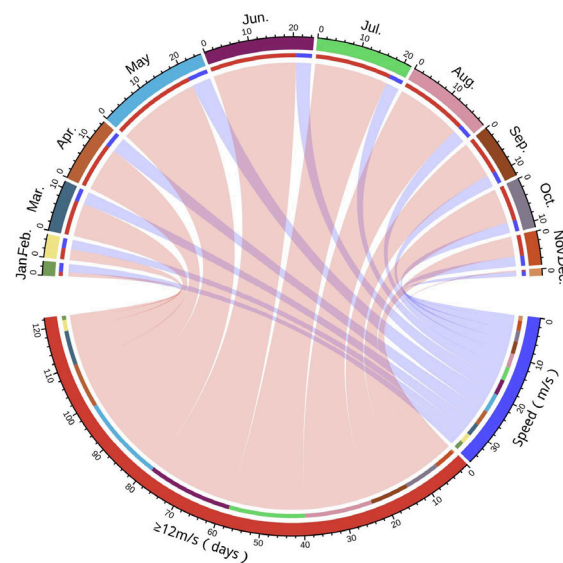


Figure 4. Seasonal distribution of wind speed and erosive wind days (≥ 12 m/s) in the study area. Notes: The 12 colored segments represent calendar months (January–December), the blue arc indicates wind speed (m/s), and ribbon widths are proportional to the number of qualifying days in each month.

These temporal patterns, when integrated with the directional wind characteristics, reveal that the study area's wind erosion risk is highest during the winter–spring season, driven by high-speed northerly/northwesterly winds, and that shelterbelt design must prioritize withstanding these persistent, erosive wind events to effectively mitigate sand transport.

Shelterbelt vegetation substantially increased aerodynamic surface roughness (z_0) compared to bare sandy land. The z_0 values calculated from wind velocity profiles were 0.0057 cm (bare sandy land), 0.123 cm (Pure forest, PF), 0.378 cm (Mixed Forest 1), and 0.569 cm (Mixed Forest 2), representing increases of 21.58, 66.32, and 99.82 times relative to bare sandy land, respectively. The higher surface roughness of forested sites enhanced frictional drag on near-surface airflow, thereby contributing to the greater wind speed attenuation observed in more structurally complex shelterbelt configurations.

The pair plot reveals strong and statistically significant correlations between vegetation height, wind speed, and windproof efficiency, which underpin the wind–sand fixation performance of different shelterbelt configurations (Figure 5). Vegetation height shows a robust positive correlation with wind speed reduction ($r = 0.817^{***}$), with site-specific correlations all exceeding 0.95^{***} (CK: 0.986^{***} , center site: 0.951^{***} , leeward site: 0.950^{***} , windward site: 0.984^{***}), (for significance levels see Notes for Figure 5). This indicates that taller vegetation acts as a more effective physical barrier, dissipating near-surface wind energy and reducing wind speed. In turn, wind speed exhibits a strong negative correlation with windproof efficiency ($r = -0.690^{***}$), with site-specific values ranging from -0.655^{***} (windward site) to -0.809^{***} (center site). This inverse relationship confirms that lowering near-surface wind speed is the primary mechanism for improving wind–sand fixation efficiency, as reduced wind energy directly limits sand entrainment and transport. A moderate negative correlation between vegetation height and windproof efficiency ($r = -0.329^{**}$) further suggests that while height drives wind speed reduction, additional factors—such as shelterbelt density, structural complexity, and spatial configuration—also modulate the final efficiency of sand fixation.

