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Exploring the complexities of sand dune transformation: the role of anthropogenic degradation and climatic conditions

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Introduction: The sandy soils in the arid Southern Balkhash region have experienced anthropogenic degradation, leading to the formation of bare mobile sand dunes. This transformation has created significant challenges for the growth of cattle feed, particularly in areas with high economic activity. As a consequence, the socio-economic situation of the local population has been significantly worsened, and even the development of tourism has not helped. The objective of this study was to investigate the relationship between the seasonal mobility of sand dune landforms and their hydrothermal regimes, as well as the climatic conditions of the region.

Methods: To achieve the study objective, we conducted field investigations and collected data on the mobility of sand dunes, hydrothermal conditions, and climatic factors in the region. Measurements were taken during the summer months when dominant North-East, North-North-East winds prevailed, with an average frequency of 20.4–26.7 days per month and wind speeds ranging from 3.0 to 3.7 m/s, occasionally reaching up to 11.90–13.3 m/s. We also analyzed humidity, air temperature, and atmospheric precipitation levels.

Results: Our findings revealed that during the summer months, a fresh-sided layer of sand actively supplied the windward part of the sand dune to the leeward one. This process occurred under very low humidity, high air temperature, and slight atmospheric precipitation conditions. Consequently, the moisture content of the surface root layer (0–20 cm) of the sand dune accumulation zone decreased to 0.2% in the middle and at the end of summer.

Discussion: The observed relationship between the seasonal mobility of sand dunes and their hydrothermal regimes, along with the climatic conditions, provides valuable insights for the development of effective technologies to rehabilitate anthropogenically degraded desert sandy soils that have transformed into mobile sands. This knowledge can serve as a theoretical basis for addressing the challenges faced by cattle breeding in the region and improving the socio-economic situation of the local population.

KEYWORDS

anthropogenic degradation, sandy soils, mobile sand dunes, hydrothermal regimes, seasonal mobility, rehabilitation technologies

1 Introduction

Sandy soils and dunes are prevalent in numerous desert regions worldwide (Danin, 1996). Extensive areas of deep aeolian sands are located on the tablelands of Central Africa, particularly in the vast Kalahari Desert, situated between the equator and 30° southern latitude. Other regions with sandy soil distribution (Arenosols) include the African Sahel region (the tropical savannah belt south of the Sahara Desert), various parts of the Sahara, central and eastern Australia, the Middle East, and western China (Zádorová et al., 2021). In semi-arid environments, sand dunes are typically covered by vegetation. However, the destruction of vegetation due to overgrazing and the harvesting of woody vegetation accelerates the process of sand movement (Tsoar, 1990). The primary challenge posed by sand dunes is their mobility and erosion, rather than a lack of moisture, which limits vegetation growth. Wind-borne sand encompasses approximately 6% of the world's continental surface area, with 97% of these areas located in arid zones (Pye and Tsoar, 2009).

In Kazakhstan, significant expanses (25 million hectares) of sandy soils are found in the Priaral, Barsukii, Caspian, Kyzylkum, Moyynkum, and Pribalkhash regions (Dzhanpensov, 1977). The Southern Balkhash sand massif, the site of our research, spans an area of 7.3 million hectares and serves as a perennially water- and forest-deficient base for cattle breeding in the Almaty region, characterized by unfavorable environmental conditions (Almaganbetov and Grigoruk, 2008). The study area is particularly prone to dust and sandstorms, especially in locations impacted by human activity (Gulnura et al., 2014; Issanova et al., 2015). In this region, sandy soils develop under arid climatic conditions and active wind activity, which, when subjected to even short-term excessive anthropogenic loads, rapidly lose the texture of their upper horizons, ultimately becoming degraded and transforming into mobile aeolian sand sources. These mobile sands encroach upon many settlements and stationary field sites of peasant farms, significantly worsening their socio-economic conditions. The movement of livestock through sand dunes during daily cattle driving, as well as the active transport of sand grains by air masses, contributes to the expansion of areas occupied by mobile sands near the sites of peasant farms.

To date, the development of aeolian processes in the foci of individual sand dunes, resulting from the degradation of sandy soils in the Southern Balhash region, has been scarcely studied, though isolated works have primarily focused on the temporal and spatial characteristics of dust storms based on meteorological observations and cartographic materials (Issanova et al., 2023; Zhu et al., 2023). Studies of sandy soils warrant increased research attention toward soil and environmental issues in these areas (Huang and Hartemink, 2020; Rau et al., 2023). Consequently, the primary objective of our research is to examine seasonal geomorphological and hydrothermal processes within a single sand dune for a comprehensive understanding of their formation and the development of aeolian processes. Numerous studies of sand dune systems have been conducted globally, with recent research shifting toward modeling and remote sensing methods for sand dune development (Tsoar, 1983; Yizhaq et al., 2009; Diniega et al., 2010; Do et al., 2018; Auyelbek et al., 2021; Laiskhanov et al., 2021; Amanbayeva et al., 2022; Smyth et al., 2022; Zheng et al., 2022; Kalybekova et al., 2023). Nonetheless, this emerging focus does not render fieldwork obsolete, as accurate empirical field studies remain essential for a clear understanding of sand dune geomorphology. Furthermore, in recent years, the number of single dune studies has significantly declined (Livingstone et al., 2007).

Our research hypothesis aims to understand the formation of landforms and the hydrothermal regime of mobile dune foci under changing climatic conditions and human activities. This understanding will facilitate the development of techniques for restoring natural vegetation and soil cover in mobile sand foci, which will not only improve the ecological situation of the territory (by mitigating dust storm foci) but also enhance the socio-economic conditions of the population. Moreover, it will provide a feed base for the improvement of livestock farms and peasant farms, ensuring stable income and reducing poverty among the population in the most degraded desert pastures.

2 Materials and methods

2.1 Study area

Field studies were conducted in the southeastern part of Kazakhstan within the sandy massif situated in the Southern Pribalkhash. This region is part of the Balkhash-Alakul lake-alluvial province, characterized by bumpy-ridge sands and takyr-like soils. Approximately 80% of the area is occupied by poorly differentiated sandy soils and loose sands with aeolian relief, formed by the deluvial, fluvioglacial, and alluvial sandy deposits of the Ile River during the postglacial period. Notably, the deeply dissected sands of SaryIsikotrau in the interfluve lower reaches of Ile-Karatal, Lukkum, and Zhamanjal, as well as the interfluve of Aksu-Lepsi, Sarykum, Karakum, and Belsaksaul between the Balkhash and Sasykkul lakes, are characterized mainly by ridge, to a lesser extent bumpy and ridge-bumpy relief with a dismemberment amplitude of 3–60 m (Faizov, 1980). Vegetation comprises ephemeral-ephemeroid-sagebrush communities, with teresken (*Krascheninnikovia ceratoides L. Gueldenst*) and juzgun (*Calligonum*) found on the tops of the hillocks and ridges.

