Ecological Processes

RESEARCH Open Access

Fixing active sand dune by native grasses in the desert of Northwest China

Linfei Zhong[1], Xiangyan Feng[2] and Wenzhi Zhao[1*]

Abstract

Background Desertification is the most severe environmental problem in arid and semi-arid regions and has caused great economic loss every year. However, artificial sand fixation barriers function on sand fixation for only 10–20 years. Searching for a native species with long-term sand fixation effect and strong environmental adaptive capacity, and low water consumption is needed. In this study, we investigated the environmental adaption and sand fixation effect of a grass from Poaceae family (*Psammochloa villosa*) that is indigenous to the desert of Northwest China.

Results The results showed that *P. villosa* has a streamlined leaf form, strong mechanical strength, and flexibility to adapt to wind. Leaf curling of *P. villosa* under drought decreased water loss rate through decreased evaporation area to adapt to drought. Significant negative relationship between adventitious root length and horizontal root burial depth indicates that adventitious roots help *P. villosa* absorb water and nutrients from soil under shallow sand burial condition, which enables *P. villosa* to adapt to different sand burial conditions. *P. villosa* fixed sand dunes through the distribution of the population at the top of the dune and the vertical relationship between the direction of windblown sand and the direction of growth of *P. villosa*, which stopped the expansion of the dune.

Conclusions Growth characteristics of wind and drought tolerant leaf traits and adventitious roots under sand burial indicate that *P. villosa* is well adapted to dry sandy desert conditions and burial by sand. The distribution of the *P. villosa* population on the sand dune is a "brake" on its expansion. These findings provide new insight for active sand dune fixation and desertification control using native grass in the desertified regions.

Keywords Sand dune fixation, Grass, Desertification, Adaption, *Psammochloa villosa*

Background

Desertification is the most serious environmental problem in arid regions (Malagnoux et al. 2007; Yu et al. 2017). Annually, desert expansion has caused great economic loss worldwide (Nash 1999; Touheti et al. 2013; Li et al. 2015). To decrease desert damage, many engineering measures such as the construction of physical sand barriers (straw checkerboard barriers) and biological barriers (planting trees and shrubs to fix sand dunes) have been conducted in the desert of Northwest China (Cao 2008; Li et al. 2018). However, sand barrier fences and straw checkerboard barriers only function on sand fixation for a relatively short period. About 70% of sand fixation barriers were buried over the last 20 years (Li et al. 2021). Therefore, searching for a more long-lasting method to fix sand by planting environmentally adapted native species, such as grass species that have high drought resistance and rapid reproduction capacity (Craine et al. 2013), becomes an urgent task for desertification control in these regions.

*Correspondence:
Wenzhi Zhao
zhaowzh@lzb.ac.cn
[1] Linze Inland River Basin Research Station, Key Laboratory of Ecohydrology of Inland River Basin, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou 730000, China
[2] Breeding Base for State Key Lab. of Land Degradation and Ecological Restoration in Northwestern China, Key Lab. of Restoration and Reconstruction of Degraded Ecosystems in Northwestern China of Ministry of Education, School of Ecology and Environment, Ningxia University, Yinchuan 750021, China

© The Author(s) 2024. **Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

For the native species habituated in the desert, windy, dry and sandy environments are the major abiotic stresses for species survival (Wang et al. 2009; Li et al. 2022; Liu et al. 2023). Plants under wind stress are characterized by low above-ground biomass and low shoot-to-root ratio as the decrease in height can significantly reduce the loadings of wind under natural conditions (Goodman and Ennos 1996; Speck 2003; Anten et al. 2010). The influence of wind stress on plant growth is coupled with soil water availability in desert environments (Wang et al. 2009; Wu et al. 2021). There are distinct responses to wind stress of plants under low and high soil water availability (Goodman and Ennos 1996; Wang et al. 2011). Besides wind stress, sand burial is also a critical environmental stress for species' survival in the desert (Tao et al. 2022; Gao et al. 2023a, b). With the increased depth of sand burial, the ramet's number and size both decreased (Yu et al. 2004). Although such findings about species in response to specific stress have been made in many desert studies, there are multiple abiotic stresses in the desert environment caused by wind, drought and sand (Li et al. 2022; Tao et al. 2022). Understanding how the desert species adapt to windy, dry and sandy environments would accelerate the sand fixation speed and reduce the huge economic losses caused by desertification.

In this study, we surveyed a native grass (*Psammochloa villosa*) across four major deserts spanning a geographical distance of about 1000 km from semi-arid deserts to arid deserts in Northwest China. *P. villosa* is a sandy rhizomatous clone species and often occurs on mobile sand dunes, which is well adapted to windy, dry and sandy burial environment and has a strong reproductive capacity. In Northwest China, *P. villosa* is a dominant sandy rhizomatous herbaceous species, which grows in vegetation patches in desert areas (Ma 1994; Yu et al. 2004). Previous studies have studied the spatial distribution (Wang et al. 2023), seed germination (Zhu et al. 2005), leaf traits (Lu et al. 2021), clonal growth (Chen et al. 2001), arbuscular mycorrhiza (He et al. 2010) and growth under different soil water conditions (Wang et al. 2011). Studies on the influences of abiotic stress on *P. villosa* are inconsistent. For instance, some studies reported the biomass of *P. villosa* decreased under wind stress (Retuerto and Woodward 1993; Niklas 1998), but increased in other studies (Anten et al. 2005; Wang et al. 2009). Regardless of these advances, the adaptive mechanisms of *P. villosa* to windy, dry and sandy environments are less understood. This is critical for *P. villosa* to successfully survive in the desert. Planting grasses to fix sand dunes has been applicated for stabilization of dunes in coastal dunes (Gao et al. 2023a, b). Although grasses play important role in sand fixation and with low water consumption compared with shrubs, the sand-fixing effect of *P. villosa* has yet to be studied, this plant may prove to be a valuable tool for sand fixation.

To figure out how this herbaceous species survived in the desert and the effect on sand fixation, we investigated the adaption to windy, dry and sandy environments. This study for the first time revealed the adaptive mechanisms of *P. villosa* in adaption to compounded environmental stresses and its sand fixation effect. We hypothesized that *P. villosa* could be well adapted to desert environments by forming environmental tolerant traits. *P. villosa* would form more environmental tolerant traits in arid deserts than it in semi-arid deserts. Since *P. villosa* occurs naturally on mobile sand dunes, we hypothesized that *P. villosa* may have a good effect on fixing mobile sand dunes and may have application value for sand desertification control engineering in desertification regions.

Methods

Study site and experimental design

The study site is located in four major deserts in Northwest China (Mu Us Desert, Ulan Buh Desert, Kubuqi Desert, Badain Jaran Desert). We set six study sites across four deserts (Fig. 1). The six study sites span a wide geographic range (about 1000 km) from arid deserts to semi-arid deserts. The study sites experience wind and drought stress with a gradient of wind speed ranging from 6.7 to 10.2 m/s and the strongest period of aeolian activity often occurred in the first half of the year; annual precipitation ranges from 92 to 484 mm, annual temperature ranges from 8.2 to 10.1 °C, altitude from 1025 to 1448 m (Table 1). *P. villosa* is the dominant species in the sampling sites and grows during April to October. The soil in the study site is desert soil that is majorly composed by gray desert soil, grey-brown desert soil and brown desert soil, which has low water storage capacity.

In June 2024, six sampling plots in each of the study sites (three sites at arid deserts and three sites at semi-arid deserts) without grazing disturbance were selected for the field survey and sample collection. In total, 6 locations × 6 replications = 36 surveys were conducted. In the study sites, we firstly conducted the community investigation. Then we measured the wind, drought and sand burial tolerant traits of *P. villosa* that are described as follows. Finally, we quantified the sand fixing effect of *P. villosa* by analyzing the sand blocking effect of *P. villosa* to sand dune movement. Environmental variables in each sampling site were collected to compare the traits' differences of *P. villosa* in different climate conditions.