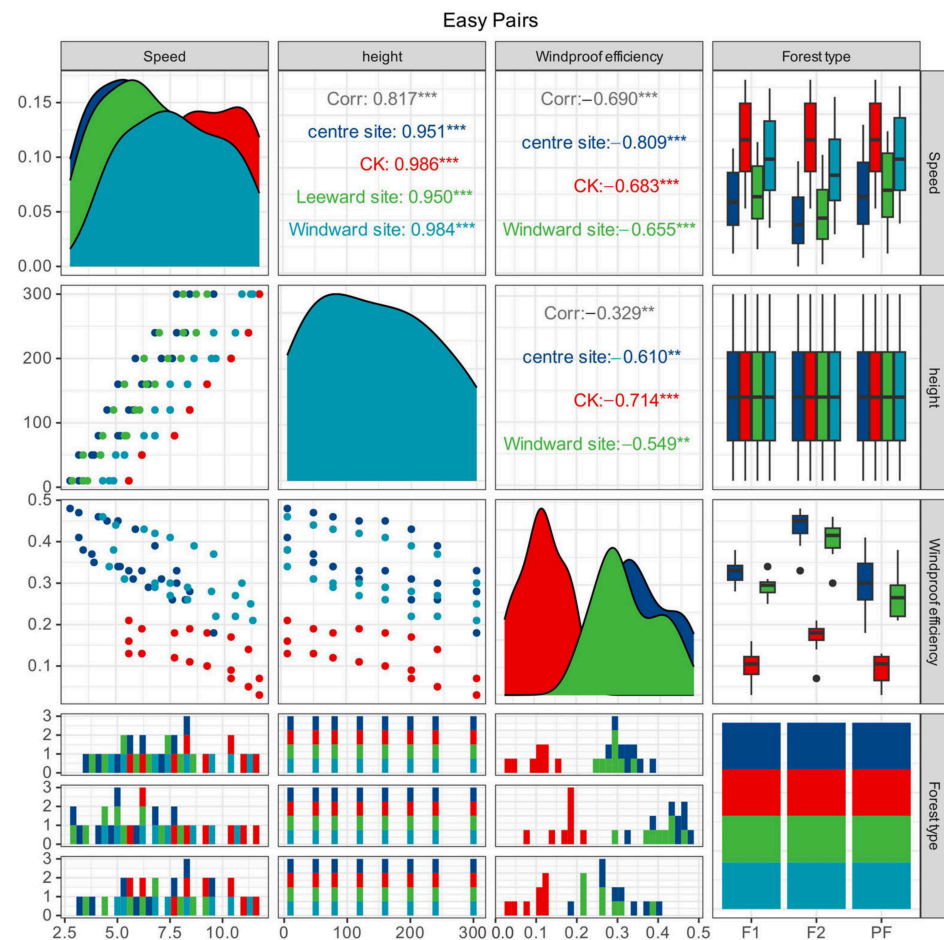


Figure 5. Pairwise correlations and distribution patterns of wind speed, vegetation height, and windproof efficiency across different shelterbelt configurations. Notes: Pearson correlation coefficients (** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$) are shown in the upper panels. Kernel density distributions (diagonal), scatter plots (lower), and box plots (right) compare variable distributions across shelterbelt configurations (CK, windward site, leeward site, center site) and forest types (F1, F2, PF). The plot highlights the key drivers of wind–sand fixation efficiency and performance differences among configurations. Colors indicate measurement positions: red = control (CK); green = leeward site; dark blue = center site; cyan = windward site.

Distribution and box plot analyses highlight clear performance disparities between shelterbelt configurations (CK, windward site, leeward site, center site). The density plot of wind speed shows that windward site configurations (blue) cluster at the lowest speed range, while CK (red, likely representing bare sand or unprotected control plots) peaks at the highest speeds. This pattern is mirrored in the box plots: CK consistently exhibits the highest median wind speeds, whereas windward and leeward sites show significantly lower and more constrained speed distributions. For windproof efficiency, the density plot reveals a stark separation: CK (red) peaks at low efficiency values (0–0.2), indicating poor wind–sand fixation, while leeward (green) and windward (blue) sites concentrate at higher efficiency ranges (0.3–0.5), demonstrating superior performance. Box plots confirm these trends, with CK showing the lowest median efficiency and widest variability, and windward/leeward sites displaying higher medians and narrower interquartile ranges. These results demonstrate that structured shelterbelt configurations (windward/leeward) effectively stabilize near-surface wind dynamics and outperform unprotected control sites in wind–sand fixation (Figure 5).

Categorical analysis of forest types (F1, F2, PF) further reveals configuration-dependent differences in wind–sand fixation efficiency, providing actionable insights for optimizing shelterbelt design. Box plots for speed and windproof efficiency show distinct profiles across F1, F2, and PF: PF and F2 generally exhibit lower median wind speeds and higher windproof efficiency compared to F1, indicating that specific structural or compositional traits of these forest types enhance wind–sand control. Scatter plots reinforce these differences, with F2 and PF points clustering at lower wind speeds and higher efficiency values, while F1 points overlap more with CK’s high-speed, low-efficiency cluster. Combined with the correlation results, these findings emphasize that both vegetation height and shelterbelt configuration (including site position and forest type) are critical determinants of wind–sand fixation success. For practical management, windward/leeward site layouts paired with forest types like F2 or PF represent the most effective strategy to minimize near-surface wind speed, reduce sand transport, and maximize wind–sand fixation efficiency in the study area.