FIGURE 1
A fragment from space of foci of mobile sands formed as a result of anthropogenic degradation of sandy soils in the Southern Balkhash.

FIGURE 2
General view of rows of installed wooden pegs.

The selection of the field research site was based on a route reconnaissance survey of the sand massifs of the South Pribalkhash, with the aim of identifying areas with the greatest manifestation of anthropogenic degradation of desert sandy soils. A section in the form of a separate mature medium-brown movable sand dune measuring 150 m^2 with a height of about 6 m was selected around a stationary parking lot of a peasant farm located 5 km east of Bakbakty village, Balkhash district, Almaty region (Figure 1).

The object is located at N 44° 34″546′, E 076° 48″704’. The farm parking area is situated on a relatively elevated sandy loam light sierozem at a height of 1–1.5 m. Single mobile sand dunes began to form in the third year after the establishment of the stationary farm parking “Nurlanbek” in 1998. The year-round use of the territory as a pasture resulted in the appearance of separate small dunes near the parking area, reaching up to 0.5 m in height by 2006. These small dunes subsequently increased in size and created continuous chains of dunes covering an area of 2.2 ha around the farm parking. These circumstances led to the rapid expansion of the degraded sandy soils in the vicinity of the parking area and the disappearance of the vegetation cover, transforming the area into a chain of movable fine-charred dunes with blowing basins.

2.2 Seasonal geomorphological conditions

To investigate the impact of the wind regime on the seasonal dynamics of landforms and the direction of sand dune movement along its geomorphological profile, we identified three zones: denudation, transitional, and accumulation. The denudation zone is where windward flow separates and removes sand grains from the surface of the windward slope. The transfer zone is transitional, while the accumulation zone is where sand is scattered in the leeward slope. Five rows of wooden pegs were installed in April to cover these zones (Figure 2). These rows cross perpendicularly the windward and leeward slopes of the sand dune, with a distance of 2 m between pegs and 3 m between rows. Each peg was marked with a zero point in the middle, above, or below which sand filling or blowing was recorded in the three zones of the sand dune. The zero mark represents the early spring state of the sand dune, while subsequent measurements determine their seasonal dynamics from April to September. The intensity of deflationary processes, indicating the dynamics of relief forms, the direction, and intensity of sand dune movement, was determined by exposing negative or rising plus marks.

2.3 Soil morphology and analysis

To determine the composition of sandy soils and their degraded analogues, i.e., mobile dunes of the Southern Balkhash region, paired pits were excavated, and their morpho-genetic features were described. The chemical and physicochemical composition of soil profiles was determined by sampling and analyzing them in the laboratory. The humus content was determined by wet burning of humus carbon and its oxidation with bichromate, using I. Tyurin’s method. The total nitrogen content was determined according to Kjeldal by decomposing soil organic substances with concentrated sulfuric acid at boiling. The content of total phosphorus was determined according to Ginzburg, based on the extraction of total phosphorus by decomposing the soil with a liquid oxidizing agent (a mixture of sulfuric and perchloric acids), followed by the determination of phosphorus by the ascorbic method in the form of a molybdenum complex on a photoelectrocolorimeter. The ion composition (HCO3-, CO32-, Cl-, SO42-, Ca2+, Mg2+, Na+, K+) of water extract from soils was determined according to Gedroits. The total of salts and pH were obtained from the suspension of soils with soil-to-water ratio of 1:5. The particle size distribution of soils was determined by the pipette method, based on the relationship between the incidence rates of particles and their size according to Stokes’ law. The content of field soil moisture was measured by the weight method, by drying in a drying oven at 105°C for 6 h and subsequent cooling in a desiccator (Vorobyeva, 2006).

Additionally, sand temperatures were measured using a portable thermometer at depths of 0, 20, 40, 60, 80, and 100 cm in the windward and leeward parts of the sand dune on clear sunny days. The hydrological regime of the movable sand dune was determined by taking sand samples from depths of 0–20, 20–40, 40–60, 60–80, and 80–100 cm into aluminum vessels. The dependence of the intensity of sand accumulation in the leeward part of the sand dune on its moisture and temperature in the thickness of 0–60 cm, and climatic indicators such as wind speed, humidity, air temperature, amount of precipitation, and windy days per month, was analyzed using the Statistica program (http://www.statsoft.com).

3 Results

3.1 Morphology, composition and properties of sandy soils and mobile dunes

The main material responsible for the formation of desert sandy soils in the Southern Pribalkhashye is the ancient alluvial deposits of the Ile River. The river, which changed direction many times in the delta region, deposited material of various grain size distribution, including sand. Subsequent waving led to the formation of modern sand massifs in Pribalkhash. These sand massifs are characterized as fixed, semi-fixed, or unsecured by vegetation, with bare moving sands forming various dune sizes as a secondary phenomenon. They are found only near wintering or along the outskirts of sand massifs, where overgrazing, cutting, and uprooting of shrub or semi-shrub and grassy vegetation for fuel are carried out. Recent disturbances have occurred in places where natural gas supply pipes were laid (Sokolov et al., 1962).

To determine the degree of transformation of the surface, composition, and properties of desert sandy soil into mobile sands of dunes in anthropogenic-degraded pastures of the Southern Balkhash region, we excavated paired pits on desert sandy soil in the basin of blowing aeolian relief of a fixed sand massif and on a bare mobile sand dune (Figure 3). The coordinates for this study are N44°34′35″, Ye76°41′55″, with macrorelief consisting of a lowland bumpy sandy massif called Sary-esikatyrau, and mesorelief consisting of a bumpy-hilly-cellular sandy ridge. The vegetation is represented by Zhuzgun shrubs (*Calligonum*), with teresken (*Krascheninnikovia ceratoides L. Gueldenst*) and cereal-sedge vegetation covering the surface between them. Shrubs cover 40% of the surface and the soil surface is fixed.