Environmental variables

Meteorological data was obtained from high-resolution meteorological service products. The precipitation data and temperature data used in this study were extracted

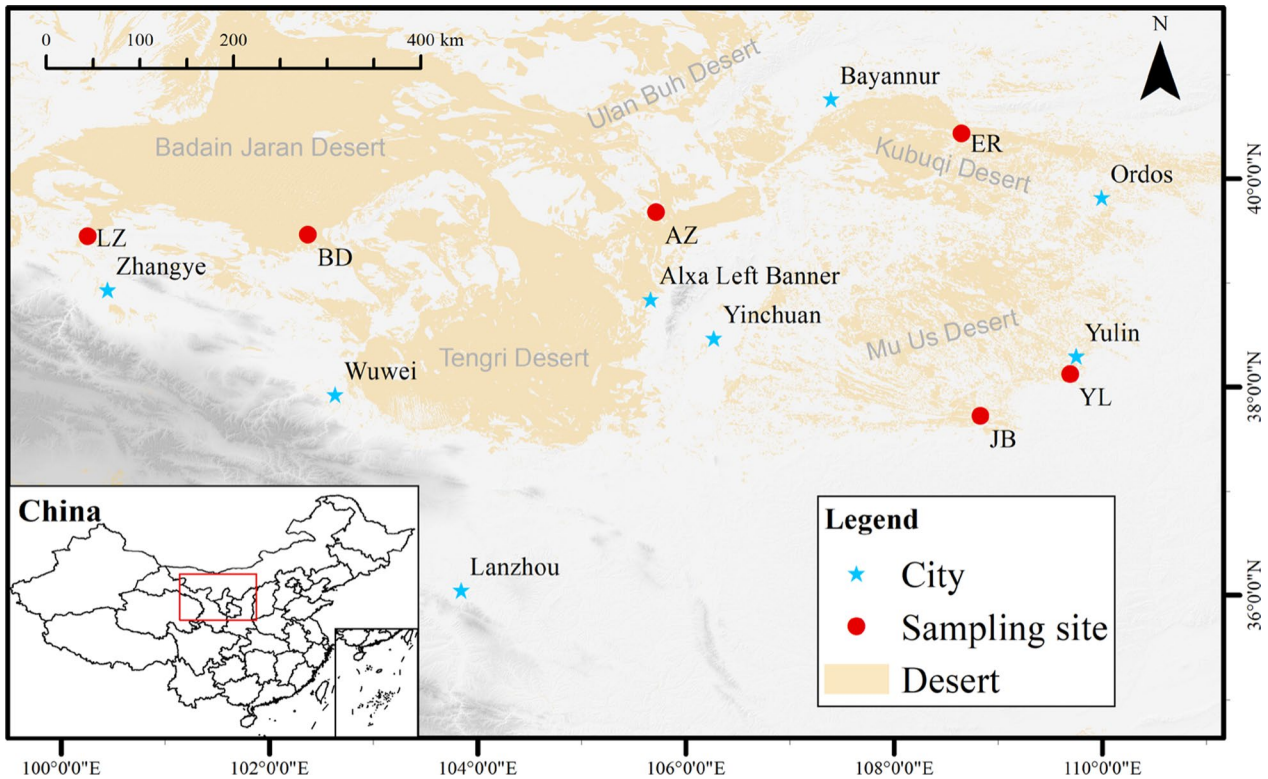


Fig. 1 Map of the study site. The study sites span across Mu Us Desert, Ulan Buh Desert, Kubuqi Desert, and Badain Jaran Desert in Northwest China. Six sampling sites were marked as red points on the map. Stars marked in blue represent major cities in this region. Yellow colored background indicates desert. The red square in the subplot represents the geographic range of the study area in China. AZ, Azuo Banner; BD, Badain Jaran; ER, Ordos city; JB, Jinbian county; LZ, Linze county; YL, Yulin city

Table 1 Environmental conditions of the sampling sites in this study

Sampling site	Abbreviation	Arid/semi-arid desert	Location	Altitude (m)	Annual precipitation (mm)	Annual temperature (°C)	Maximum wind speed (m/s)
Badain Jaran	BD	Arid desert	102°22′21.07″E, 39°27′39.70″N	1448	92	8.7	10.2
Azuo Banner	AZ	Arid desert	105°42′56.93″E, 39°40′35.31″N	1025	117	10.1	8.6
Linze county	LZ	Arid desert	100°15′19.56″E, 39°26′51.21″N	1438	123	8.2	7.6
Ordos city	ER	Semi-arid desert	108°39′9.53″E, 40°25′52.33″N	1115	229	8.3	8.2
Yulin city	YL	Semi-arid desert	109°41′42.97″E, 38°7′16.13″N	1155	484	9.7	6.7
Jingbian county	JB	Semi-arid desert	108°50′2.22″E, 37°43′20.47″N	1335	387	9.2	6.9

The sampling sites were classified as arid deserts (annual precipitation < 200 mm) and semi-arid deserts (annual precipitation at 200–500 mm) (Huang et al. 2019)

from the Tibetan Plateau Data Center (Peng et al. 2019). Based on the 0.5° global meteorological dataset of CRU (Harris et al. 2020) and the 30" resolution global meteorological dataset of WorldClim2 (Fick and Hijmans 2017), this dataset was generated by downscaling in China using the Delta spatial downscaling scheme and verified by meteorological observation data. The wind speed data used in this study was extracted from the spatial interpolation of the meteorological station database and ECMWF Reanalysis v5 (ERA5) database (Hersbach et al.

2020). The meteorological data were extracted from the China Meteorological Data Service Centre. Based on the resampled 250 m resolution, using ANUSPLIN software to spatially interpolate wind speed observation data from 36 meteorological stations around the sampling sites (Hutchinson and Xu 2004). In the year when meteorological data were insufficient, wind speed data from ERA5 were used as a supplement (He et al. 2020).

Community investigation

We surveyed the population distribution of *P. villosa* at the lower, middle, and upper position of the mobile sand dune. In each sand dune position, we set three 2 m × 2 m plots to conduct community investigation. Species composition, coverage, abundance, density, and plant height were recorded. We took photos for the plot and processed the plot with ImageJ software (Schneider et al. 2012) to calculate the coverage of each species. The plant height of the individuals was measured by a commercial measure tape. The distribution of *P. villosa* at different positions of the mobile sand dune was quantified as the percentage of the number in the position to whole individuals.

Leaf morphology, mechanical strength and flexibility for wind adaption

To evaluate the wind adaption of *P. villosa* in the desert environment, we analyzed the leaf morphology and mechanical strength of *P. villosa* as different leaf shape has different wind resistance and the leaves with higher mechanical strength could resist strong wind stress. For leaf morphology, the leaf width and thickness were measured from the leaf base to the tips per two centimeters (Schrader et al. 2021). For the mechanical strength, we measured the tearing force of the leaf that could pull off the leaf blade, and expressed the mechanical strength of *P. villosa* as Newton per meter (He et al. 2019). Additionally, to simulate the wind-blowing effect in natural conditions, we artificially bent the leaf from 30° to 180°, and then we measured the recovery angle of the leaf blade after artificially bending. This reflected the flexibility of *P. villosa* under a strong wind environment. We expected if the leaf blade could recover or approach to previous status after the bend, this means *P. villosa* could be well adapted to the strong wind-blowing environment.

Leaf curling for drought adaption

We monitored the leaf curling of *P. villosa* when the environment becomes drying. The extent to which the leaf curled during drought could be used as an index of drought adaption as the previous studies indicated that leaf curling could largely decrease sunlight interception area, which is an adaptation to a dry environment (Nar et al. 2009; Feng et al. 2022). To quantify the leaf curling extent, we monitored the variation of leaf width of *P. villosa* when it detached. We set the time series as 0 min, 2 min, 5 min, 10 min, 15 min, 20 min, and 25 min (as the leaf dries out at this time). Finally, we calculated the percentage of the final leaf width to the initial leaf width to compare the leaf curling extent in different sampling sites.

Adventitious root for sand burial adaption

To investigate how *P. villosa* survived under different depths of sand burial, we measured the depth of sand burial of the horizontal root at six sampling sites. The depth of sand burial and the length of the adventitious root were measured with a tape rule using the excavation method. To figure out the relationship between adventitious root and depth of sand burial, we analyzed the relationship between adventitious root length and depth of sand burial.

