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The effects of different types of vegetation restoration on wind erosion prevention: a case study in Yanchi

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Abstract

Improving wind erosion prevention in the key ecological zones of sand fixation are closely linked to human welfare in China and Northern Eurasia. In this research, we studied the sand transport rate (STT), soil water content (SWC), and retention rate of the wind erosion prevention services (RR) in five experimental zones in Yanchi Country, including bare sandy land (BL), and four restoration zones with different types of vegetation restoration approaches, including artificial restored grassland with low-coverage (AGL), artificial restored grassland with high-coverage (AGH), and naturally restored grassland (NG). The results showed that: (1) From 2006 to 2018, the STTs of the four restoration zones were lower than those of BL, and those of the AS were much lower than those of AGL, AGH, and NG; (2) in the rainy season, the SWCs of AS, NG, AGH, AGL, and BL were 3.01%, 2.80%, 2.79%, 2.68%, and 2.41% respectively. In the dry season, the SWCs of NG, BL, AGH, AGL, and AS were 2.86%, 2.93%, 3.00%, 3.08%, and 3.20%, respectively. The differences in the SWCs between the two seasons of BL were the largest (0.52%), while those of NG were the lowest (0.06%); (3) the annual average RRs in AS, AGH, NG, and AGL were 74.41%, 69.41%, 69.28%, and 61.64%, respectively, while the annual change of the RR in the NG was the smallest. This study reveals the effects of different types of vegetation restoration on wind erosion prevention in Yanchi country, thereby providing a scientific basis for policymakers to engage in effective vegetation restoration and formulate ecological protection policies.

1. Introduction

Soil erosion by wind is one of the most serious environmental issues; it causes land degradation and threatens the sustainability of ecosystem services and socioeconomic development around the dryland areas of the world (Ayub et al 2020, UNCCD 2017, Zhang et al 2018). Approximately 30% of the global land area, mostly in the dry parts of the world, suffers from wind erosion (Gemma et al 2016). The largest area of wind erosion is located in the northern hemisphere, mainly in a broad ‘dust belt’ that extends from the west coast of North Africa, through the Middle East and Central and South Asia, to China (Prospero et al 2002). During the wind erosion process, soil and nutrients are blown away, thereby degrading soil function and land productivity and negatively influencing food security (Li et al 2020, Lal 2017, Zhao et al 2017). In addition, wind erosion is the main cause of sand and dust storms, which reduce air/water quality and cause problems for human migration and health (Jiang et al 2018, Shen et al 2018, Goudie 2020).

Systematic studies of ecosystem restoration and integrated ecological management technologies are urgently needed to ensure the coordinated development of ecology–economy–society and the ecological security of wind erosion regions (Duniway et al 2019, Zhen et al 2020). Since the 21st century, China has developed hundreds of core technologies for controlling wind erosion, including planting, the use of straw checkerboard barriers, and determining the livestock carrying capacity according to grass. These technologies were summarized and optimized based on nearly one hundred of the best restoration cases (Jiang 2008, Fu and Liu 2013). In the adjacent territories of Russia and Kazakhstan, which experience terrible soil erosion and dust storms, restoration practices such as the planting of forest shelter
belts and the introduction of innovative farming methods were implemented in agricultural territories (Artamonova et al 2019). In the desert-steppe zone of Mongolia, tree planting and silvopasture fencing with a forest shelter belt are widely used restorations, including a large-scale planting scheme known as the Great Green project (Tsognamsrai and Dugarjav 2016, Middleton 2018). In Iran, petroleum mulching, biological soil crust (BSC) bacteria, and synthetics (clay minerals, polyvinyl acetate, and palm biochar) have been employed to stabilize sandy land (Azoogh and Jafari 2018, Feizi et al 2019, Kheirfam and Asadzadeh 2020). Integrated interventions, including long term livestock exclusion and revegetating, have been implemented in the degraded grasslands of the Baviaanskloof Hartland Bawarea Conservancy in South Africa (Del Río-Mena et al 2020).