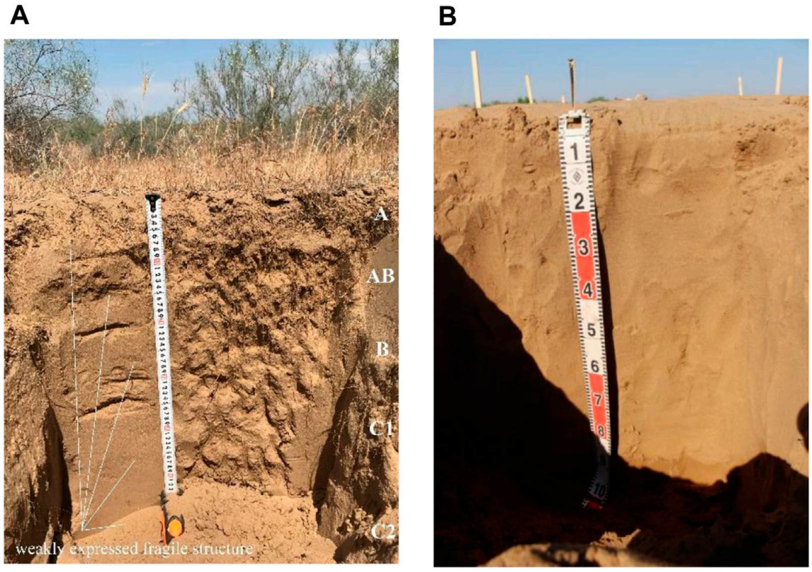

FIGURE 3
The profile of sandy soil **(A)** and its degraded forms, including a mobile sand dune **(B)**.

The sand soil fixed by vegetation has a profile consisting of weakly differentiated genetic horizons and a weakly expressed fragile structure. Rapid boiling from 10% hydrochloric acid is observed on the surface and throughout the profile. The A horizon (0–8 cm) has a light gray color with a yellowish tint, a dry, loose, fragile-lumpy-dusty structure, rootiness, a sandy composition, and no visible chemical neoplasms. According to the density difference, this horizon gradually passes into the underlying AB horizon, with a thickness of 8–20 cm. The AB horizon has a light yellowish-brown color with a yellowish tint, fresh, slightly compacted, fragile lumpy-dusty fine-porous structure, rootiness, and sandy particle size distribution. The transition to the lower horizon occurs gradually in color. The illuvial B horizon (20–35 cm) is colored yellowish-brown, has a fresh, structureless, sandy composition, and isolated roots of vegetation. The described horizon gradually turns into the parent material by color. The parent material is divided into two horizons: C1 (35–70 cm) and C2 (70–120 cm). They differ in their saturation in yellowish-brown color and have a weakly compacted, structurally-free, finely porous, and sandy structure without visible chemical neoplasms.

In contrast, the mobile sand dune had no vegetation on the surface and was represented by a homogeneous fresh-sided sand with a thickness of about 50 cm in composition and properties. Within the latter, the loose sand in dry inspired sand has a grayish-pale-rosy yellowish color, wet slightly compacted, in places thin-bedded structure due to winding up, without visible roots of psammophytic shrubs. The physicochemical analysis of samples of desert sandy soils showed that the humus content in the upper 0–5 cm layer is 0.37% (Table 1). It gradually decreases to 0.27% and 0.17% as it deepens down the profile.

The humus content in degraded mobile dune sand is very low, ranging from 0.17% to 0.10%. The low humus content in sandy soil and mobile sand results in extremely low levels of total nitrogen and phosphorus. In the 0–5 cm layer of sandy soil, the total forms of nitrogen and phosphorus are 0.028% and 0.080%, respectively. These values decrease with depth to 0.018% and 0.064%, respectively. In the sand dune, the total forms of nitrogen are similar to those in sandy soil, at 0.028%, but are found within the 0–20 cm layer. The phosphorus content in the sand dune is inferior to that in sandy soil, at 0.064% and 0.060% in the 0–20 cm and 20–40 cm layers, respectively. Throughout the profile, these formations have very low carbonate content. However, the CO2 content in sandy soil (1.49%–2.42%) is slightly higher than in mobile sand (1.14%–1.59%).

The mechanical fraction composition of sandy soil and mobile sand is dominated by sand (2.0–0.05 mm), which accounts for 94.0%–95.0% of the meter thickness (Table 1). The second most significant fraction is dust (0.05–0.005 mm), which accounts for 3.62% of the upper part (0–15 cm) of sandy soil. In the sand dune, the dust content drops to 2.82%, but it increases to 4.02% deeper along the profile before decreasing to 3.3%. The clay fraction (<0.005 mm) in the root soil zone (0–33 cm) of sandy soil is slightly higher (1.61%) than in other parts of sandy soil (1.21%). In the sand dune, the clay content is unevenly distributed among the layers. Its maximum (2.01%–2.41%) is observed mainly in the lowest layers (60–80 and 80–100 cm), whereas in other parts of the sand dune, the clay content is the same (1.61%) as in sandy soil.

The mineralogical composition of the sands of the Southern Pribalkhash is more favorable in terms of their fertility. It is characterized by a lower content of quartz (30%–60%), an increased content of feldspar and calcite. These sands are polymineral. They are dominated by medium-resistant minerals (feldspars, horn blende, biotite, augite) and poorly stable minerals (calcite, dolomite, gypsum) have survived. These are the "young" sands in the history of the Earth (Gael and Smirnova, 1999). The above is evidenced by the mass fraction of the elemental composition of the sand fraction of the sand dune, where the silicon content varies from 23.63% to 35.22%. Whereas the mass fraction of oxygen varies from 7.12% to 11.45%, calcium from 23.92% to 43.03%, carbon from 6.12% to 9.44%, aluminum from

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TABLE 1 The chemical composition and physicochemical properties of sandy soil and their degraded counterparts in the form of mobile sands.

Name	Sample depth, cm	Total humus, %	Total nitrogen, %	Total phosphorus,%	CO_2	Total salts, %	Fraction			CEC, meg/100 g of soil
					%		Sand (2.0–0.05 mm)	Dust (0.05–0.005 mm)	Clay (<0.005 mm)	
Sandy soil	0–5	0.37	0.028	0.080	1.49	0.027	95.18	3.62	1.21	3.04
	5–15	0.27	0.018	0.064	1.97	0.040	94.78	3.62	1.61	2.55
	23–33	0.17	0.018	0.064	2.42	0.039	94.37	4.02	1.61	3.55
	50–60					0.046	94.78	4.02	1.21	2.56
	90–100					0.038	95.18	3.62	1.21	2.58
Sandy dune	0–20	0.17	0.028	0.064	1.14	0.038	95.18	2.82	2.01	2.57
	20–40	0.10	0.018	0.060	1.59	0.038	94.38	4.02	1.61	2.07
	40–60					0.038	94.38	4.02	1.61	2.07
	60–80					0.033	94.00	4.01	2.01	2.57
	80–100					0.038	94.38	3.21	2.41	3.07