This bivariate boxplot set dissects the proportional distribution of wind–sand fixation efficiency across stratified height classes, shelterbelt positions, and forest types—providing granular insights beyond the earlier correlation analysis (Figure 6).

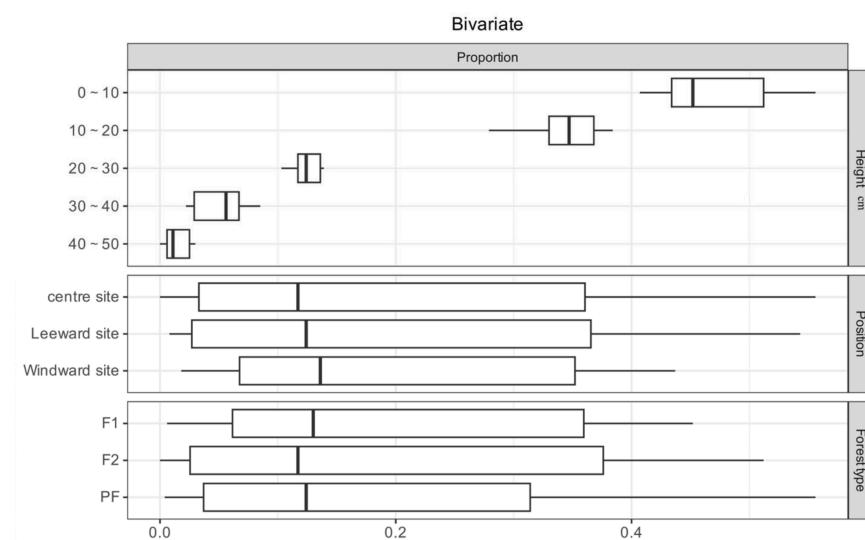


Figure 6. Bivariate proportional distribution of wind–sand fixation efficiency across height classes, shelterbelt positions, and forest types. Notes: Boxplots display the proportional efficiency of wind–sand fixation (x-axis) across vegetation height classes (0–10, 10–20, 20–30, 30–40, 40–50 cm), shelterbelt positions (center site, leeward site, windward site), and forest types (F1, F2, PF).

The top height-stratified panel reveals a clear inverse pattern: shorter vegetation layers (0–10 cm and 10–20 cm) show significantly higher median proportional efficiency (≈ 0.45 and ≈ 0.30 , respectively) with wider interquartile ranges, while larger height classes (30–40 cm and 40–50 cm) exhibit much lower medians (≈ 0.08 and ≈ 0.05) and narrower variability. This indicates that shorter, denser vegetation structures are the primary contributors to strong proportional wind–sand fixation, rather than total vegetation height alone.

The middle position panel shows that all three shelterbelt positions (center site, leeward site, windward site) maintain broad, overlapping proportional efficiency distributions spanning 0–0.4. The leeward site extends furthest right, reaching the highest upper quartile values, suggesting it captures residual wind energy most effectively after the primary shelterbelt, while the windward site acts as a consistent frontline barrier with more stable baseline performance. The center site aligns closely with the leeward site in

median efficiency, confirming that internal shelterbelt zones also play a key role in overall wind–sand control.

The bottom forest type panel demonstrates subtle but meaningful differences between configurations: F2 and PF share nearly identical median proportional efficiency (≈ 0.15) and upper quartile ranges, with F2 showing marginally superior peak performance (extending to ≈ 0.5). In contrast, F1 exhibits a left-shifted median and narrower upper tail, confirming it lags behind F2 and PF in proportional wind–sand fixation. All three types maintain broad interquartile ranges, highlighting that within-type structural variability is nearly as influential as between-type differences in shaping shelterbelt performance.