Individual growth and distribution for sand fixation

We used three methods to evaluate the sand-fixing effect of *P. villosa* on sand dunes. For the first method, we surveyed the distribution of *P. villosa* on the position of the moving sand dune. We summarized the distribution of *P. villosa* on the upper, middle and lower positions of the moving sand dunes. Due to the sand on the top of sand dunes is easier to be blown away by the wind, more individuals distributed in the upper position of sand dunes would have a better sand-fixing effect (Zhang et al. 2021). For the second method, we measured the height and distance of individuals from the maternal plant to explore whether *P. villosa* could form a fence-like sand barrier. The maternal plant was identified as the plant from which it originated. We analyzed the variation of plant height from the maternal individual to its clones, and calculated the distances between two individuals and analyzed its distribution density. If the distance between cloned individuals was rather short and with a similar plant height, it means *P. villosa* could formulate a dense fence-like block to stop wind and sand movement. For the third method, we evaluate the sand-fixing effect of *P. villosa* by measuring the angle between the horizontal root growing direction and sand dune moving direction with a commercial angulometer. The sand dune moving direction was identified by the morphology of the sand dune. The sand dune moves from a gentle windward slope to a steeper leeward slope (Qian et al. 2021). If the angle between the horizontal root and sand dune moving direction approached 90°, it indicates that *P. villosa* could directly detain sand dune moving as it is perpendicular to the sand dune moving direction (Qiu et al. 2004; Gao et al. 2023a, b).

Statistics

One-way ANOVA with Fisher's LSD test was used to examine the differences of *P. villosa* characteristics among different sampling sites from semi-arid deserts to arid deserts. The correlations between variables were fitted by *loss* or *lm* functions of ggplot2 packages in R programming (Wickham 2016). Except for model plot, all the figures and data analysis were conducted using R programming (R Core Team 2023).

Results

Wind environment adaption

The leaf morphology of *P. villosa* showed adaptations to windy environments in both arid and semi-arid deserts. The leaf width was streamlined from the leaf base to the tip, indicating that *P. villosa* has low wind resistance in a windy environment (Fig. 2A). The leaf thickness decreased linearly from the leaf base to the tip, indicating strong mechanical strength in the leaf base to guarantee that the plant can withstand strong wind blows (Fig. 2B). A positive relationship between leaf thickness and leaf width was observed, indicating the adaption to wind of wider leaf width achieved by thick leaf (Fig. 2C). In addition, the leaf of *P. villosa* showed strong mechanical strength and flexibility. The tearing force of the leaf was greater than 8.7×10^3 N/m. Although there were some differences among different sampling sites, the tearing force was overall higher in arid deserts than it in semi-arid deserts (Fig. 3A). The leaf blade of *P. villosa* showed strong flexibility as it could recover to its previous status if the bend angle was less than 150°. Even if the leaf blade was artificially bent to 180°, the leaf could also recover to 150° (Fig. 3B).

Drought environment adaption

P. villosa was well adapted to a dry environment as leaf curling occurred when the environment became dry (Subplot in Fig. 4A). We observed the leaf width decrease rapidly over time as it curled in all six sampling sites to decrease the water loss rate. The leaf fully curled at about

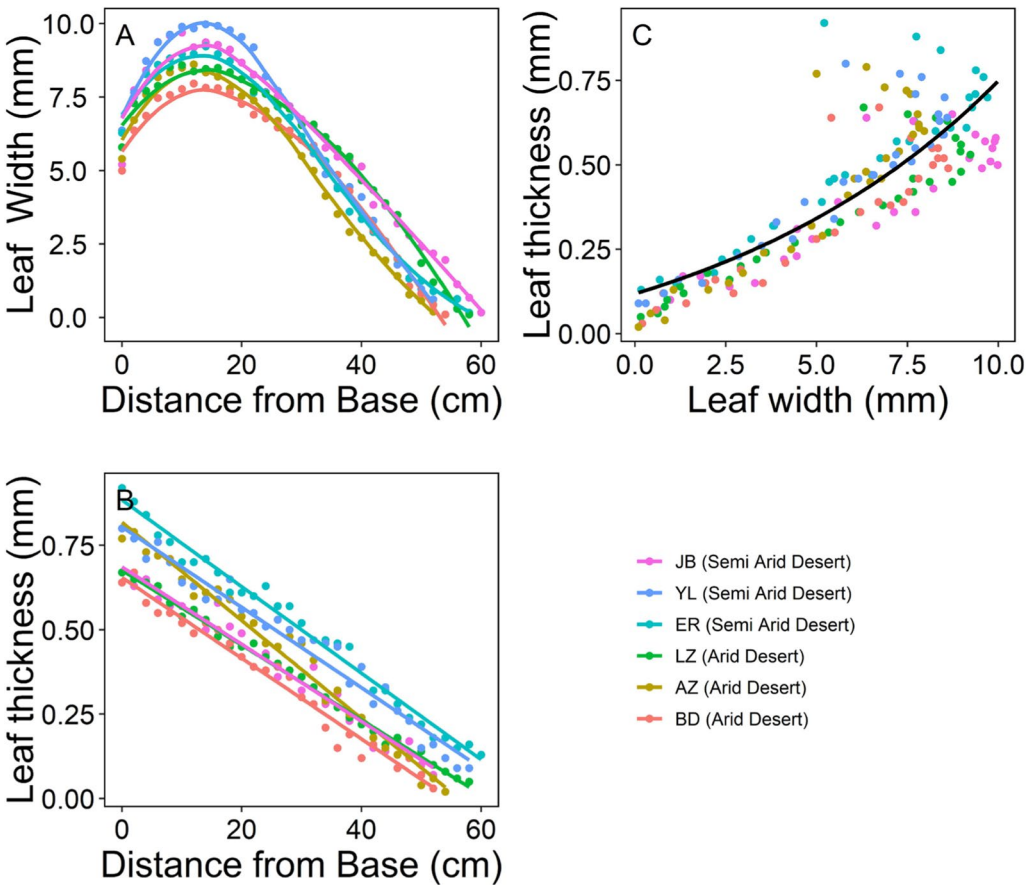


Fig. 2 Leaf width and thickness change trends from leaf base to tip. **A** Leaf width changed as streamlined with the distance from the leaf base ($R^2 > 0.90$, $P < 0.001$). **B** Leaf thickness decreased linearly from the leaf base to the tip ($R^2 > 0.90$, $P < 0.001$). **C** Leaf thickness and leaf width showed a positive relationship ($R^2 = 0.71$, $P < 0.001$). Different colors represent different sampling sites as the legend showed in plot A. AZ, Azuo Banner; BD, Badain Jaran; ER, Ordos city; JB, Jinbian county; LZ, Linze county; YL, Yulin city

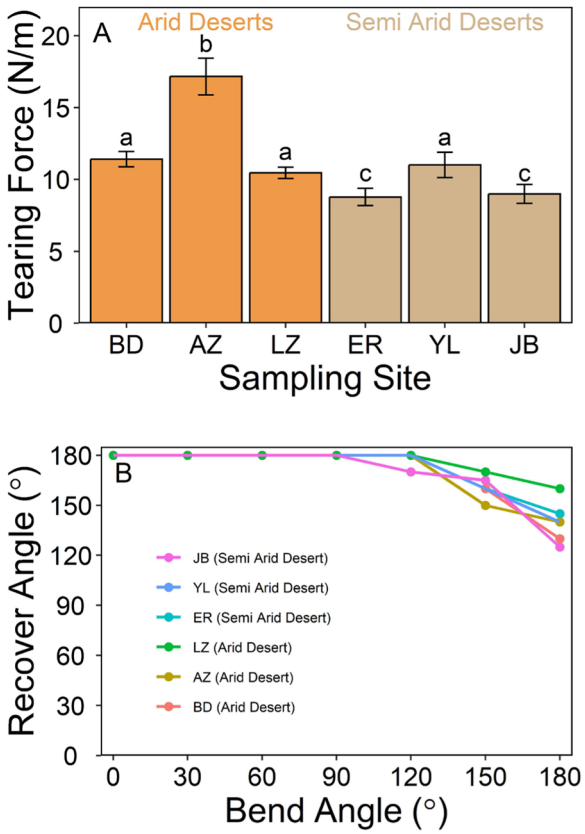


Fig. 3 Leaf mechanical strength and flexibility in adaption to wind stress. **A** Tearing force of *P. villosa* at different sampling sites. **B** The mean recover angle ($n=6$) of leaf blade after artificially bending the leaf from 30° to 180°. Different colors in plot **B** represent different sampling sites. The bar in plot **A** represents the standard error ($n=8$). The different letters above the bar indicate significant differences among sampling sites ($P<0.05$). AZ, Azuo Banner; BD, Badain Jaran; ER, Ordos city; JB, Jinbian county; LZ, Linze county; YL, Yulin city