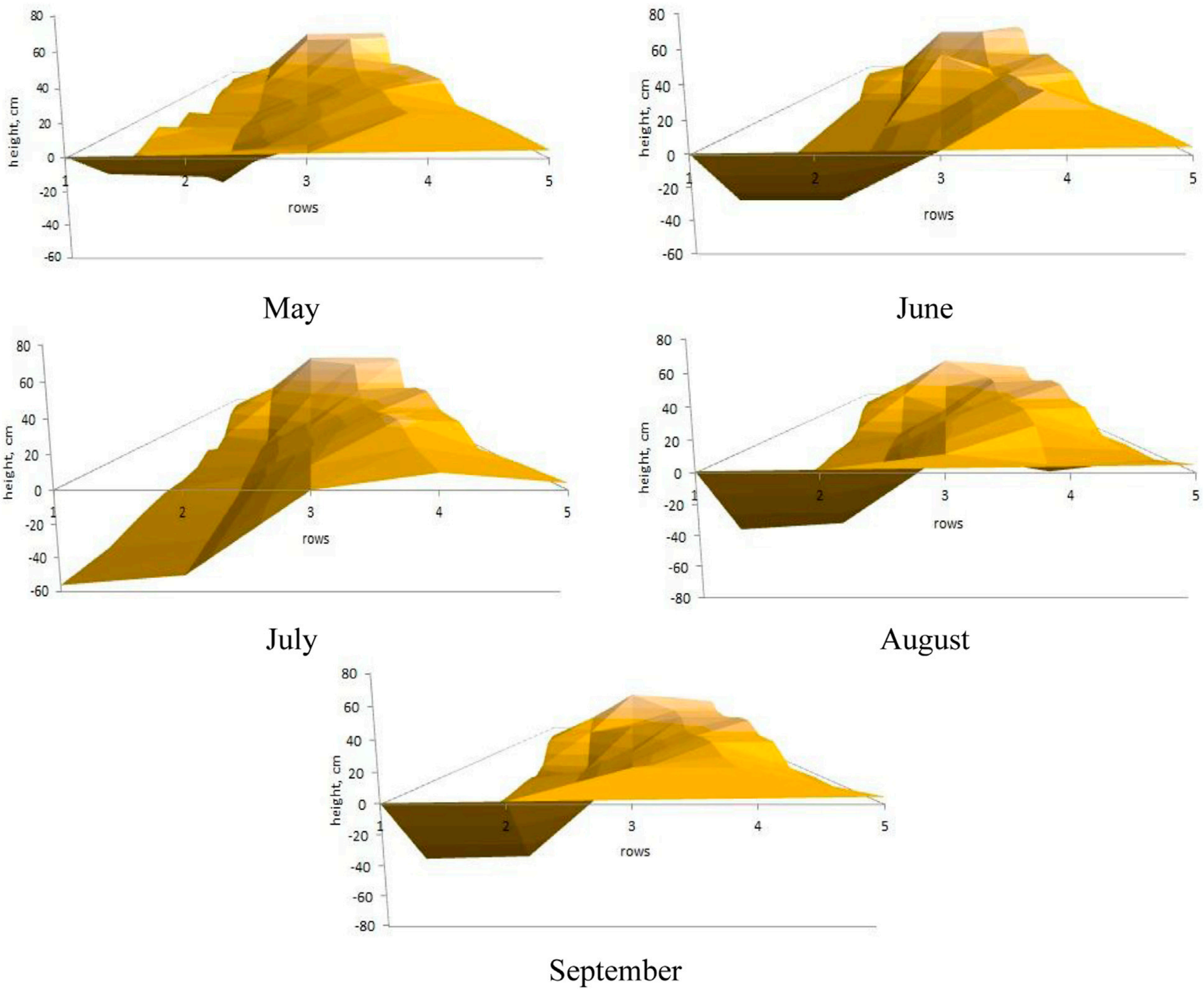

FIGURE 4
Influence of wind activity in the area on the change in relief shape, direction, and intensity of movement of the sand dune.

6.41% to 17.06% and potassium on average 5.1%. It follows that in the mineralogical composition of sand particles a significant part is occupied by quartz (SiO_2). Because of its high resistance to physical weathering without changing its chemical composition, it mainly concentrates in coarse and fine sand fractions. Under a microscope, quartz has transparency and glass sheen in transmitted light, as well as reddish deposits of iron hydroxide rust on their surfaces. Against the background of freestanding quartz minerals, its secondary crypto - crystalline forms are in close fusion with other minerals ($KAlSi_3O_8$), which do not transmit light and are painted in darker colors (Naushabayev et al., 2022a).

The total content of water-soluble salts in the sandy soil and mobile sand of the desert does not exceed 0.1%, indicating non-salinity (Table 1). However, it is important to note that South Pribalkhash is located within the soda-sulfate province of salt accumulation (Borovskiy, 1982). A small fraction of the dust and clay fraction of sandy soil and mobile sand has a practically uniform very low absorption capacity (2.07–3.07 meq per 100 g of soil). However, in sandy soil in the horizons of plant root propagation (0–5 and 23–33 cm), the absorption capacity is slightly higher (3.04 and 3.55 meq per 100 g of soil, respectively).

3.2 Seasonal geomorphological and hydrothermal regimes of mobile dunes

Fixed sand dunes exhibit dynamic relief forms that depend on various factors, including prevailing wind speed and direction, sand particle size distribution, and moisture content. While particle size distribution remains relatively constant for a given sand massif, wind direction and speed, as well as sand moisture and temperature, may vary throughout the year. Consequently, studying the seasonal dynamics of mobile sand dune relief forms requires a comprehensive investigation. This enables the determination of the duration and intensity of deflationary processes by season and over several years, which is essential for establishing the direction and rate of movement of individual dunes and entire sand massifs.

Considering the above, we examined the seasonal changes in relief forms of an aeolian sand dune in relation to the seasonal humidity, thermal regime, and wind activity of the area. Our observations indicated that the sand dune, which developed during the previous wet months, formed a shape in May that consisted of gentle windward and steep leeward parts. The dune

