A Review of Research on the Windbreak and Sand-Fixing Functions of China' s Desert Grasslands in the Context of Ecological Engineering

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Abstract

Desert steppe is an important component of the sand prevention belt in northern China. Against the backdrop of the continuous advancement of ecological protection, management, and restoration projects, clarifying the intrinsic relationship between plant trait characteristics and windbreak and sand-fixation functions has become key to precise policy implementation. This paper systematically reviews research progress on vegetation management and restoration and the assessment of windbreak and sand-fixation functions in China' s desert steppe, clarifies the new requirements for the overall restoration of vegetation structure and ecological functions under ecological management projects, and focuses on the windbreak and sand-fixation functions of desert steppe areas. It compares and analyzes the advantages and limitations of different monitoring and assessment methods and, based on an in-depth discussion of the mechanisms by which plant functional traits affect windbreak and sand-fixation functions, proposes directions for improving windbreak and sand-fixation function models applicable to ecological management project areas, thereby providing decision-making references for the construction of major ecological projects in China' s desert steppe and the advancement of sand prevention and control.

Full Text

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Zhang Biao[1], Zhu Jiashun[2], He Xiaohui[1], Xu Jie[3], Liu Hongyu[1], Sun Hailian[1]

(1. School of Ecology and Environment, Baotou Teachers' College, Baotou 014030, Inner Mongolia; 2. Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101; 3. School of Ecology and Nature Conservation, Beijing Forestry University, Beijing 100083)

Abstract: Desert grasslands are an important component of the sand-control belt in northern China. Against the background of continuously advancing ecological protection, governance, and restoration projects, clarifying the intrinsic relationship between plant functional traits and windbreak and sand-fixing functions has become the key to precision policymaking. This paper systematically reviews research achievements on vegetation governance and restoration and on the assessment of windbreak and sand-fixing functions in China' s desert grasslands, clarifies the new requirements for the overall restoration of vegetation structure and ecological functions under the background of ecological governance projects, focuses on the windbreak and sand-fixing functions of desert grassland areas, compares and analyzes the advantages and deficiencies of different monitoring and assessment methods, and, on the basis of an in-depth discussion of the mechanisms by which plant functional traits affect windbreak and sand-fixing functions, proposes directions for improving models of windbreak and sand-fixing functions applicable to ecological-governance project areas, thereby providing decision-making references for the construction of major ecological projects in China's desert grasslands and for the advancement of sand prevention and control work.

Keywords: ecological restoration; windbreak and sand fixation; functional traits; desert grassland

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Land desertification is a global ecological and environmental problem[1], and China is one of the countries with the largest desertified area in the world, the largest affected population, and the most severe wind-sand disasters. To prevent and control desertification and land sandification, since the 1970s China has deployed and implemented major ecological projects such as the Three-North Shelterbelt Program, natural forest protection, returning farmland to forest and grassland, and governance of the Beijing–Tianjin sandstorm source areas[2-3]. Ecological protection and restoration have made substantial progress, ecological degradation has been effectively curbed, and regional ecological environments have continued to improve. However, in arid areas, water resources are scarce, and long-term activities such as artificial afforestation and grass sowing have left some local land surfaces exposed, reduced the soil' s resistance to wind erosion[4], and made the degradation of local windbreak and sand-fixing functions increasingly prominent[5-7]. In 2020, the National Development and Reform Commission and the Ministry of Natural Resources jointly issued documents such as the *Master Plan for Major Projects for the Protection and Restoration of Important National Ecosystems (2021–2035)* and the *Construction Plan for Major Projects for Ecological Protection and Restoration in the Northern Sand-Prevention Belt (2021–2035)*, continuously promoting the construction of major ecological protection and restoration projects and emphasizing a new orientation in which improving vegetation coverage shifts toward the overall recovery and transformation of vegetation structure and function. Therefore, it is urgently necessary to pay attention to the intrinsic relationship between vegetation structural configuration and ecological-function restoration, so as to scientifically guide the coordinated improvement of vegetation quantity, quality, and function during ecological restoration.

To strengthen functional restoration and scientific management of damaged ecosystems, research on ecosystem service supply and regulation mechanisms has received increasing attention[8-10]. Plant functional traits directly participate in multiple ecosystem processes, influence ecosystem service supply, and provide a new perspective for research on the relationship between ecosystem structure and function[11-13]. At present, many scholars have paid attention to the interactions between plant functional traits and ecosystem services[14-15], but the focus has been on ecosystem services related to nutrient cycling and material production[14]; only a small number of studies have explored the relationship between plant functional traits and windbreak and sand-fixing functions[16]. Windbreak and sand fixation is an important ecological function of the arid and semi-arid regions of northern China[17], and northern desert grasslands are a key ecological barrier against sandstorms on the southern edge of the Mongolian Plateau and in northern Xinjiang, China. However, because long-term fixed-location monitoring of plant functional traits and windbreak and sand-fixing functions in arid areas, as well as studies on the influence patterns and feedback mechanisms between the two, remain weak, it is difficult to support the national demand for the construction of major ecological projects and the advancement of sand prevention and control work.

Therefore, this paper comprehensively reviews assessment technologies for windbreak and sand-fixing functions in desert grasslands and research achievements on vegetation structural configuration, clarifies the requirements for ecological-function restoration under the background of ecological governance, focuses on key ecological functions in desert grassland areas, and reviews the advantages and

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Author profile: Zhang Biao (1980-), male, Ph.D., research fellow, mainly engaged in regional ecology research. E-mail: zhangbiao@igsnrr.ac.cn
Corresponding author: Sun Hailian (1972-), female, Ph.D., research fellow, mainly engaged in grassland ecology research. E-mail: 66497@bttc.edu.cn

insufficient; reviews progress in research on how the structure of vegetation communities affects windbreak and sand-fixing functions, with a focus on examining the relationship between plant functional traits and regional windbreak and sand-fixing functions; and analyzes and seeks improved approaches for evaluation and prediction models of windbreak and sand-fixing functions. It proposes directions for improving models of windbreak and sand-fixing functions that are suited to the requirements of ecological governance, thereby providing decision-making references for the construction of major ecological projects in desert grasslands and for the advancement of sand-prevention and sand-control work.