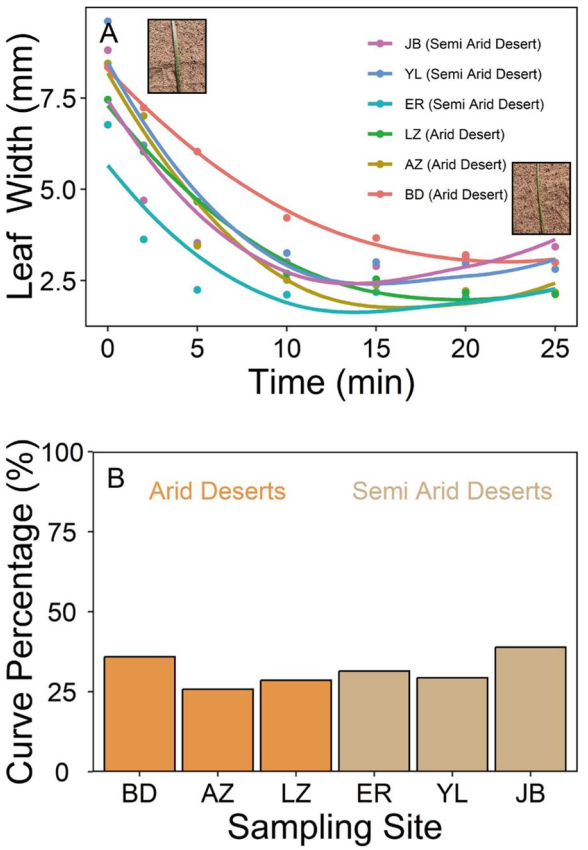


Fig. 4 Leaf curing in adaption to drought. **A** leaf width decreased rapidly with time as it curled under bench drought stress. The subplot in plot A indicates the unfolded leaf before bench drought and the curled leaf after the bench drought. **B** the curling percentage of the leaf at different sampling sites. Different colors in plot A represent different sampling sites as the legend showed. AZ, Azuo Banner; BD, Badain Jaran; ER, Ordos city; JB, Jinbian county; LZ, Linze county; YL, Yulin city

20 min (Fig. 4A). The curling of the leaf was very significant where the final leaf width was about 25% of the original leaf width. No significant differences were detected among the curling percentage of the leaf in arid deserts and semi-arid deserts, indicating that leaf curling is a general drought adaptation for *P. villosa* (Fig. 4B).

Sand burial adaption

P. villosa showed a strong adaption to sand burial. Depth of sand burial of *P. villosa* showed a very large range from 15 to 55 cm among six sampling sites (Fig. 5A, B). Depth of sand burial was shallower in arid deserts compared with semi-arid deserts (Fig. 5B). For the individuals with shallow depth of sand burial, we observed adventitious root occurred from the cloned individual's horizontal root (Fig. 5C). A negative relationship was shown between adventitious root length and depth of sand burial of horizontal root, indicating that adventitious root would occur to compensate for less moisture in the shallow soil profile (Fig. 5D) (Knipfer and Fricke 2011; Gonin et al. 2019).

Sand-fixing effect

In both arid deserts and semi-arid deserts, the plant height and root depth of *P. villosa* do not vary with the distance from the maternal plant (Fig. 6A, B). *P. villosa* with a plant height ranged from 25 to 75 cm, which could fix sand dunes through reducing wind speed and promote sand accumulation and deposition. The length of the horizontal root from one maternal plant ranged from 400 to 900 cm (Fig. 6C). The distance between cloned individuals was about 20 cm, which means *P. villosa* could formulate a dense fence-like block to stop wind and sand movement (Fig. 6D). Under natural conditions, we observed that the angle between leaf blade and horizontal root was less than 30° (Fig. 7A, B). The angle between

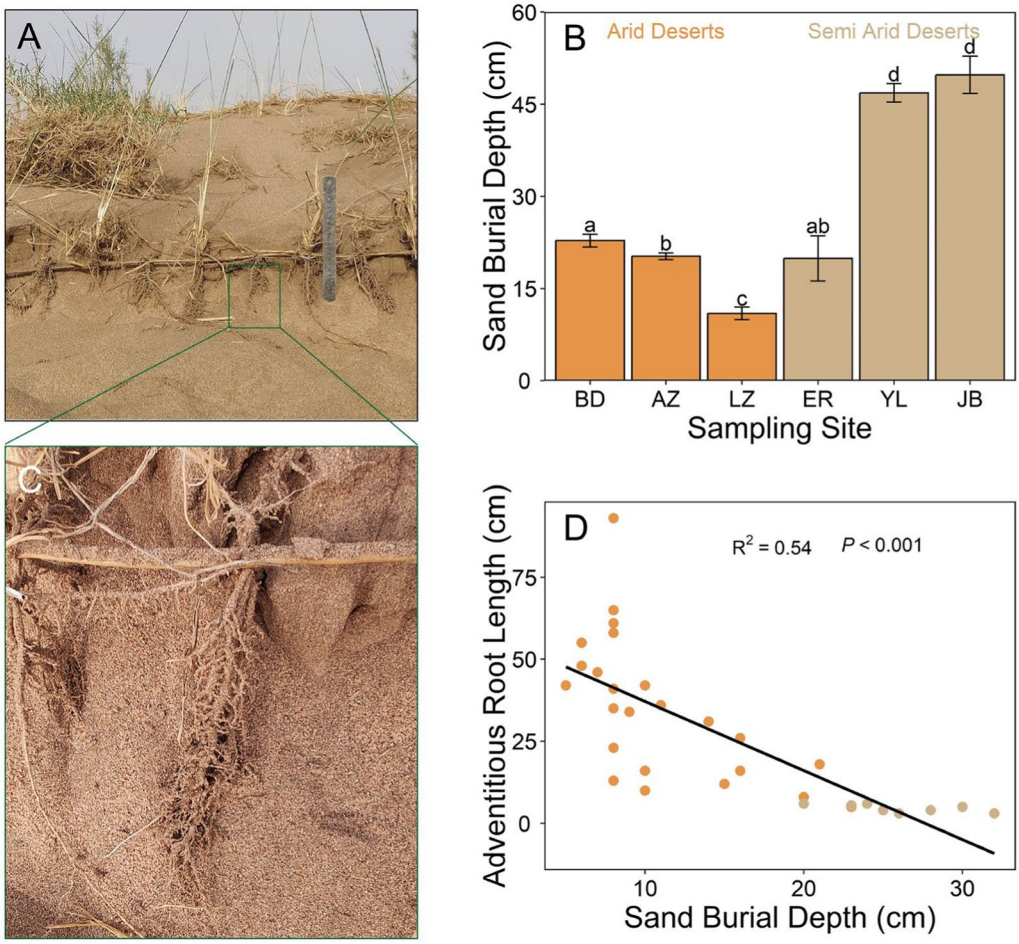


Fig. 5 Sand burying depth and adventitious root length of *P. villosa*. **A** The example of an excavated profile of the horizontal root. **B** Sand burying depth of horizontal root in different sampling sites. The bar in plot B represents the standard error ($n = 6$). The different letters above the bar indicate significant differences among sampling sites ($P < 0.05$). **C** The example of adventitious root occurred in the clone site of horizontal root. **D** The significant negative relationship between adventitious root length and sand burial depth of horizontal root

the horizontal root and the direction of sand dune movement approached 90°, indicating that the horizontal root was perpendicular to the wind-blown sand, thus impeding the movement of the sand dune (Fig. 7C) (Lee et al. 2020). Additionally, individuals distributed in the lower (15%), middle (25%) and upper positions (60%) of sand dune, which helped sand dune fixation as the sand in the upper position of sand dunes is vulnerable to blowing away by wind (Fig. 8).

Discussion

Adaption of *P. villosa* to windy, dry and sandy environments

This study demonstrated *P. villosa* was well adapted to windy, dry and sandy environments. For windy environment adaption, we found the leaf width showed a streamlined form from the leaf base to the tip, as leaf with a streamlined form has a good performance of flow diversion and low wind resistance (Zhang et al. 2022; Liang et al. 2024). Leaf thickness showed a linear form from the leaf base to the tip. This indicates strong mechanical strength in the leaf base to guarantee that it can support the whole leaf weight and withstand strong stretch force under wind blow (Wang et al. 2010). Additionally, we found that the leaf blade of *P. villosa* showed very strong mechanical strength as the tearing force of the leaf among the six sampling sites is greater than 8.7×10^3 N/m. This is 10 times greater than normal plants indicating that *P. villosa* has evolved strong mechanical strength to adapt to wind environment (Vogel 2009; He et al. 2019). Besides strong mechanical strength, we also found that the leaf blade of *P. villosa* showed strong flexibility as it could recover to its previous status after being artificially bent. This suggests that the leaf of *P. villosa* could recover to its previous status after strong wind stress.