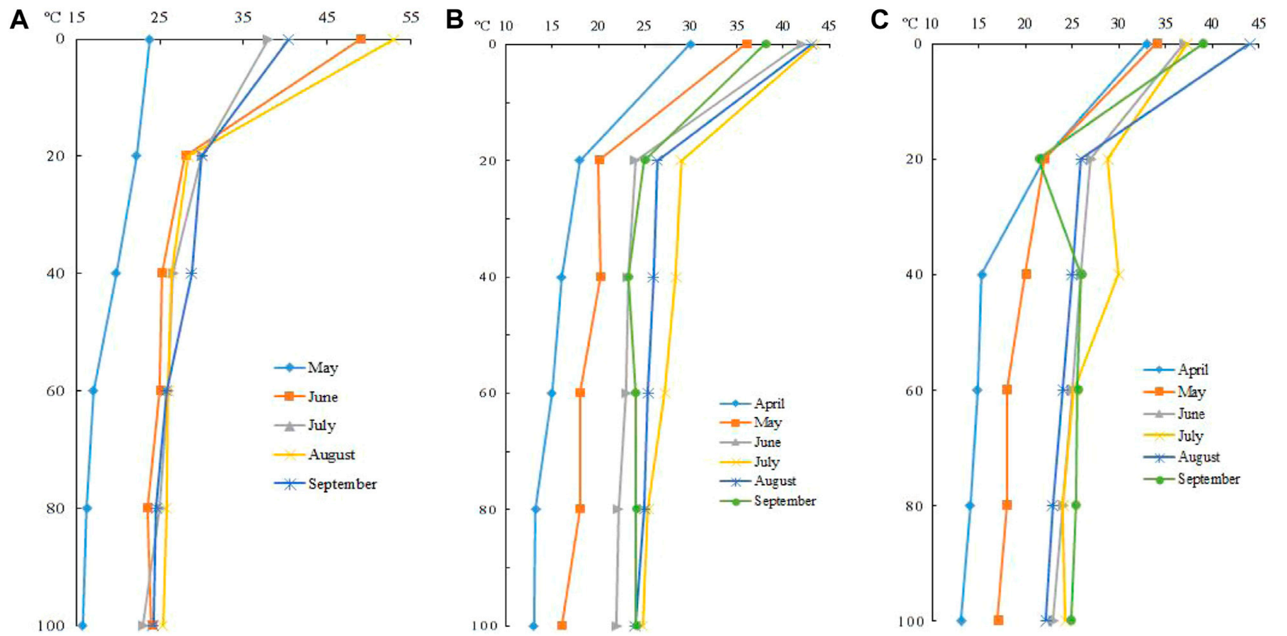

FIGURE 5
Seasonal temperature dynamics of desert sandy soil **(A)** along with the windward **(B)** and leeward **(C)** parts of the sand dune.

was oriented towards the south and southwest directions. Sand removal from the northeast windward slope reached a thickness of −28–30 cm, occurring in the first and second rows of parallel pegs, whereas sand accumulation on the southwest slope reached a thickness of 4 and 5 rows of the sand dune (Figure 4).

During the beginning of summer (June), there is further intensive sand removal on the same slope of the sand dune, reaching a level of −50 cm. This influence was observed in 80% of the pegs of the 1st and 2nd rows of the sand dune. On the leeward slope of the 4th and 5th rows, sand growth was observed to be +70 cm. In the hottest month (July), sand is moved and removed to −55 and −60 cm from the windward part of the dune, with an increase in the blown layer to +80 cm on the leeward side. Deflationary sand removal continues in the same direction in August and September, resulting in a small volume of sand mass removal and an increase in the height of the ridge lines. However, there is a gradual stabilization of the sand dune surface compared to previous months, as indicated by the data on measuring pegs indicators, which were the same as in August (Figure 4).

The seasonal dynamics of the landforms of a free-standing sand dune show that in the summer months (June, July, and August), a round-scale shape forms in the sand dune. Sand removal occurs from the destructive gentle windward part of the dune (depression up to −50 cm from the early spring surface) into its first destructive-accumulative, and then into the steep accumulative leeward. As a result, the thickness of the blown layer of sand increases by +70 cm as it approaches the ridge line. These indicators suggest the presence of a high intensity of deflationary processes on the dune, as evidenced by a significant excess of the volume of the new blown layer of sand in the accumulative part, removed from the destructive and destructive-accumulative parts.

It is known that the normal growth and development of sand-strengthening shrubs (*Haloxylon*, *Calligonum*) on sandy soils and mobile sands depend not only on the variability of relief forms depending on the wind regime but also on their provision with optimal hydrothermal conditions. The results of determining the thermal regime of normal desert sandy soil showed that the soil surfaces are highly heated in June to 49°C and in August to 53°C, against the background of the general trend of temperature growth within 1 m (Figure 5).

In July, the soil surface temperature drops slightly to 38°C due to a slight moisturization of its 0–4 cm layer from short-term rains before our measurements. From the beginning of June, the soil temperature rises sharply at a depth of 20 cm to 28°C–30°C and remains at this level until the end of September. The surface of all parts of the sand dune starts heating up in April and remains heated until the end of summer and beginning of autumn. The windward part of the sand dune is less heated in April, with the sand temperature at a depth of 20 cm reaching 18.0°C, gradually decreasing to 13.0°C with depth. The leeward part of the sand dune is slightly more heated at the same depth (22°C). From April to the end of August, there is a general trend of an increase in surface temperature and in the meter of sand dune. However, in July, the temperature of the sand dune at a depth of 20 cm reaches maximum values (29°C), gradually decreasing to 24.8°C with depth. From the beginning of August, there is a gradual decline in temperatures in the thickness of 20–60 cm in the denudation zone of the sand dune, while there is first a decrease in the zone of sand accumulation in August, followed by a reverse increase in its underlying layers (40–100 cm) in September. The latter seems to be due to the influence of overlying inspired sand, which creates a slight warming of the underlying layers. Within the months of April-September, the temperature difference between the sand surface and the depth of 20 cm in the windward part of the sand dune is 12, 16, 18, 14.5, 16.7, and 13.1°C, respectively. Therefore, the temperature regime of the sand dune for the months of April-August is quite favorable for growing seedlings of sand-strengthening woody-shrub plants.