Vegetation restoration is the most effective and widely used practice to prevent wind erosion (Cheng et al 2019) and largely involves the following two mechanisms. Firstly, vegetation influences aerodynamic forces and removal-resisting forces. Wind erosion is the consequence of two types of forces at work: aerodynamic forces (removing particles from the surface) and removal-resisting forces (including gravity and inter-particle cohesion). Aerodynamic force can be quantified by the surface wind shear stress, which is related to the atmospheric flow conditions (such as wind, rainfall, etc) and the surface’s aerodynamic properties (such as surface roughness, landforms, etc) (Shao 2009). As a rough element, vegetation increases the surface roughness, reduces the wind speed, and decreases the surface wind shear stress (Hong et al 2020, Dong et al 2001). Removal-resisting force can be quantified by the minimum friction velocity required for wind erosion to occur, which is related to soil properties, including soil texture, hydraulic properties, wetness, compactness, etc (Shao 2009). The litter and root systems of vegetation can effectively improve the underground ecosystem, including soil texture, soil properties, soil water content, and compactness, thereby increasing the removal-resisting forces (Cotrufo et al 2015, Jian et al 2015). Secondly, vegetation intercepts a certain proportion of moving sand particles, thereby reducing sand transport flux (Van de Ven et al 1989).

Currently, wind erosion studies have concentrated on the spatial and temporal variations of wind erosion (Yue et al 2019; Borrelli et al 2017), as well as the dynamics of wind erosion and the driving forces behind it (Touré et al 2019, Wu et al 2019). Most field studies on the effects of vegetation restoration researched the effects on the sand transport rate (Kaplan et al 2020), soil properties (Gao et al 2018, Kalhoro et al 2019), and ecosystem services (Liu et al 2019, Del Río-Mena et al 2020). However, comprehensive studies of the effects of vegetation restoration on sand transport, soil properties, and ecosystem services are still limited. Vegetation restoration with different vegetation types (e.g. shrub and herb) using different approaches (i.e. natural or artificial) and coverage types (i.e. high coverage or low coverage) can have diverse effect on wind erosion. Therefore, comprehensive studies on the effects of different vegetation restoration types on sediment transport, soil properties, and ecosystem services are needed.

Yanchi Country is located in the southeast area of Mu Us Sandy Land, which is an important dust source area in the northwest of China (Liu et al 2003, Wang et al 2014). It is also a key ecological function zone of sand fixation, which refers to areas with a high sensitivity to desertification and the large-scale impacts of sandstorms (Huang et al 2013). Due to the significant inter-regional flow effects of wind and sand (Rashki et al 2015), the scope of sandstorms in this area effect not only areas in the north and northeast of China but also some regions in Northern Eurasia (Pan et al 2014, Song et al 2016, Xu et al 2018). Xu et al (2018) found that the flow paths of wind erosion prevention services in Yanchi Country mainly extend to Eastern and Central China, North Korea, South Korea, Japan, Mongolia, and Eastern Russia, covering an area of 1153.2 × 10⁴ km² in 2010. Therefore, improving the sand fixation capacity and decreasing wind erosion in Yanchi Country has great significance for human welfare and socio-economic development in both China and Northern Eurasia (Chen et al 2014).

To address these issues, we investigated the sand transport rate, soil water content, and retention rate of wind erosion prevention services under different experimental vegetation restoration zones located in Yanchi Country. In line with these concerns, the research question is the following: What are the effects of vegetation restoration approaches on sand transport and soil water content in desertification-stricken areas? To provide answers to this question, this study aims to (1) explore the effects of different vegetation restorations on the sand transport rate and soil water content and (2) quantify the retention rate of wind erosion prevention services on these vegetation restorations. This research can help determine better vegetation restoration approaches for wind erosion prevention in key ecological function zones of sand fixation and thus improve the health of the ecosystem and environment of the surrounding areas in China and other countries in Northern Eurasia.

2. Methodology and data

2.1. Study area

Yanchi County (32°04′ ~ 38°10′N; 106°30′~107°41′E) is located in the east of the Ningxia Hui Autonomous Region, located in the southwestern margin of the Mu Us Sandy Land in the transition zone from the Ordos platform to the Loess Plateau, with a total area of 6777.97 km² and an average altitude of 1600 m. The area has a typical continental climate, with average rainfall of 271 mm and average evaporation of
1444 mm. The annual average temperature is 7.7 °C, and the annual average wind speed is 2.8 ∼ 4.1 m s⁻¹; the main wind direction is northwest, and the average annual number of wind and sandstorm days is 24.2 and 20.6. The vegetation here is a transitional zone type (ranging from desert steppe to steppe), and perennial wild herbs are widely distributed across the region.