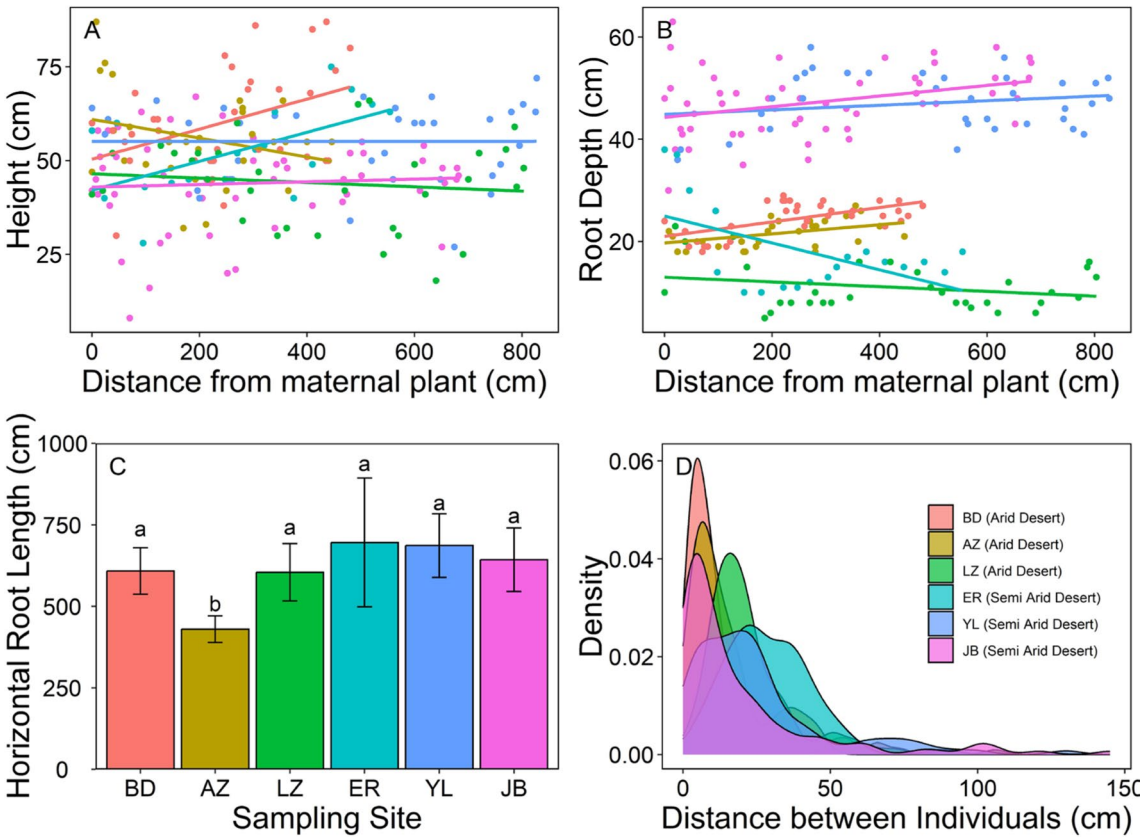


Fig. 6 Individual growth and distribution characteristics. **A** Plant height of *P. villosa* (cloned individual) along with the distance from the maternal plant. **B** Root depth of *P. villosa* along with the distance from the maternal plant. **C** Horizontal root length at different sampling sites. The bar in plot B represents the standard error ($n = 6$). The different letters above the bar indicate significant differences among sampling sites ($P < 0.05$). **D** The density of the distance between individuals. Different colors in plot **A, B, D** represent different sampling sites as the legend showed in plot **C**. AZ, Azuo Banner; BD, Badain Jaran; ER, Ordos city; JB, Jinbian county; LZ, Linze county; YL, Yulin city

For drought adaption, we found that the leaf blade of *P. villosa* could curl as the drought intensified to decrease the water loss. Such leaf curling mechanism under drought conditions has been observed in many other species from the Leguminosae family (Amador-Vargas et al. 2014; Lin et al. 2017; Feng et al. 2022). Our findings for the first time proved that leaf curling could also happen in the species from the Poaceae family. This to some extent explained the wide distribution of *P. villosa* over the desert of Northwest China. The active leaf curling under drought condition also provided insight that although the individual couldn't move like an animal, it could also avoid stress though modifying the tissue's shape (Kadioglu et al. 2012).

For sand burial adaption, our results showed a large range of root depth of *P. villosa* over the sampling sites. This suggests *P. villosa* has a strong tolerance to burial by sand, which might help *P. villosa* to survive at mobile sand dunes where the sand thickness always changes after wind storms. Sand burial depth could affect the herbs' survival in the desert by affecting the plants access to soil moisture (Gao et al. 2023a, b). In the desert environment, the shallow soil profile with low soil water availability might cause the horizontal root with shallow soil burial depth to be unable to absorb sufficient water for survival. In the desert environment, the roots surviving in the shallow soil profile could not absorb enough water due to the low water content of this soil layer (Zhou et al. 2017; Duniway et al. 2018). We found that individuals with shallow depth of sand burial have adventitious roots that occur at the horizontal roots. This suggests that the plants' growth could be stimulated under a certain threshold level of burial (Maun 1998). Adventitious roots would compensate for less moisture in the shallow soil profile. This is consistent with a previous work reporting that soil moisture is the dominant factor regulating the underground bud bank of rhizomatous species *P. villosa* (Dong et al. 2023). Our finding, to a large extent, has explained the water absorption of *P. villosa* under shallow soil burying depth conditions. But it needs to be noted

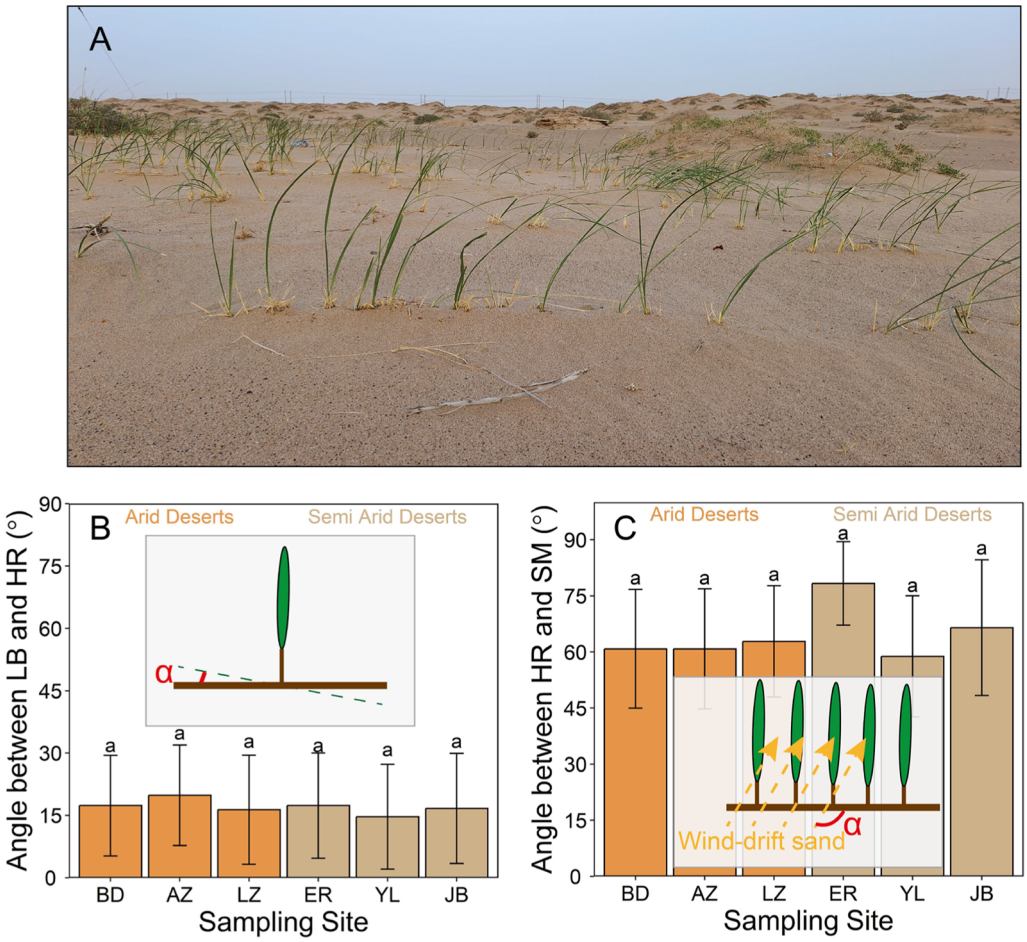


Fig. 7 The angle between *P. villosa* growing direction and sand dune moving direction for sand fixation. **A** The growth of *P. villosa* under natural conditions. **B** The angle between the leaf blade and horizontal root is less than 30°, indicating the leaf blade parallel to the horizontal root as the subplot showed in plot B. **C** The angle between the horizontal root and sand dune moving direction approaches 90°, indicating the horizontal root is perpendicular to wind-drift sand. Bar in plot **B, C** represents the standard error ($n = 6$). The different letters above the bar indicate significant differences among sampling sites ($P < 0.05$). LB, leaf blade; HR, horizontal root; SM, sand dune moving direction; AZ, Azuo Banner; BD, Badain Jaran; ER, Ordos city; JB, Jinbian county; LZ, Linze county; YL, Yulin city