3.2. Variation in Soil Wind Erodibility Among Shelterbelts with Different Configurations

Across all configurations, fine sand (green) and very fine sand (dark red) dominate the particle size distribution, with F2 and PF exhibiting the highest proportions of these erodible fractions (approaching 100% at the F2 and PF axes). In contrast, medium sand (light orange) is most abundant in F1, where it reaches nearly 100%, indicating a coarser overall texture in this configuration. The control site (CK) is distinguished by the highest proportion of gravel (dark blue), which extends to the outermost radial limit, signifying a stony, coarse-textured surface with inherently lower wind erodibility compared to vegetated sites. For finer particles, clay particles (red) and powder particle (light purple) are present in low proportions across all configurations, with F2 showing marginally higher clay content relative to other sites, suggesting slightly enhanced soil aggregation. Coarser fractions (coarse sand, very coarse sand) exhibit moderate variability: very coarse sand (light green) is most prominent in CK, while coarse sand (light blue) peaks in F1, further differentiating the textural traits of each shelterbelt type (Figure 7).

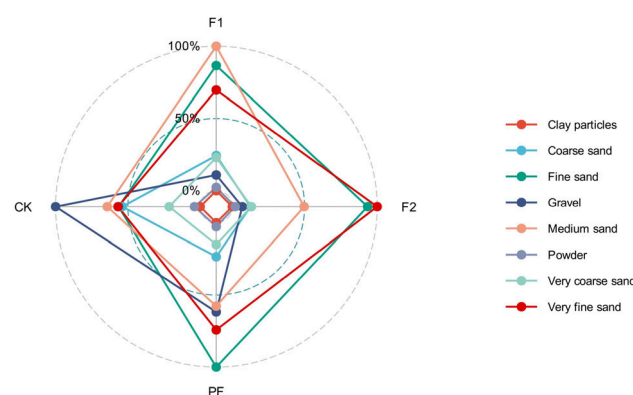


Figure 7. Soil particle size composition across different shelterbelt configurations.

These compositional differences directly link to soil wind erodibility: F2 and PF, with their high fine/very fine sand content, represent the most erodible configurations, as these particle sizes are most easily entrained by wind. F1, dominated by medium sand, exhibits intermediate erodibility, while CK, with its high gravel and very coarse sand content, is the least erodible. This pattern highlights that shelterbelt configuration modulates soil particle size distribution, with vegetated sites (F1, F2, PF) accumulating finer, more erodible particles compared to the unprotected control (CK), a key finding for understanding how shelterbelt design influences soil wind erodibility.

This correlation heatmap quantitatively elucidates the relationships between soil wind erodibility (erodibility) and key soil properties (mechanical composition, moisture, nutrients), while also revealing the interdependencies among soil variables—providing a mechanistic basis for understanding variations in soil wind erodibility across different shelterbelt configurations (Figure 8).

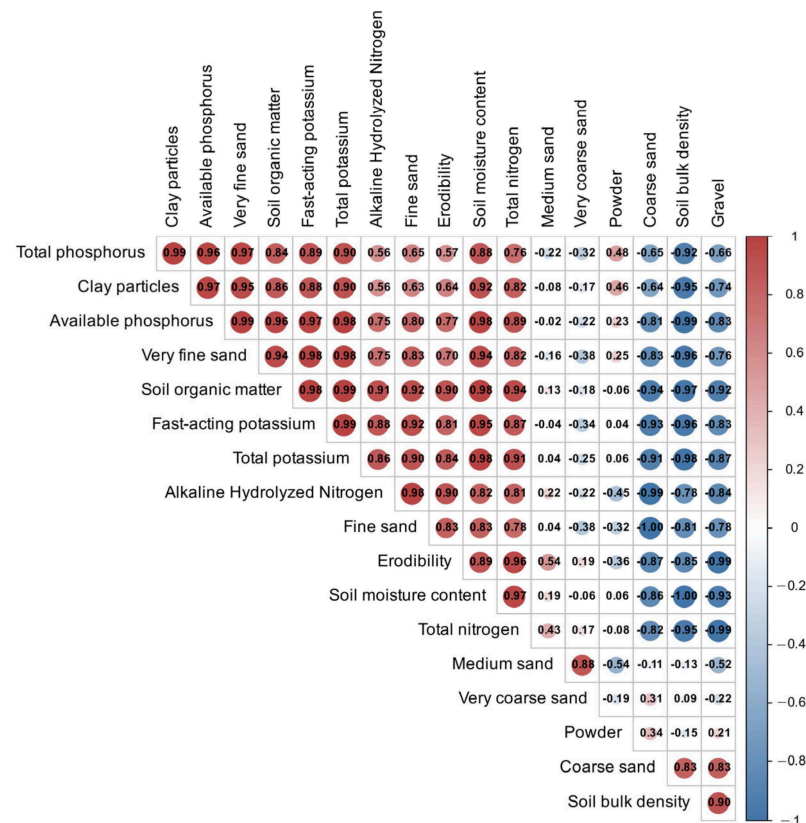


Figure 8. Pearson correlation matrix between soil wind erodibility and key soil physicochemical properties across different shelterbelt configurations. Notes: Color coding indicates the strength and direction of correlations (red: positive, blue: negative). Values represent correlation coefficients, with bold highlighting indicating strong relationships ($|r| > 0.8$).