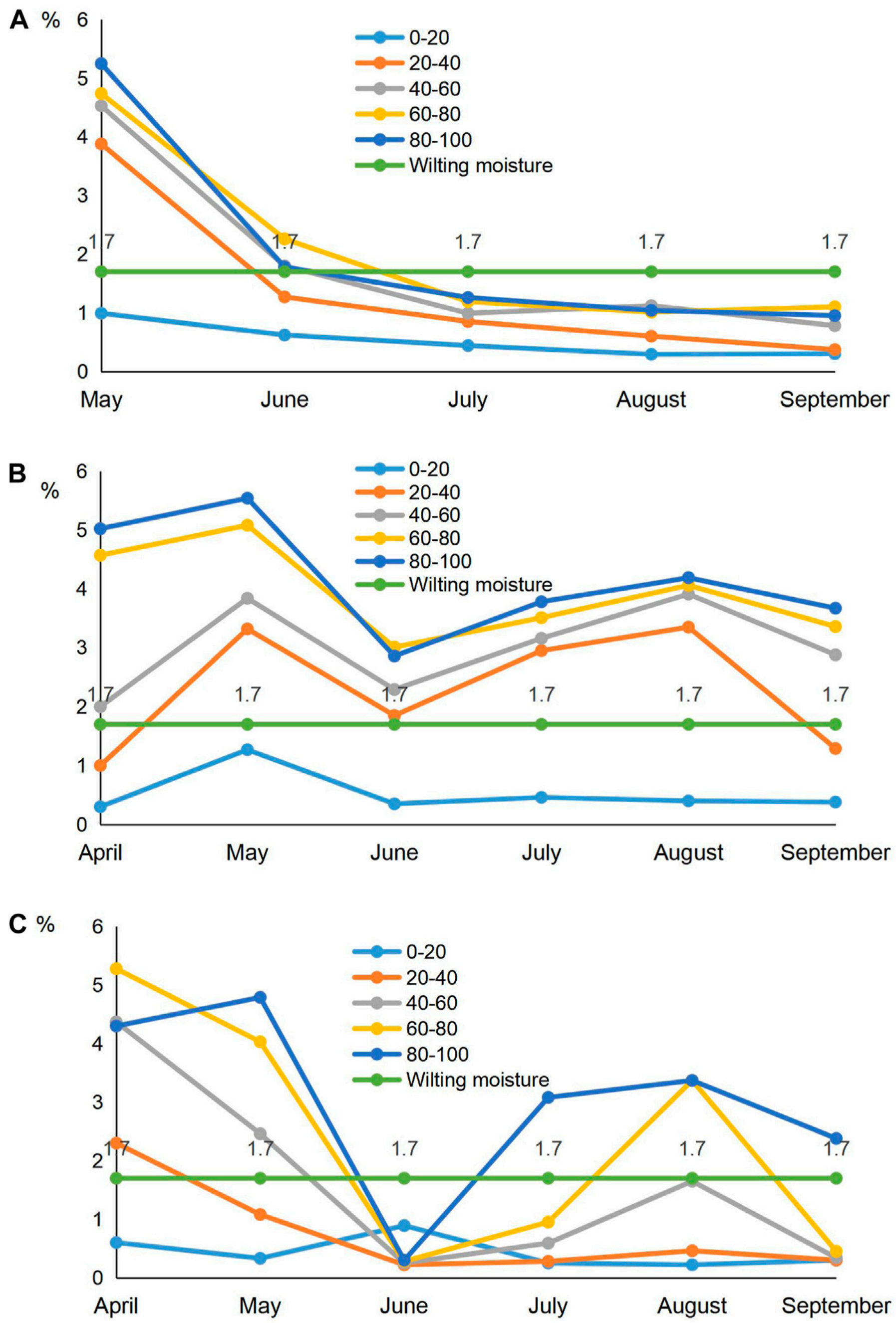

FIGURE 6
Dynamics of field moisture of sandy soil **(A)** as well as the windward **(B)** and leeward **(C)** parts of the mobile dune.

The dominant winds of the Northeastern and North-Northeastern directions with high speed and gusts, along with a gradual increase in air temperature and decrease in humidity, lead to the drying up of not only sand dunes without vegetation but also normal fixed sandy soils. Since May, these soils have been lacking moisture in the 0–20 cm layer, and the meter thickness since June (Figure 6). In May, the humidity of sandy soil ranges from 3.88% to 5.25% within 20–100 cm, decreasing sharply to small values (~1%) in the following months. From June to September, the natural humidity of a meter of sandy soil falls below the wilting moisture content of plants (1.7%), established by us through physical modeling in laboratory conditions (Naushabayev et al., 2022b).

The water regime of the sand dune presents a different picture compared to normal sandy soil. In April, the thickness of the 0–60 cm windward and leeward parts of the sand dune contains moisture that does not exceed 2%. The studies revealed that the windward part of the sand dune has better moisture provision than its leeward part. However, from April to September, the surface 0–20 cm layer of all parts of the sand dune has low moisture. In the windward part of the sand dune, the humidity rises from 0.3% to 1.27% at the same depth in April, drops to 0.35% in the next month, and remains practically constant until October. For instance, in May, field observations showed that the denudation and transition zones of the sand dune have visually dry and loose surface layers with a thickness of 5 and 25 cm, respectively. Deep desiccation of the sand dune is also observed in the accumulation zone, i.e., in its leeward part since June. During this period, the humidity of the sand within the meter thickness ranged from 0.22% to 0.89%, which was below the wilting moisture content of plants (1.7%). Such a picture remains until October in the first half of the meter layer. A slight increase in humidity in the leeward part of the sand dune in June is associated with a slight wetting of the 0–20 cm layer after precipitation. Obtaining moisture from precipitations, the wetted surface layer of sand reduces aeolian transport even at wind speeds of more than 4–5 m/s. Mist and dew condensation do not affect the humidity of deeper layers of sand, which occurs after precipitation (Żmudzka et al., 2014). In the hottest month, the depth of desiccation of the leeward part of the sand dune reached 80 cm, which was established during sampling, when the incision was covered with dry and loose sand, despite the fact that the 0–4 cm layer was slightly humid. The low humidity of the leeward part of the sand dune during the summer months is supported by data showing that in June, the humidity in the meter thickness varied from 0.22%–0.89%, in July from 0.25%–0.95%, and in August 0.22%–3.37%. The reason for this low moisture content in this zone is the rather strong warming of the ridge and slopes of the southern and southern-western exposure against the background of a small amount of precipitation (total 168.2 mm on average for 2020–2021), which is typical for sandy deserts, high temperature (24.9°C–27.8°C), and low relative air humidity (5.2%–7.2%) of the summer months, the activity of the winds of the Northeastern and North-Northeasterndirections, blowing at a speed of 3.0–3.5 m/s, and its attenuation in this zone and the formation of a wind shadow. These humidity values, which fall below the wilting moisture content of plants (<1.7%), even in May, limit the survival of seedlings in their first year of life.

4 Discussion

The presence of widespread degradation in sandy pastures due to constant grazing at the same site in close proximity to settlements contributed to the development of deflationary processes (Torekhanov and Ernst, 2005), which caused a change in the botanical composition of vegetation, a decrease in productivity and food quality (Kaldybayev et al., 2019). After the collapse of state farms in the mid-1990s, most pastoralists were forced to graze their animals in circles around populated areas as they could not afford to make seasonal migrations (Kerven et al., 2008). Because of this, the most serious degradation of pastures is observed in areas adjacent to rural settlements, wells and pastures (Laiskhanov et al., 2018; Tokbergenova et al., 2018). Uncontrolled grazing and high livestock rates around human settlements have led to both environmental degradation and decreased livestock productivity, despite the overall decline in sheep numbers in the post-socialist period (Alimaev et al., 2008). In addition, poor pasture management has been exacerbated by land privatization (Suleimenov et al., 2012). Kazakhstan has undergone a long-term expansion of cultivated land occupied by high-quality pastures, which has led to the movement of livestock products to desert vegetation areas (Yan et al., 2020). In South Pribalkhash, which includes the area of our research, the reason for the degradation of sandy pastures was the active predatory use by the local population of saxaul (*Haloxylon*) as fuel after the construction of a rice farm in 1968–1978, which caused a decrease in their number (Lebed et al., 2012). In addition, shrub - herbaceous vegetation was used as pasture feed. This process continues at this time. This led to the complete disappearance of the soil cover with the formation of bare mobile sands, where even traces of the original soil did not remain. In this regard, an important and urgent task is to organize measures to protect territories and structures from filling with sands, as well as stop breaking overgrown sands by maintaining a system of rational grazing. Active measures against mobile sands should be aimed mainly at combating the consequences of breaking of fixed sandy soils, and preventive measures are aimed at eliminating the causes of mass formation of bare foci of mobile sands.