that we measured the depths of the roots over the same time frame. The relationship between sand accumulation and adventitious roots at different time frames needs to be validated in future works by controlled experiments.

Sand dune fixing effect of *P. villosa* in desert

In the desert environment, the key reason of sand dune movement is due to the lack of vegetative cover. Plants that grow on the sand dune could function in stabilizing sand (Hesp 1989; Bel and Ashkenazy 2014; Wang et al. 2019). Our findings showed that adaptions to windy, dry and sandy environments enable *P. villosa* to survive in mobile sand dunes (Fig. 8). This provided a prerequisite for sand fixation of *P. villosa* in this harsh environment. *P. villosa* with a mean plant height of 50 cm has a good effect on slowing down wind speed and could help sand accumulation and deposition surround the individuals. This has been demonstrated previously that the sand fixation species *Sesuvium portulacastrum* with a plant height of 25–50 cm was successfully planted to fix coast line sand dunes (Lokhande et al. 2013). A large portion of the population distributed in the upper position of mobile sand dune helped sand dune fixation because sand in this position is vulnerable to wind stress (Dong et al. 2003; Zheng et al. 2004; Jiang et al. 2014). With the species expansion among the sand dune, the sand dune would be fixed and the dune shape tended to be stabilized (Zarnetske et al. 2012). Our findings also found that *P. villosa* could formulate a dense fence-like block to stop wind and sand movement (Fig. 4). This natural sand barrier is similar to straw checkerboard barrier, which has a good sand-fixing effect and has been successfully applied to sand fixation engineering (Tian et al. 2015; Xu et al. 2018).

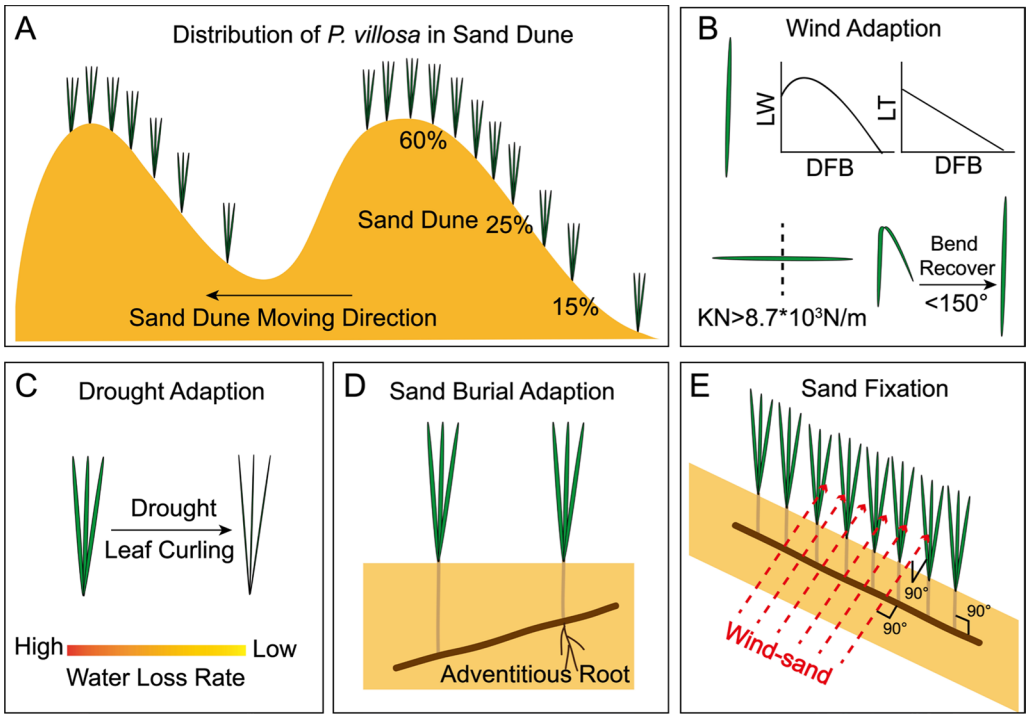


Fig. 8 Model plot for *P. villosa* in adaption to the windy, dry and sandy environment and the effect on fixing sand dune. **A** The distribution of *P. villosa* on sand dunes. About 15%, 25% and 60% individuals distributed in the low, middle and top positions of moving sand dunes. **B** Wind adaption of *P. villosa*. The leaf blade of *P. villosa* showed adaptive leaf morphology as the leaf width showed a streamlined form from the leaf base to the tip, and leaf thickness showed a linear form from the leaf base to the tip. The leaf blade of *P. villosa* showed very strong mechanical strength as the tearing force of the leaf is greater than 8.7×10^3 N/m. The leaf blade of *P. villosa* showed strong flexibility as it could recover to its previous status if the bend angle less than 150°. **C** Drought adaption of *P. villosa*. The leaf blade would curl as the drought intensified to decrease the water loss rate. **D** sand burying adaption of *P. villosa*. Adventitious roots would occur to compensate for less moisture in shallow soil profiles. **E** sand fixation effect of *P. villosa*. The horizontal root is perpendicular to wind-drift sand, which helped *P. villosa* to fix mobile sand dune. LW, leaf width; LT, leaf thickness; DFB, distance from base; KN, tearing force

Additionally, *P. villosa* has low water consumption and long-lasting sand fixing effect compared with shrubs or trees formed shelterbelts (Liu et al. 2020).

Besides the survival advantage and distribution feature of *P. villosa* in the desert, our findings provided a novel mechanism for sand fixation. We found a growth feature that the angle between leaf blade and horizontal root was less than 30°, and this suggests the plane of leaf blade is parallel to the horizontal root growth direction. Combined with the strong mechanical strength and flexibility of the leaf blade to wind stress, *P. villosa* is well adapted to wind blowing from the front of the leaf blade (where wind direction is perpendicular to the leaf blade). If this is the case, the wind blow direction is perpendicular to the horizontal root growth direction. Our survey in the field perfectly matched this case, where the horizontal root is perpendicular to wind-drift sand (Fig. 7). This finding indicates that *P. villosa* is a natural and ideal species for sand dune fixation, and has potential application value for sand fixation in the desert environment.

Implications for desert ecosystem conservation in Northwest China

The previous experience of artificial sand-fixing vegetation construction has demonstrated that it is not only possible but also feasible to construct and improve the sand-fixing vegetation based on native plants (Li and Xu 2019; Deng et al. 2024). It should be noted, however, that the construction of sand-fixing vegetation should aim at slowing down the expansion of sand dunes, and should not overly pursue the fixation of sand dunes, let along mention the formation of a complete plant sand-fixing system. Sand-fixing plant species must come from native plants and should be constrained by the carrying capacity of vegetation and soil, and we should adhere to the principle that natural vegetation is mainly nurtured and protected, with moderate supplement by artificial sand-fixing vegetation. Along the traffic routes and around the villages and towns, artificial sand-fixing vegetation can be appropriately established based on the sand acitivity condition. In the regions where sand damage is not severe, introducing native herbs such as *P. villosa* to slow down

the expansion of sand dunes would be a better choice to protect the desert ecosystem.