Soil particle size exerts a dominant control on erodibility, with clear directional correlations observed across the texture spectrum. Clay particles show a strong positive correlation with erodibility (0.89), confirming that fine clay fractions are highly susceptible to wind entrainment and represent a primary source of erodible material. In contrast, coarse sand exhibits a strong negative correlation (-0.83), while gravel shows an even stronger negative correlation (-0.90); these coarse, stable fractions physically protect the soil surface and effectively reduce wind erosion potential. Medium sand, very coarse sand, and powder also display negative correlations with erodibility (-0.54 , -0.19 , -0.34 respectively), reinforcing the principle that coarser soil textures are less erodible by wind. Conversely, fine sand and very fine sand, critical components for erodibility, show positive correlations (0.17 and 0.43 respectively), as these intermediate particles are easily lifted and transported by wind turbulence.

Soil physicochemical properties are significantly linked to erodibility and particle texture, reflecting complex soil system feedback. Soil moisture content displays a strong negative correlation with erodibility (-0.97), highlighting its role as a primary stabilizing agent; higher moisture increases soil cohesion, significantly reducing wind erosion risk. This moisture variable also shows strong positive correlations with nutrient elements such as total potassium (0.83) and alkaline hydrolyzed nitrogen (0.22), suggesting that moist conditions generally support higher nutrient availability. Among nutrient indices, total phosphorus, available phosphorus, and total potassium exhibit strong positive correlations with each other (0.88 to 0.96), forming a nutrient cluster that generally aligns with higher erodibility, likely because finer-textured, more erodible soils tend to retain nutrients more readily. In contrast, soil bulk density shows a strong negative correlation with mois-

ture (-0.83) and a strong positive correlation with coarse fractions (0.83 for coarse sand, 0.87 for gravel), indicating that denser soils correspond to coarser, more stable, and less erodible substrates.

Collectively, the heatmap establishes a clear causal pathway: shelterbelt configurations that modify soil texture (e.g., increasing fine sand/very fine sand fractions) or elevate soil moisture (e.g., through vegetation litter retention) directly modulate erodibility. The strong negative correlation between moisture and erodibility, coupled with the textural controls, demonstrates that both physical stabilization (via coarse particles and bulk density) and chemical stabilization (via nutrient-moisture interactions) are key to reducing wind erosion in effectively configured shelterbelts. These findings quantify how shelterbelt design shapes soil structure and chemistry, thereby regulating the fundamental soil property that drives wind erosion risk.

3.3. Clustering Analysis of Wind Speed Profiles Across Shelterbelt Configurations and Heights

The hierarchical clustering heatmap (Figure 9) revealed distinct patterns of wind speed similarity across measurement heights and shelterbelt positions. Two primary clusters emerged: (1) a high-wind cluster comprising the bare sand control (CK) and all windward shelterbelt sites, characterized by high wind speeds (red coloration) at heights of 200–300 cm, indicating minimal shelterbelt influence on upper-level wind fields; and (2) a low-wind cluster comprising leeward and center shelterbelt sites, exhibiting significantly reduced wind speeds (blue coloration) at heights of 10–50 cm, indicating pronounced near-surface wind attenuation. Intermediate heights (80–160 cm) displayed transitional wind speed patterns.