The study area is located in Liuyaotou Soil Erosion Monitoring Station (37°39′55″N, 107°13′02″E) of Yanchi Country, where five wind erosion experimental zones were set up with a uniform size of 25 × 25 m, each of which is surrounded by fences and wire netting. The five zones are bare sandy land (BL) and four vegetation restoration lands, including anthropogenic grassland with low-coverage (AGL), anthropogenic grassland with high-coverage (AGH), anthropogenic shrub land (AS), and naturally restored grassland (NG) (figures 1 and 2; table 1). The slope gradient of these five plots are within 0–13° (table 1) and the soil texture of this area is sandy soil. The BL, AGL, AGH and AS are 50–200 m
Table 1. Vegetation conditions of the five experimental zones.

| Type | Slope gradient (°) | Restoration pattern | Vegetation type | Coverage degree (%) | Vegetation Height (m) | Soil crust coverage (%) |
|------|--------------------|---------------------|-----------------|--------------------|----------------------|------------------------|
| BL   | 13.0               | —                   | Herbage         | 7.8%               | 0.25                 | 0.9                    |
| AGL  | 2.5                | Anthropogenic       | Herbage         | 46.3%              | 0.38                 | 2.2                    |
| AGH  | 3.0                | Anthropogenic       | Herbage         | 55.0%              | 0.38                 | 2.5                    |
| AS   | 3.6                | Anthropogenic       | Shrub           | 75.7%              | 1.78                 | 6.1                    |
| NG   | 0                  | Natural             | Herbage         | 43.9%              | 0.19                 | 1.1                    |

Note: The coverage degree and height are averaged by the monthly values shown in figure 3.

Figure 3. Vegetation coverage degree and height of the five experimental zones.

Note: The monthly coverage degree and vegetation height are averaged by the monthly values measured during 2015–2018.

apart from each other, the distance between NG and these four plots is more than 1000 m, and the surroundings of these five plots are grassland with scarce forest. These five experimental zones were established in October 2005, the initial land use form of BL, AGL, AGH and AS are bare land, and the initial land use form of NG is cultivated land. The vegetation coverage and heights of these five experimental zones are recorded twice a month. The vegetation coverage degree is measured with the line interception method and the visual estimation method (Yang et al. 2020), while the vegetation height is measured with line interception method (Xu 2015). The restoration treatment, annual average for the coverage degrees and heights of these five experimental zones and the soil crust coverage can be found in table 1. The monthly average of the coverage degree and height can be found in figure 3. The BL was sandy land with no restoration practices. The vegetation coverage in the area is extremely low (the annual average is 8%). The AGL and AGH are planted with Artemisia Arenaria, a common herb in Yanchi Country, and the vegetation coverage of AGL (46.3%) is less than that of AGH (55.0%). The AS is planted with Salix psammophil, a widely used shrub for preventing wind soil erosion in the Mu Us Sandy Land with coverage of 75.7%. The NG is a naturally restored grassland transferred from cultivated land. The vegetation type here is herb, including Artemisia Arenaria, Medicago sativa, Sorghum sudanense, and Astragalus adsurgens, with a coverage of 43.9%.

2.2. Methodology

2.2.1. Data resources

All 13 year meteorological datasets for sand transport, soil erosion, and soil water content were provided by the Liuyaotou Soil Erosion Monitoring Station in Yanchi County. The annual rainfall and annual average wind speed (16 directions) were monitored by the meteorological station near the five experimental zones with a high-precision automatic observation instrument. The sand transport rate (STT) was measured with an omni-directional sand collector located 40 cm above the ground. This device can collect the sand from 16 directions. Each of the experimental zones has an omni-directional sand collector located in the middle of the zone. The collected sand (W) was weighed every month. The soil erosion thickness according to wind (SET) was determined with erosion pins method (Couper et al. 2002, Li et al. 2016). The erosion pins used were 30–50 mm long, 3–2 mm diameter silicon-bronze welding rods, which were installed by pushing them into the soil and leaving 10–20 mm exposed. Twenty-five erosion pins were placed in each experimental zone with 5 m apart from each other. The height differences of the
Figure 4. The sand transport rate in the five experimental zones. Note: the sand transport rate here is the annual average of the sum of 16 directions. (A) The sand transport rate in five experimental zones from 2006 to 2018; (B) the sand transport rate in five experimental zones from 2008 to 2018.