Three aspects should be focused in the sand dune fixation research in the future. (i) Determining the carrying capacity of vegetation and the model for establishing vegetation sand control belts based on species' adaption to windy, dry and sandy environments. Examing the drought-resistant and wind-erosion-resistant sand-burial capacity of native plants, as well as the interaction between wind and sand activities and the composition, spatial pattern, inter-species relationship and stability of vegetation communities. (ii) Investigating the mechanism of maintaining the stability of natural vegetation. Exploring the composition, diversity and stability of natural vegetation at the desert and its relationship with precipitation, redistribution of precipitation and soil water, and the impact of precipitation and its redistribution on soil water and vegetation, and determining the distribution pattern and stability conditions of sparse and patchy desert vegetation. (iii) Developing the conservation of native plant species and vegetation construction technology, such as the techniques of breeding, restoration and renewal of native plants in sandy, drought and windy environments.

It should be noted that there are some limitations of using grasses to fix sand dunes. The relatively shallow root system of grasses limits their sand fixation capacity to a certain extent. Compared with shrubs or trees, it is difficult for grasses to penetrate deep into the soil, so their sand fixation effect is mainly concentrated in the soil surface. In desert areas with strong winds, the sand fixation effect of this shallow layer may not be sufficient to resist the erosion of wind and sand, resulting in unstable sand fixation effect. Although the populations of native grasses are constantly renewed, the relatively small biomass and short growth cycle of grasses make the durability of their sand fixation effect questionable. The applicability of the sand fixation approach using grasses needs to be investigated in future researches and engineering practices.

Conclusion

In this study, we found the native grass species (*P. villosa*) is well adapted to windy, dry and sandy environments and has a good sand dune fixing effect and potential application value for sand fixation in the desert environment. *P. villosa* adapts to compounded environmental stresses across a large geographical gradient mainly through forming environmental tolerant traits. These findings provide new insight for sand dune fixation and desertification control by native grass in desertification regions over the world.

Acknowledgements
The authors thank the support by the National Natural Science Foundation of China (42230720) and Central-guided Local Science and Technology Development Program (2024ZY0014).

Author contributions
Linfei Zhong: Investigation, Formal analysis, Writing-original draft. Xiangyan Feng: Investigation, Formal analysis, Reviewing-original draft. Wenzhi Zhao: Conceptualization, Experimental design, Reviewing-original draft, Funding acquisition.

Funding
National Natural Science Foundation of China (42230720), Central-guided Local Science and Technology Development Program (2024ZY0014).

Availability of data and materials
The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
All authors approved the manuscript for publication in ecological processes.

Competing interests
No competing interest exists in this manuscript.

Received: 29 July 2024 Accepted: 2 October 2024
Published online: 22 October 2024

References

Amador-Vargas S, Dominguez M, León G, Maldonado B, Murillo J, Vides GL (2014) Leaf-folding response of a sensitive plant shows context-dependent behavioral plasticity. Plant Ecol 215:1445–1454

Anten NPR, Casado-Garcia R, Nagashima H (2005) Effects of mechanical stress and plant density on mechanical characteristics, growth, and lifetime reproduction of tobacco plants. Am Nat 166:650–660

Anten NPR, Alcalá-Herrera R, Schieving F, Onoda Y (2010) Wind and mechanical stimuli differentially affect leaf traits in *Plantago major*. New Phytol 188:554–564

Bel G, Ashkenazy Y (2014) The effects of psammophilous plants on sand dune dynamics. J Geophys Res-Earth Surf 119:1636–1650

Cao SX (2008) Why large-scale afforestation efforts in China have failed to solve the desertification problem. Environ Sci Technol 42:1826–1831

Chen Y, Yu F, Zhang C, Dong M (2001) Role of clonal growth of the rehizomatous grass *Psammochloa villosa* in patch dynamics of Mu Us sandy land. Acta Ecol Sin 21:1745–1750

Craine JM, Ocheltree TW, Nippert JB, Towne EG, Skibbe AM, Kembel SW, Fargione JE (2013) Global diversity of drought tolerance and grassland climate-change resilience. Nat Clim Change 3:63–67

Deng XH, Du HQ, Li ZX, Chen H, Ma N, Song YL et al (2024) Sand fixation and human activities on the Qinghai-Tibet Plateau for ecological conservation and sustainable development. Sci Total Environ 912:17

Dong Z, Liu X, Wang H, Wang X (2003) Aeolian sand transport: a wind tunnel model. Sed Geol 161:71–83

Dong YW, Guo ZY, Ma Q, Xin ZM, Tao J, Tian JT et al (2023) Soil moisture rather than soil nutrient regulates the belowground bud bank of rhizomatous species *Psammochloa villosa* in arid sand dunes. Phyton-Int J Exp Bot 92:1301–1309

Duniway MC, Petrie MD, Peters DPC, Anderson JP, Crossland K, Herrick JE (2018) Soil water dynamics at 15 locations distributed across a desert landscape: insights from a 27-yr dataset. Ecosphere 9:36