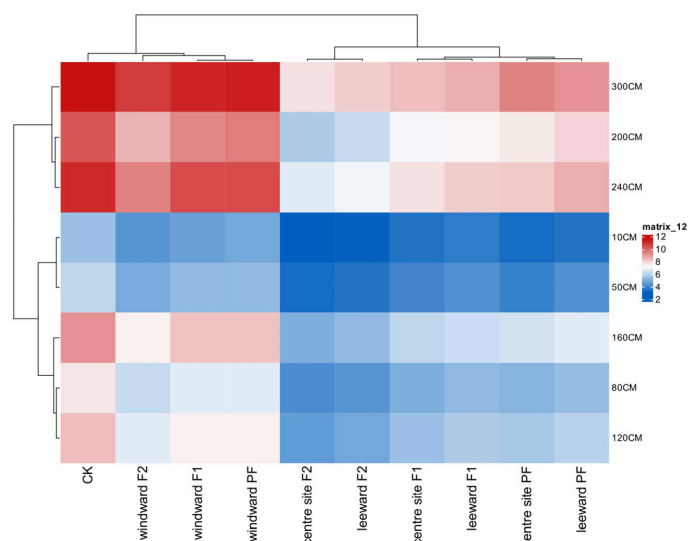


Figure 9. Hierarchical clustering heatmap of wind speed profiles across different shelterbelt types and heights in a windbreak system. Notes: Color scale: red represents high wind speed/similarity, blue represents low wind speed/similarity. CK: bare sand dune; F1/F2/PF: shelterbelt types; windward/leeward/center: shelterbelt positions.

This clustering pattern demonstrates that shelterbelt position (windward vs. leeward/center) exerted a stronger influence on near-surface wind speed distribution than shelterbelt configuration type (F1, F2, PF), highlighting the dominant role of shelterbelt layout in wind erosion control.

4. Discussion

4.1. Wind Regime Dynamics and Erosive Wind Potential in the Study Area

The wind regime of this study area exhibits strong directional heterogeneity and clear seasonal clustering, which is consistent with the typical wind energy environment of desert–oasis ecotones in the Hexi Corridor region [39,44]. Wind speed peaks sharply in the NNW direction (≈ 5.5 m/s), while occurrence frequency is highest in the W and WSW directions (120–170 times), showing a significant anti-correlation pattern between wind speed and frequency. This pattern indicates that the study area is controlled by the combined effects of the Mongolian High and topographic constraints, forming a stable dominant wind direction system [45,46].

Temporally, strong winds (>10 m/s) and erosive wind events (≥ 12 m/s) are concentrated in winter and early spring (January–March), with a secondary peak in late autumn, while summer has the lowest wind energy input. This seasonal distribution is consistent with the high-incidence period of wind erosion in arid regions of northwestern China [47,48]. Approximately 120 days of erosive winds per year confirm that the study area is under long-term high-intensity wind erosion pressure, similar to the ecologically fragile zone around the Minqin Oasis [40,49]. Such a wind regime provides the basic dynamic background for evaluating the efficiency of shelterbelts and soil wind erodibility.

4.2. Vegetation–Wind Feedback and Shelterbelt Configuration Controls on Sand-Fixing Efficiency

Vegetation height, near-surface wind speed, and windproof efficiency form a robust causal chain that dominates the sand-fixing performance of shelterbelts. Vegetation height is significantly positively correlated with wind speed reduction (overall $r = 0.817^{***}$, site-specific $r > 0.95^{***}$), confirming that taller vegetation acts as a more effective physical barrier to dissipate wind kinetic energy [50,51]. Meanwhile, wind speed is strongly negatively correlated with windproof efficiency (overall $r = -0.690^{***}$), demonstrating that reducing near-surface wind speed is the primary mechanism for suppressing sand entrainment and transport. The moderately negative correlation between vegetation height and efficiency (overall $r = -0.329^{**}$) indicates that height alone is insufficient to explain shelterbelt efficiency; shelterbelt configuration—including lateral cover, porosity, and spatial structure—also mediates sand-fixing performance [40,52,53]. Forest-type comparisons further reveal that F2 and PF consistently outperform F1, with lower median wind speeds and higher efficiency. This advantage arises from higher structural integrity, denser canopies, and weaker gap effects in multi-row mixed shelterbelts [54,55]. Intact shelterbelts can exceed 85% efficiency, while degraded belts drop below 40% [40,44], consistent with the efficiency gaps observed in this study. Vertical stratification analysis highlights a critical insight: short, dense vegetation layers (0–10 m and 10–20 m) contribute disproportionately high proportional efficiency (≈ 0.45 and ≈ 0.30), whereas upper layers (30–50 m) contribute little (≈ 0.08 and ≈ 0.05). This reflects the fact that aeolian sand transport is concentrated within 0–60 cm of the surface, making the shrub layer the frontline barrier for intercepting saltating sand [56,57]. Degradation and fragmentation of this layer directly reduce efficiency and can even activate nebkhas to form new sand sources [58,59].