Figure 5. The relationship between the sand transport rate and wind speed in the five experimental zones. Note: The wind speed in this figure is the annual average of the wind speed in 16 directions, and the sand transport rate here is the annual average in each of the 16 directions corresponding to the wind speed. (A) The annual wind speed in 16 directions from 2006 to 2018. The small circle (with the purple background) indicates the annual wind speeds in 2011, 2012, 2013, 2015, 2016, 2017, 2018, which were between 0 and 4 m s\(^{-1}\). The big circle (with a grey background) indicates the wind speeds in 2006, 2007, 2008, 2009, 2010, and 2014, which were between 20 and 60 m s\(^{-1}\); (B) the relationships of the annual wind speed (16 directions) with the sand transport rate (16 direction separately) in AGL (artificial restored grassland with low-coverage), AGH (artificial restored grassland with high-coverage), AS (artificial shrub land), and NG (naturally restored grassland); (C) the relationship of the annual wind speed (16 directions) with the sand transport rate (16 direction separately) in BL.

Exposed parts of the erosion pins were measured every month for calculating the SET and then calculating soil erosion modulus (SEM), soil erosion prevention service (SS), and retention rate of the soil erosion prevention service (RR). Soil water content (SWC) was measured via the drying–weighing method in 2016 (Zhang et al 2005). Soil samples were collected twice a month (i.e. early month (1st to 3rd) and mid-month (15th to 16th)) at fixed locations, five soil samples were taken from each experimental zone, and the depth of the collected soil was 30 ~ 60 cm.

2.2.2 Data processing
The sand transport rate (STT, g/m/min) represents the amount of sand transported through a unit width per unit time and is calculated as
STT = \( W / (t \cdot d) \) \hspace{1cm} (1)

where \( W \) is the weight of sand collected by the omni-directional sand collector (g), \( t \) is the collection time (min), and \( d \) is the width of the collection holes of the omni-directional sand collector (m). The annual STT used in figure 4 is the total of the 16 directions, while the annual STT used in figure 5 features 16 directions separately.

The soil erosion modulus (SEM, \( t/km^2/yr \)) represents the amount of soil eroded by wind as the unit area per unit time and is calculated as

\[
SET_{yr} = \frac{1}{25} \sum_{1}^{12} \sum_{1}^{25} |L|
\]

\[
SEM = 1000^2 \times 1.7 \times SET_{yr}
\] \hspace{1cm} (3)

where \( L \) is the change in the erosion pins' above-ground height over a month (m); \( SET_{yr} \) is the soil erosion thickness over a year (m/yr); and 1.7 is the bulk density (t/m\(^3\)).

The soil erosion prevention service (SS, \( t/km^2/yr \)) was calculated by the difference of the wind erosion modules in the bare sandy land and the vegetation land. The retention rate of the soil erosion prevention service (RR, \%) was used to describe the contribution of the vegetation itself to soil erosion, which is expressed by the ratio of wind erosion prevention services under the bare sandy land and the services under the vegetation-covered ground (Gong et al. 2014):

\[
SS_V = |SEM_V - SEM_S| \hspace{1cm} (4)
\]

\[
RR = \frac{SS_V}{SEM_S} \times 100\%
\] \hspace{1cm} (5)

where \( SEM_V \) is the soil erosion modulus for the vegetation-covered land (t/km\(^2\)/yr); and \( SEM_S \) is the soil erosion modulus for bare sandy land (t/km\(^2\)/yr).

The soil water content (SWC, %) is calculated as

\[
SWC = \frac{W_F - W_D}{W_D} \times 100\%
\] \hspace{1cm} (6)

where \( W_F \) is the weight of the fresh soil sample, and \( W_D \) is the weight of the fresh soil sample.