A comparative study was conducted on the morphology, composition, and properties of fixed sandy soils and mobile dune sands formed from them. The results revealed that due to anthropogenic degradation, the latter were completely devoid of vegetation and pronounced upper humus and underlying rooty layers. The upper layer of the sand dune with a thickness of about 50 cm was represented by a homogeneous fresh-sided moving sand in composition and properties. Normal sandy soil has low levels of fertility, with an average humus content of 0.3%, which is further reduced to 0.1% in the sand dune. The fractional composition data showed that the sand soils of South Pribalkhash, together with sand dunes, consist of 95.0% sand fraction (2.0–0.05 mm).

The seasonal dynamics of the landforms of a single sand dune revealed that it consists of more or less gentle windward and steeper leeward slopes, and gradually shifts towards the south and southwest directions due to the widespread development of deflations. This process occurs against the background of a gradual increase in the average air temperature (from 21.0°C to 26.95°C), a decrease in relative average monthly humidity (from 16.7% to 7.7%), and a decline in the amount of precipitation (from 19.35 to 5.3 mm). High wind activity (22–25 windy days per month) is also observed from Northeastern, North-Northeastern, and East-north-eastern directions, blowing at a speed of 3.3–3.5 m/s, with breakthroughs up to 11.90–13.3 m/s (http://www.kazhydromet.kz). It is worth noting that with a weak wind at a speed of 3.5 m/s (at a height of 15 cm from the surface), the movement of medium and small sand particles (0.5–0.05 mm) begins. At a speed of 6.5 m/s (moderate wind), transported particles can be raised to a height of up to 11 cm above the surface, forming a wind flow. Almost the entire surface layer of sand comes into motion starting from 15 m/s (Dobrin, 1965).

The South Balkhash winds' repeatability analysis revealed that in the warm season, the wind regime of the mobile sand dune is affected by winds from different directions. In June, besides the consistently dominant Northeastern and North-Northeastern winds, the winds blowing across the South-western, Western, and South-southeastern directions intensify. It is likely that similar northeast and northwest wind systems control the orientation and morphology of modern Takla Makan Desert dunes in China (Sun and Gao, 2022). The speed of westerly winds is usually higher than that of easterly winds, which is attributed to the significant temperature gradient and pressure between a wetter and cooler air mass in the north-northwest and a dry and warmed-up air mass in the east-southeast of the studied territory.

The variability of the sand dune relief forms depends not only on the wind regime but also on the optimal hydrothermal conditions. The intensity of sandy particle transfer by wind is inversely proportional to the sand's humidity. Therefore, accumulative and deflationary processes on bare mobile sand dunes receive the greatest development in the summer months. For example, in the denudation zone in the surface root layer (0–20 cm) of the sand dune, the humidity was below 0.4%–0.5% from April to September, while in the zone of sand accumulation, it completely dropped to 0.2% by the middle and end of summer. The windward part of the sand dune is slightly better provided with moisture than its leeward part. The introduction and application of fresh, air-dry sand material from the windward part of the sand dune into the leeward dune leads to deep drying of the sand accumulation zone within the meter layer. In June and September, the sand humidity did not exceed 0.4%. In July and August, the months with the highest temperatures, the humidity of the sand did not rise above 0.5%–0.6%. Even the natural humidity of the meter layer of sandy soil from June to September falls below the wilting moisture (1.7%) of plant cover. Since the beginning of June, there has been a lack of moisture (0.4%–0.6%) in the 0–20 cm layer, especially in late summer and early autumn (0.3%). In more favourable climate conditions, such as in Studland, Dorset, on the south coast of England, average humidity levels in the dunes (excluding depressions) were close to 7% and ranged from 1% to 18%. There, the speed and sensitivity of the reaction of barchan sands to humidification and drainage decreased noticeably with a depth of 1.3 m. The uppermost layer was the most sensitive and experienced the most wetting and drying cycles. In dunes without vegetation, moisture remained at a depth of. Spatially, dune ridges represent the driest places, as in our case, small but persistent differences in humidity were recorded between windward and leeward slopes (Gardner and McLaren, 1999). The high surface temperature of the windward and leeward parts of the sand dune is the indirect reason for this. By mid-summer (July), the surface temperature of the windward and leeward parts heats up to 43.1°C and 37.3°C, respectively, while in sandy soil, it reaches 38°C. The surface temperature of the latter heats up strongly in June to 49°C and in August to 53°C against the background of the general trend of temperature growth within 1 m. A slightly wide variation in surface temperature from 13°C to 57.5°C of unstabilized dunes was recorded in the Bikaner region of India. In this case, daily fluctuations extended to a depth of up to 50 cm (Gupta, 1979). Correlative analysis shows a significant positive dependence of the intensity of sand accumulation in the leeward part of the sand dune on the amount of precipitation ($r = 0.9$) and windy days per month ($r = 0.8$). Moreover, there is a close natural relationship between the sand temperature in the thickness of 0–60 cm and the surface layer of the atmosphere's humidity ($r = -0.9$) and temperature ($r = 0.9$).

Thus, under the above conditions, the surface layer of sand dunes dries rather quickly, and sand masses predominantly transfer along a more gentle windward slope to the leeward in the west and west-south-western directions. Wind in the air carries particles with a diameter of <0.5 mm, while particles >0.5 mm move by rolling over the surface (Dobrin, 1965). However, in places with insufficient wind speed, the upper and lateral wind flows lose their speeds when meeting the zone of reduced pressures behind the dune ridge line, leading to sand falling out of the flow and accumulating on the leeward slope. As a result, the surface level of the windward slopes of the sand dune decreases, and its ridge part's height increases, where accumulative relief forms are observed. Sand is blown and removed to the level of −50 and −60 cm from the windward part of the dune and added to +80 cm in the leeward. This intensive movement of sand material from one part of the dune to another creates unfavorable conditions for the growth and development of psammophytes, filling their root necks, or exposing their root system. The gradual stabilization of the sand dune surface occurs in late September.