Feng XY, Zhong LF, Tian QY, Zhao WZ (2022) Leaf water potential-dependent leaflet closure contributes to legume leaves cool down and drought avoidance under diurnal drought stress. Tree Physiol 42:2239–2251
Fick SE, Hijmans RJ (2017) WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas. Int J Climatol 37:4302–4315
Gao JJ, Kennedy DM, McSweeney S (2023a) Patterns of vegetation expansion during dune stabilization at the decadal scale. Earth Surf Process Landforms 48:3059–3073
Gao YH, Jia RL, Liu YP, Zhao Y, Wu YS, Yang HT et al (2023b) Biocrust and sand burial together promote annual herb community assembly in an arid sandy desert area. Plant Soil 491:645–663
Gonin M, Bergougnoux V, Nguyen TD, Gantet P, Champion A (2019) What makes adventitious roots? Plants 8:240
Goodman AM, Ennos AR (1996) A comparative study of the response of the roots and shoots of sunflower and maize to mechanical stimulation. J Exp Bot 47:1499–1507
Harris I, Osborn TJ, Jones P, Lister D (2020) Version 4 of the CRU TS monthly high-resolution gridded multivariate climate dataset. Scientific Data 7:109
He X, Li Y, Zhao L, Liu X (2010) Effects of the growth of clonal plant *Psammochloa villosa* Trin. Bor on ecological distribution of arbuscular mycorrhizal fungi in Mu Us Sandland. Acta Ecol Sin 30:751–758 (**in Chinese**)
He PC, Wright IJ, Zhu SD, Onoda Y, Liu H, Li RH et al (2019) Leaf mechanical strength and photosynthetic capacity vary independently across 57 subtropical forest species with contrasting light requirements. New Phytol 223:607–618
He J, Yang K, Tang W, Lu H, Qin J, Chen Y et al (2020) The first high-resolution meteorological forcing dataset for land process studies over China. Scientific Data 7:25
Hersbach H, Bell B, Berrisford P, Hirahara S, Horányi A, Muñoz-Sabater J et al (2020) The ERA5 global reanalysis. Q J R Meteorol Soc 146:1999–2049
Hesp P (1989) A review of biological and geomorphological processes involved in the initiation and development of incipient foredunes. P Roy Soc Edinb B 96:181–201
Huang J, Ma J, Guan X et al (2019) Progress in semi-arid climate change studies in China. Adv Atmos Sci 36:922–937
Hutchinson MF, Xu T (2004) ANUSPLIN version 4.4 user guide. Centre for Resource and Environmental Studies, The Australian National University, Canberra, 54
Jiang H, Huang N, Zhu YJ (2014) Analysis of wind-blown sand movement over transverse dunes. Sci Rep 4:11
Kadioglu A, Terzi R, Saruhan N, Saglam A (2012) Current advances in the investigation of leaf rolling caused by biotic and abiotic stress factors. Plant Sci 182:42–48
Knipfer T, Fricke W (2011) Water uptake by seminal and adventitious roots in relation to whole-plant water flow in barley (*Hordeum vulgare* L.). J Exp Bot 62:717–733
Lee JT, Yen LZ, Chu MY, Lin YS, Chang CC, Lin RS, Chao KH, Lee MJ (2020) Growth characteristics and anti-wind erosion ability of three tropical foredune pioneer species for sand dune stabilization. Sustainability 2020(12):3353
Li DJ, Xu DY (2019) Sand fixation function response to climate change and land use in northern China from 1981 to 2015. Aeolian Res 40:23–33
Li CJ, Lei JQ, Zhao Y, Xu XW, Li SY (2015) Effect of saline water irrigation on soil development and plant growth in the Taklimakan Desert Highway shelterbelt. Soil Tillage Res 146:99–107
Li CJ, Liu R, Wang SJ, Sun YQ, Li SY, Zhang H et al (2018) Growth and sustainability of *Suaeda salsa* in the Lop Nur, China. J Arid Land 10:429–440
Li CJ, Wang YD, Lei JQ, Xu XW, Wang SJ, Fan JL et al (2021) Damage by wind-blown sand and its control measures along the Taklimakan Desert Highway in China. J Arid Land 13:98–106
Li CJ, Han H, Ablimiti M, Liu R, Zhang H, Fan JL (2022) Morphological and physiological responses of desert plants to drought stress in a man-made landscape of the Taklimakan desert shelter belt. Ecol Indic 140:109037
Liang L, Hu L, Li J (2024) Streamline fin structure design and optimization based on simulation. In: Fu S (ed) 2023 Asia-Pacific International Symposium on Aerospace Technology (APISAT 2023) Proceedings. Springer Nature, Singapore, pp 1569–1579
Lin H, Chen YJ, Zhang HL, Fu PL, Fan ZX (2017) Stronger cooling effects of transpiration and leaf physical traits of plants from a hot dry habitat than from a hot wet habitat. Funct Ecol 31:2202–2211
Liu ZQ, Jia GD, Yu XX (2020) Variation of water uptake in degradation agroforestry shelterbelts on the North China Plain. Agr Ecosyst Environ 287:106697
Liu Y, Gao YF, He J, Zhou YD, Ge WJ (2023) An experimental investigation of wind erosion resistance of desert sand cemented by soybean-urease induced carbonate precipitation. Geoderma 180:106644
Lokhande VH, Gor BK, Desai NS et al (2013) *Sesuvium portulacastrum*, a plant for drought, salt stress, sand fixation, food and phytoremediation: a review. Agron Sustain Dev 33:329–348
Lu T, Liu T, Liang R, Su X, Liu Y (2021) Morphological variations of different populations from *Psammochloa villosa*, a peculiar sandy plant. Bull Bot Res 41:60–66 (**in Chinese**)
Ma YQ (1994) Flora Intramongolica. Inner Mongolia People Press, Huhhot, China (**in Chinese**)
Malagnoux M, Sène E, Atzmon N (2007) Forests, trees and water in arid lands: a delicate balance. Unasylva 58:24–29
Maun MA (1998) Adaptations of plants to burial in coastal sand dunes. Can J Bot 76:713–738
Nar H, Saglam A, Terzi R, Várkonyi Z, Kadioglu A (2009) Leaf rolling and photosystem II efficiency in *Ctenanthe setosa* exposed to drought stress. Photosynthetica 47:429–436
Nash DJ (1999) World atlas of desertification. Geogr J 165:325–326
Niklas KJ (1998) Effects of vibration on mechanical properties and biomass allocation pattern of *Capsella bursa-pastoris* (Cruciferae). Ann Bot 82:147–156
Peng S, Ding Y, Liu W, Li Z (2019) 1-km monthly temperature and precipitation dataset for China from 1901 to 2017. Earth Syst Sci Data 11:1931–1946
Qian GQ, Yang ZL, Tian M, Dong ZB, Liang AM, Xing XG (2021) From dome dune to barchan dune: airflow structure changes measured with particle image velocimetry in a wind tunnel. Geomorphology 382:107681
Qiu GY, Lee IB, Shimizu H, Gao Y, Ding GD (2004) Principles of sand dune fixation with straw checkerboard technology and its effects on the environment. J Arid Environ 59:449–464
R Core Team (2023) R: A language and environment for statistical computing. R foundation for statistical computing, Vienna, Austria
Retuerto R, Woodward FI (1993) The influences of increased CO_2 and water-supply on growth, biomass allocation and water-use efficiency of *Sinapis alba* L. grown under different wind speeds. Oecologia 94:415–427
Schneider CA, Rasband WS, Eliceiri KW (2012) NIH Image to ImageJ: 25 years of image analysis. Nat Methods 9:671–675
Schrader JL, Shi PJ, Royer DL, Peppe DJ, Gallagher RV, Li YR, Wang R, Wright IJ (2021) Leaf size estimation based on leaf length, width and shape. Ann Bot 128:395–406
Speck O (2003) Field measurements of wind speed and reconfiguration in *Arundo donax* (Poaceae) with estimates of drag forces. Am J Bot 90:1253–1256
Tao YY, Shang TC, Yan JJ, Hu YX, Zhao Y, Liu Y (2022) Effects of sand burial depth on *Xanthium spinosum* seed germination and seedling growth. BMC Plant Biol 22:43
Tian LH, Wu WY, Zhang DS, Lu RJ, Wang XQ (2015) Characteristics of erosion and deposition of straw checkerboard barriers in alpine sandy land. Environ Earth Sci 74:573–584
Touheti N, Abulaiti M, Ahmed Z, Maimaiti N (2013) Anti-desertification legislation and ecological problems in Xinjiang China. J Polit Law 6:160–168
Vogel S (2009) Leaves in the lowest and highest winds: temperature, force and shape. New Phytol 183:13–26
Wang YH, He WM, Yu FH, Zhang LL, Cui QG, Chu Y et al (2009) Brushing effects on the growth and mechanical properties of *Corispermum mongolicum* vary with water regime. Plant Biol 11:694–700
Wang SJ, Ren LQ, Liu Y, Han ZW, Yang Y (2010) Mechanical characteristics of typical plant leaves. J Bionic Eng 7:294–300
Wang YH, Dong M, Yu FH, Jiang H, Yu SQ, Lin XQ et al (2011) Mechanical shaking and soil water affect the growth of *Psammochloa villosa* in the Mu Us Sandland. J Arid Environ 75:974–977
Wang YC, Chu L, Daryanto S, Lu LY, Ala M, Wang LX (2019) Sand dune stabilization changes the vegetation characteristics and soil seed bank and their correlations with environmental factors. Sci Total Environ 648:500–507
Wang Z, Ren H, Xin C (2023) Spatial pattern of *Psammochloa villosa* asexual cluster populations under different precipitation conditions. Acta Ecol Sin 43:4121–4129 (**in Chinese**)

Wickham H (2016) ggplot2: Elegant Graphics for Data Analysis. Springer-Verlag New York. Retrieved from https://ggplot2.tidyverse.org
Wu XG, Fan JQ, Sun L, Zhang HF, Xu Y, Yao YF, Yan XD, Zhou J, Jia YS, Chi WF (2021) Wind erosion and its ecological effects on soil in the northern piedmont of the Yinshan Mountains. Ecol Indic 128:107825
Xu B, Zhang J, Huang N, Gong K, Liu YS (2018) Characteristics of turbulent aeolian sand movement over straw checkerboard barriers and formation mechanisms of their internal erosion form. J Geophys Res-Atmos 123:6907–6919
Yu FH, Dong M, Krüsi B (2004) Clonal integration helps *Psammochloa villosa* survive sand burial in an inland dune. New Phytol 162:697–704
Yu X, Li S, Wang H, Ma X, Jia W (2017) Aeolian-sand flow structure at different locations along desert highway shelterbelt. Arid Zone Res 34:707–715 (**in Chinese**)
Zarnetske PL, Hacker SD, Seabloom EW, Ruggiero P, Killian JR, Maddux TB, Cox D (2012) Biophysical feedback mediates effects of invasive grasses on coastal dune shape. Ecology 93:1439–1450
Zhang H, Wu Z, Hu J, Zhang ZP, Xiao B, Ma JP (2021) Numerical simulation of wind field and sand flux in crescentic sand dunes. Sci Rep 11:4973
Zhang L, Dai Z-Y, Li T, Zhang J-Y (2022) Multi-objective aerodynamic shape optimization of a streamlined high-speed train using Kriging model. J Zhejiang Univ-Sci A 23:225–242
Zheng XJ, He LH, Wu JJ (2004) Vertical profiles of mass flux for windblown sand movement at steady state. J Geophys Res-Solid Earth 109:10
Zhou H, Zhao WZ, Zhang GF (2017) Varying water utilization of *Haloxylon ammodendron* plantations in a desert-oasis ecotone. Hydrol Process 31:825–835
Zhu Y, Dong M, Huang Z (2005) Effects of sand burial and seed size on seed germination and seedling emergence of *Psammochloa villosa*. Acta Phytoecol Sin 29:730–739 (in Chinese)

Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.