3. Results

3.1. Sand transport rate in the five experimental zones

Based on the observations of the sand transport rates (STTs) in BL, AGL, AGH, AS, and NG from 2006 to 2018, since 2006, the STTs of these five experimental zones have continued decreased. The STT in BL was significantly higher than that under the four types of experimental vegetation restoration zones (figures 4(a) and (b)). Among the four types of vegetation restoration zones, the STT of AS land was the lowest in almost every year from 2006 to 2018, excluding 2007; the STTs of NG, AGH, AGL, were lower than the STT of BL but higher than that of AS (figures 4(a) and (b)). From 2006 to 2007, the STTs of NG, AGH, and AGL were as follows: AGL < AGH < NG (figure 4(a)). From 2009 to 2018, there were no significant differences in the STTs between the three types of vegetation restoration zones.

After regression fitting the data between the annual STT (16 directions separately) and annual wind speed (16 directions separately) in the five experimental zones, all regression curves presented a good correlation \((R^2 > 0.5)\) (figures 5(b) and (c)). The slope between the STT and the wind speed on the BL was significantly higher than that of the other four vegetation restoration zones (figure 5(b)). In the four vegetation restoration zones, the STT in NG increased sharply with an increase in wind speed. This slope was followed by the slopes of the AGL and AGH land. As the wind speed increased, the STT in AS increased the most slowly.

The results of the STT for the five experimental zones showed that the four vegetation restorations impacted sand fixation. Among these four types of vegetation restorations, artificial shrub land restoration had the best effects on sand fixation.

3.2. Soil water content in the five experimental zones

In 2016, the rainfall maintained a low level from October to February, showing a slight increase in March, a secondary peak in May, and the highest peak in July. Then, the rainfall maintained a high level from August to September (figure 6(a)). The soil water content (SWC) is closely related to rainfall and vegetation growth. The highest SWC of the five zones all appeared in April, possibly due to the increase in rainfall during late March (21st–24th). The secondary peak of SWC occurred from August to September, possibly due to the large amount of rainfall from July to September (figures 6(a) and (b)). From May to July, the SWC decreased despite the high rainfall during this period (figures 6(a) and (b)), which may have been caused by increased transpiration due to vegetation growth.

From November to February (i.e. the rainy and vegetation growing season (figures 3 and 6(a))), the SWCs of AGH, AS, and NG changed less, while the SWCs in BL and AGL changed drastically. The average SWC of BL was the lowest (2.41%), while the SWC of AS was the highest (3.01%). The SWCs of NG (2.80%), AGH (2.79%), and AGL (2.68%) were less than the SWC of AS (figure 6(c)). From June to September, which is the dry season, all SWCs in all five zones changed drastically. The average SWC of NG was the lowest (2.86%), and the SWC of AS was the highest (3.20%). The SWCs of AGL (3.08%), AGH (3.00%), and BL (2.93%) were less than the SWC of AS (figure 6(c)). The differences in SWC between the
The soil water content of the five experimental zones.

Note: (A) Sum of the monthly rainfall in 2016; (B) the soil water content of the five experimental zones in 2016; (C) the average soil water content from November to February and June to September.

The wind soil erosion modules of the five experimental zones.

Note: (A) The wind soil erosion modules of the five experimental zones from 2006 to 2018; (B) the annual average of the wind soil erosion modules of the five experimental zones from 2006 to 2018.

Rainy season and dry season in BL (0.52%) were the largest, the difference in NG (0.06%) was the lowest, and the differences in AS (0.19%), AGH (0.32%), and AGL (0.40%) were greater than those in AS (figure 6(c)).

The results show that the four vegetation restoration measures increased the SWC and that the increased SWC in the shrub land was better than that of the grassland. The seasonal changes of SWC were most stable in the naturally restored grassland.