In October, due to a sharp decrease in the average monthly air temperature (to 8.0°C) and a slight increase in the amount of precipitation (6.3 mm), the relative humidity of the air (19.6%) increases noticeably. This generally leads to cooling and an increase in the humidity of the surface layer of the dune during the warm season. Under similar air and soil conditions, even moderate active winds blowing uniformly from the northeast, north-northeast, and south directions with an average speed of 2.4 m/s (breakthrough 9.4 m/s) for 16 days cannot have a noticeable impact on the deflation process's development or the change in the relief forms of sand dunes.

The restoration of the soil and vegetation cover of the mobile sands of the South Balkhash can be carried out by sowing or planting native or promising species of feed plants recommended for sandy soils of the zone. In this case, many species of arid plants can be used, such as *Haloxylon*, *Calligonum*, *Turanga (Populus)*. They will not only increase the productivity of pastures, but will also contribute to the consolidation of mobile sands. However, the results of our studies show that the survival rate of seedlings or seedlings of sand-strengthening plants can be very low due to the low humidity of sand (<1.7%) and its strong warming in the summer months and the continuous movement of sand from the denudation part of the sand dune to the accumulative one by the dominant north, north-east winds. It is recommended to develop a combined technology for effective restoration of the soil and vegetation cover of fluttering sand centers, the essence of which is to protect (isolate) the exposed surface of sand from the influence of wind and weaken the blowing processes using vertically standing wind shields, and to provide additional moisture, use polymer hydrogels when planting phytomeliorant seedlings. If you take into account the change in the configuration of the sand dune relief over time, mechanical shields should be installed in early spring (in March) or late autumn after moistening the sand with sediments, since the dryness and flowability of the sand will make it difficult to install shields. In the summer months, in the windward part of the sand dune, sand removal reached a depth of −50 cm from the early spring surface and led to the formation of a thick suspended layer of sand with a capacity of +80 cm in the leeward accumulative part. Therefore, to ensure the wind resistance of the mechanical panels, they must be installed in the above-mentioned parts of the sand dune and connected to each other, thus forming a continuous network of square cells. The main design data shall be board height and slope steepness. Distances between rows of standing windshield panels shall be calculated for wind shadow, i.e., the height of the top of the lower row of mechanical panels shall coincide with the base of panels located above the level. The size of reed cells depends on the material and can be $2 \times 2 = 4\ m^2$, for example, when using reeds. The size of each reed shield can be $1\ m^2$, its size must be increased in the leeward part of the dune. Each panel is installed in a 0.50 m deep ditch, and its remaining above ground part will protrude on the surface 0.50 m high. *Haloxylon* or *Calligonum* seedlings are planted in each such cell in early spring (in March) in the amount of 4 pieces in pits 20 × 20 cm in size. At the same time, polymer hydrogels are installed in their roots, which, in combination with slowing down or stopping blowing winds with mechanical protections, allows seedlings of the first year of planting to survive in the hot summer months. Forest shrubs that survived this period develop a highly developed root system that allows you to retain the movable layer of the sand dune.

5 Conclusion

Sandy soils are widely distributed on the sand massifs of Southern Balkhash and are characterized by a weak humus horizon and low humus content (0.30%). In the absence of reasonable grazing, these soils are usually found near settlements or stationary field sites of peasant farms and lead to the rapid suppression and disappearance of vegetation cover, as well as the destruction of the natural composition of the soil's surface horizons. Despite their eternal moisture deficit, they are valuable pastures for the region's cattle breeding. However, under the influence of dominant winds for over 5–10 years, they turn into movable sands, forming separate dunes and dune chains with depressions between them, which cause social and economic inconvenience to the population in areas of active manifestation. Studies have shown that sandy soils and mobile sand dunes formed from them as a result of anthropogenic degradation consist of 95.0% of the sand fraction (2.0–0.05 mm) and their mineralogical composition is dominated by quartz. The mass fraction of elements (Si, O) forming quartz varied from 23.63% to 35.22% and from 7.12% to 11.45%, respectively.

Since April, the surface layer of windward slopes of the sand dunes has been drying, and deflationary processes have started. During the summer months, the active wind activity of the dominant winds blowing from the northeast, north-northeast, northern, and east-northeastern directions for an average of 20.4–26.7 days per month at a speed of 3.0–3.7 m/s (with a breakthrough of 11.90–13.3 m/s), and low moisture (7.7%–9.7%) and high air temperature (27°C), with slight atmospheric sediment soaking, creates various landform configurations of the sand dunes. Due to deflationary processes, sand material is blown from the windward northeast slope to the leeward southwest slope of the dune. Maximum warming is observed in July, reaching 29°C at a depth of 20 cm with a gradual decrease to 24.8°C with depth. The moisture content of the sand is below the wilting moisture content of plants (<1.7%), and this, coupled with high temperature and low relative humidity of the surface layer of air, makes it impossible for seedlings of shrubs to survive.

In October, a sharp decrease in air temperature and a rapid increase in precipitation (6.3 mm) lead to a noticeable increase in the relative humidity of the air (19.6%). Even moderate wind activity in the area cannot have a significant impact on the change in the landforms of the dunes and their mobility, which stabilizes in November, taking on the dune fields characteristic of the centers of mobile sands of the region with a round-scaly landform.

The rehabilitation of aeolian sand dunes can be carried out by planting indigenous promising sand-strengthening forest shrubs. However, the results of our studies suggest that the survival rate of germinations or seedlings of sand-strengthening plants can be very low due to low sand moisture in the summer months and sand mobility, which can lead to bare their root neck, or to their falling asleep. Therefore, it is recommended to develop a combined technology including the use of mechanical shields and polymer hydrogels when planting shrubs to effectively restore the soil and vegetation cover of fluttering sands.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding authors.

Author contributions

NA: Conceptualization, Data curation, Writing–original draft. KZ: Conceptualization, Data curation, Funding acquisition, Project administration, Resources, Supervision, Visualization, Writing–original draft, Writing–review and editing. RB: Investigation, Methodology, Writing–original draft. VT: Investigation, Methodology, Writing–original draft. SN: Investigation, Methodology, Writing–original draft. DD: Investigation, Methodology, Writing–original draft. SY: Investigation, Methodology, Writing–review and editing. ZK: Investigation, Methodology, Writing–original draft. YI: Data curation, Project administration, Resources, Visualization, Writing–original draft. SA: Writing–original draft, Investigation, Methodology. AU: Investigation, Methodology, Writing–original draft. LD: Writing–original draft, Data curation, Funding acquisition, Project administration, Resources, Supervision, Visualization.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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