4.3. Soil Texture and Profile Modulation of Wind Erodibility Under Shelterbelts

Soil particle size distribution exerts dominant control over wind erodibility, with clear and predictable textural effects. Clay shows a strong positive correlation with erodibility ($r = 0.89$), fine and very fine sand show moderate positive correlations ($r = 0.17$ and 0.43), while coarse sand and gravel show strong negative correlations ($r = -0.83$ and -0.90). These patterns align with classic aeolian theory: fine particles are easily entrained, whereas coarse fractions armor the surface to resist erosion [60]. Shelterbelts systematically modify

surface texture by trapping finer particles, resulting in higher fine/very fine sand content in F2 and PF, intermediate levels in F1, and the lowest in CK. This deposition pattern is a well-documented effect of reduced wind energy within vegetated belts [40,61]. Although finer textures increase inherent erodibility, vegetation cover offsets this risk by suppressing surface shear stress, creating a stable vegetated–soil system.

The clear separation between high-wind (CK/windward) and low-wind (leeward/center) clusters confirms that shelterbelts primarily attenuate wind speeds in the near-surface layer (≤ 50 cm), while upper-level winds (≥ 200 cm) remain largely unaltered. The dominance of positional effects over shelterbelt type differences suggests that optimizing shelterbelt placement (e.g., maximizing leeward coverage) may be more impactful for wind erosion mitigation than varying shelterbelt structural configurations alone.

5. Conclusions

Wind regime and wind erosivity potential: The study area exhibited a distinct decoupling of wind speed and directional frequency. Wind speed peaked in the NNW direction (≈ 5.5 m s^{−1}), while occurrence frequency was highest in the W and WSW directions (120–170 events). Erosive winds (≥ 12 m s^{−1}) were concentrated in January–March, contributing approximately 120 high-erosion days annually. Strong winds were rare in summer, indicating strong seasonal variability in wind energy.

Vegetation controls on sand-fixing efficiency: Vegetation height was significantly positively correlated with wind speed reduction ($r = 0.817$ ***), while wind speed was negatively correlated with windproof efficiency ($r = -0.690$ ***). Vertical stratification showed that short, dense layers (0–20 m) contributed over 75% of total sand-fixing efficiency, whereas tall layers (> 30 m) contributed little. Among forest types, F2 and PF achieved significantly higher efficiency and lower wind speeds than F1. Intact shelterbelts reached $> 85\%$ efficiency, while degraded belts fell below 40%.

Hierarchical clustering of wind speed profiles across shelterbelt positions and heights revealed two distinct groups: the bare sand dune (CK) and windward sites formed a high-wind cluster at 200–300 cm, while leeward and center shelterbelt sites constituted a low-wind cluster at 10–50 cm. This pattern indicates that shelterbelts effectively reduce near-surface wind speeds, with positional effects (windward vs. leeward/center) playing a more dominant role in wind regime modification than shelterbelt type differences.

Shelterbelts effectively attenuate near-surface wind speeds (≤ 50 cm), while upper-level winds (≥ 200 cm) remain largely unaffected. Positional effects (windward vs. leeward) outweigh shelterbelt structural differences, indicating that optimizing placement to maximize leeward coverage is a more effective wind erosion mitigation strategy than varying structural configurations alone.

In the context of ongoing climate change, increasing aridity and surface instability in dryland regions are projected to intensify wind erosion pressure, making the role of shelterbelt systems increasingly critical. The erosive wind patterns documented in this study—concentrated in January–March with approximately 120 high-erosion days annually—are consistent with trends reported in similarly vulnerable arid regions worldwide, including Central Asia and the Sahel, where wind erosion remains a major land degradation driver.

Author Contributions: Conceptualization, methodology, investigation, writing—original draft, K.Z.; software, resources, and writing—review and editing, A.B.; conceptualization, methodology, validation, data curation, and writing—original draft, R.M.; validation, data curation, review and editing J.W. All authors have read and agreed to the published version of the manuscript.

Funding: This study was financially supported by the Ministry of Science and Technology of China, The Third Xinjiang Scientific Expedition and Research Program: Meteorological Element Survey of the Turpan-Hami Basin (Grant No. 202134120009), and the National Natural Science Foundation of China (Grant No. 31971713).

Data Availability Statement: The data presented in this study are available on request from the corresponding author due to (specify the reason for the restriction).

Conflicts of Interest: The authors declare no conflicts of interest.

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