3.3. The retention rate of soil erosion prevention services in the five experimental zones

According to research on the soil erosion modules (SEM) of BL, AGL, AGH, AS, and NG from 2006 to 2018, the SEMs of the four vegetation restorations were significantly lower than the SEM of BL, except in 2017 (figure 7). The annual average of the SEM in BL was 251 244 t km⁻², and that in AS was 55 584 t km⁻², which is the lowest value among the four vegetation restorations. The SEMs of NG, AGH, and AGL were
77,951 t km$^{-2}$, 77,240 t km$^{-2}$, and 94,114 t km$^{-2}$, respectively.

According to research on the retention rate of soil erosion prevention services (RR) for BL, AGL, AGH, AS, and NG, the RRs in the four vegetation restorations were all above 60% in 2006, and the RRs of these four vegetation restoration zones reached their peaks (AGL is 93.6%, AGH is 94.2%, AS is 93.4%, and NG is 89.9%) in 2011 (figure 8(a)). Subsequently, the RRs of these vegetation restoration zones began to show a downward trend. In 2017, the RRs were below 35% (AGL is 2.0%, AGH is 0.9%, AS is 34.1%, and NG is 29.2%) (figure 8(a)). Comparing the annual average RR under the four vegetation restorations, the RR of AS is the highest (74.41%); here, AHG and NG are 69.41% and 69.28%, respectively, and AGL is the lowest (61.64%) (figure 8(b)). The annual change of the RR in AGL is higher than that in other vegetation restorations, while the annual change of RR in NG is the lowest (figure 8(b)).

The research on SEM and RR in the five experimental zones showed that these vegetation restorations are helpful for improving the land's resistance against wind erosion. The land's resistance against wind erosion in shrub land was shown to be better than that in the other three grasslands.

4. Discussion

This study reflects the effects of different types of vegetation restorations on wind erosion prevention. We found that artificial shrub land has a better effect on wind prevention and sand fixation, improvements in soil water content (SWC), and the retention of soil wind erosion prevention services than bare sandy land and the region restored by grass. This might be caused by the aboveground height and underground root system (Musick and Gillette 1990, Gyssels et al 2005, Bardgett et al 2014). In our study, compared with NG, AGH, and AGL, AS had a better effect on wind prevention and sand fixation. Similar with our results, Li et al (2013) studied the responses of different types of plants to wind erosion in Dun-huang, China, through the yearly change in accumulated sand. The authors suggested that shrub belts offer better sand prevention effects than grass, and that Hedysarum scoparium, a typical kind of shrub, is the most suitable desert shrub in this area. The differences between the vegetation restoration measures on wind prevention and sand fixation may be because the vegetation height of shrubs is higher, thereby increasing the aerodynamic roughness and friction rate and intercepting moving sand particles (Wasson and Nanninga 1986, Van de Ven et al 1989). In our research, plants in the AGH and AHL zones were mostly herb, and the average vegetation height in AS was 4~5 times that in AGH, AHL, and NG. Lee (1991) found that the wind effectively skims over the shrubs and encounters little friction from the ground surface and the shrubs, indicating that the wind flow above desert surfaces is modified by shrubs, which slow the wind via friction. On the other hand, roots can bind soil together and tie weak surface soil layers into strong and stable subsurface layers. The differences in shrub and herb roots may be the reason for their different sand blocking capabilities. Li et al (2017) suggested that plant roots significantly affect the soil erosion process of overland flow via physical consolidation (i.e. as a root link and root–soil adhesive). Biological chemical functions and a physical consolidation effect were the key factors in soil erosion resistance, accounting for 70.9% of the total root effect, while the root string function was the key element (78.2%) in the physical consolidation effect. The exponential function accurately expressed the relationship between the root physical consolidation effect and the root surface area density (Li et al 2017).

The water restoration capacity of shrub vegetation restoration may be better than that of grass because of the hydraulic lift effect of plant roots, which refers to the process by which plants passively transfer water from their deep, moist soil layers to their shallow, dry soil layers (Caldwell et al 1998). Zapater et al (2011) used the method of stable isotope labelling to demonstrate this phenomenon. The authors injected $^{18}$O-enriched soil water at a depth of 75~90 cm and observed isotopic enrichment in the shallower soil layers six days later. The intermediate soil layers did not show any enrichment. Moreover, only superficial enrichment was observed in the vicinity of the plant trunks along with an increase in the isotopic signature of xylem sap. The results clearly indicate hydraulic lift by tree roots. Gibbens and Lenz (2001) studied the root systems of 11 shrub or shrub-like species and 11 grass species in the northern Chihuahuan Desert in southern New Mexico. The authors found that all shrub species roots could be traced to depths of 5 m, while the grass root systems on sandy soils extended radially up to 1.4 m. Because the soil sample in our research was taken from 30 cm of the soil layer, and because the extremely deep roots of shrubs can raise the depth to a more shallow soil layer, the SWC increased. On the other hand, because the root–microorganism–soil is an interacting agglomeration, the roots of plant will affect the physical structure and chemical properties of the soil. Wu et al (2016) investigated the effects of different artificial grasslands on soil physical properties and soil infiltration capacity, suggesting that the use of legume–shrub mixtures to create grasslands provides an effective ecological restoration approach to improve soil infiltration properties due to such mixtures’ greater root biomasses. Third, the soil surface crust may also be one of the factors affecting soil moisture content. Biological soil crusts (BSCs) are extensively developed...
and commonly regarded as a type of vegetation in desertification areas around the world. Xiao et al. (2014) monitored the SWC at a 0–90 cm depth under the two treatments (i.e. natural BSCs (without disturbance) and disturbed BSCs (with the BSC layer removed)) in a semi-arid environment. The results showed that BSC disturbance greatly decreased the SWC by up to 18%, an effect that remained for three to four years. In our experimental zones, the shrub vegetation restoration land had a high degree of crusting cover (table 1), which may be caused by the blocking effect of shrubs on wind and sand, decreasing the surface disturbances and facilitating crusting.

In our research, we found that the shrub ecosystem had greater wind erosion prevention services than the other three restoration regions. Similar with our results, Gong et al. (2014) also found that wind erosion prevention services have a significant positive relationship with vegetation coverage in most regions in Yanchi, which means that a decrease or an increase in vegetation coverage can significantly intensify or mitigate soil wind erosion. Additionally, Wang et al. (2019), based on the RWEQ model, quantitatively estimated the wind prevention and sand fixation service function of the Ningxia grassland from 2000 to 2015. Their results showed that the average annual area of wind and sand fixation material per unit area for the Ningxia grassland was between 0.33~1.77 kg m$^{-2}$. The retention rate of soil wind erosion prevention services was 0.65~0.79, which is close to the retention rate found in our study. However, the wind and sand-fixing mass of the Ningxia grassland measured by Wang was far less than that of the areas measured in the present study, possibly because these two studies used different calculation methods. Another reason may be that the research object of Wang included the entire Ningxia grassland, whereas the study area in this research was located in the southern edge of the Mu Us Sandy Land, which has more severe wind erosion.

The occurrence of wind erosion has an important relationship with the surrounding environment. The region around the study area (including the entire key ecological functional zone of sand fixation) has implemented many restoration technologies and projects, such as the Three North Shelterbelt, Natural Forest Protection Project, and Green for Grain (Bryan et al. 2018). Our research found that since 2006–2018, all five experimental zones experienced a decrease in their sand transport rate and soil erosion modulus; this downward trend is particularly obvious in the data for 2006–2008. This result may be related to an improvement in the overall environment, which the significant decrease in wind speed from 2006 to 2018 also supports.

5. Conclusions

This study analysed the effects of different types of vegetation restoration on wind erosion prevention and soil water retention. The conclusions can be summarized as follows: (1) The four vegetation restorations all decrease the sand transport rate, and the shrub land showed a better effect than the three grasslands; (2) the four vegetation restorations had effects on increasing soil water content, and the shrub land showed better effects than the three grasslands. Moreover, the SWC in naturally restored grassland

![Figure 8. The retention rate of the soil wind erosion prevention services in the four vegetation restoration zones. Note: (A) The retention rate of the soil wind erosion prevention services of the five experimental zones from 2006 to 2018; (B) the annual average of retention rate of the soil wind erosion prevention services of the five experimental zones from 2006 to 2018.](image-url)
was more stable than those in the three anthropogenic restoration zones; (3) the shrub land exhibited the highest retention rate of soil wind erosion prevention services than the other three grasslands, with small fluctuations between different years.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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