1 Research on the Effectiveness of Ecological Governance in Desert Grasslands

Continuously carrying out governance and restoration of desert grasslands is an important task advanced under China's ecological engineering programs. Ecological restoration is an important means of responding to ecological environmental degradation and ensuring sustainable development. Since the 1950s, China has approved and implemented a series of ecological protection and restoration projects, achieving notable results. According to calculations by Wang Lan et al.[18], over the past nearly 40 years, vegetation cover in China' s major ecological project areas increased by 0.19%-26.00%, biomass varied by −13%-187%, and carbon sequestration changed between −7.41% and 200.00%. From 1958 to 2015, 45.76% of the land in China' s arid regions showed a trend of improvement or "greening" [19]. In addition, from 2001 to 2020, the Yellow River Basin became significantly greener, and vegetation carbon-sequestration capacity increased markedly, although water consumption also rose substantially[20-22]. Northern desert grasslands are an important ecological security barrier in northern China and play an irreplaceable role in protecting the source regions of major natural disasters such as dust storms originating in the southern Mongolian Gobi region and northern Xinjiang of China[23]. However, the distribution of their vegetation and the realization of their ecosystem service functions are constrained by environmental factors such as soil, climate, and hydrology in desert grassland areas[24-26]. In recent years, driven by ecological projects such as the northern sand-prevention belt, the Three-North Shelterbelt Program, sand-source control, and ecological security barrier construction, the area of forests and grasslands in northern arid regions of China has increased rapidly, and ecosystem functions have improved[19]. Yet while ecological engineering in desert grasslands has advanced rapidly, it can readily increase the vulnerability of forest and grass ecosystems, damage the original soil moisture conditions and surface soil structure[4], and induce dry soil layers[27-28]. Therefore, in past ecological restoration processes, the excessive pursuit of restoring vegetation cover, insufficient attention to vegetation community structure and its ecological functions, and related problems deserve reflection. These include afforestation in excess of the water-carrying capacity of arid regions; large-scale destruction of native vegetation for plantation establishment; the introduction of exotic tree species for large-scale afforestation; afforestation on original grasslands; and afforestation on mobile sand under extremely harsh natural conditions[29]. Such phenomena sometimes occur, causing some areas that appear to have high vegetation cover to in fact have simple vegetation structure and limited core ecological functions[30].

Overall, in the desert grassland regions of northern China, climatic conditions are harsh and vegetation succession frequently shifts in a negative direction. Although the construction and implementation of a series of major ecological projects have effectively improved local ecological environmental conditions, vegetation ecosystem structure remains highly unstable; under climatic constraints, vegetation cover has no further potential for increase; and the effects of various ecological protection projects are far from ideal[31]. Northern desert grasslands face prominent problems such as unclear ecological restoration effects, ecosystem instability, and declining ecosystem service functions[6,18]. For example, in regions such as northern Yinshan, the Hunshandake Sandy Land, and the Horqin Sandy Land, the annual decline in windbreak and sand-fixing function exceeds 2.5 $t \cdot hm^{-2}$; in southwestern Altay and western northern Yinshan, the annual decline reaches 1.0-2.0 $t \cdot hm^{-2}$[7]. From 2000 to 2015, the windbreak and sand-fixing function in the western part of the Beijing–Tianjin sand-source control project area declined markedly[6]. Part of the reason is that ecological restoration practice has placed excessive emphasis on restoring vegetation quantity, mainly in terms of cover[30], while neglecting optimization of vegetation structure centered on plant functional-trait configuration. Therefore, strengthening multidisciplinary integration in desert grassland ecological restoration, emphasizing systematic and holistic restoration across different dimensions and multiple trophic levels[32], and optimizing the configuration of plant functional traits are feasible pathways for precisely improving the effectiveness of ecological restoration[16].

2 Research on Monitoring and Evaluation of Windbreak and Sand-Fixing Functions

Changes in key ecosystem functions are an important means of monitoring and evaluating the effectiveness of desert grassland governance. Windbreak and sand fixation are key ecological functions in China' s northern arid and semiarid regions[6,17,33]. Wind-erosion models are mainly used to quantitatively assess the spatiotemporal differences in windbreak and sand-fixing functions. British scientist Bagnold (1941) was the first to establish a sand-transport-rate formula mainly applicable to sandy surfaces[34]. In the 1960s, against the background of rapid development in computer, geographic information system, and remote-sensing technologies, wind-erosion models based on statistics and experience were successively proposed, such as the Wind Erosion Equation (WEQ)[35], the Texas Erosion Analysis Model (TEAM)[36], the Bocharov model[37], the Revised Wind Erosion Equation (RWEQ)[38], and the Wind Erosion Prediction System (WEPS)[39] (Table 1), among which the RWEQ model is the most commonly used[4,46]. For example, calculations by Zhang et al.[5] found that the wind-erosion modulus in Inner Mongolia decreased by 49.23% during 1990–2015. Studies of the spatiotemporal changes in windbreak and sand-fixing functions in the Beijing–Tianjin sand-source area, as well as the spatial heterogeneity of windbreak and sand-fixing services in Inner Mongolia' s desert grasslands, have all adopted the RWEQ model[4,6]. This model is an empirical model developed by Fryrear et al.[41] on the basis of numerous experiments in the United States. It fully considers climatic conditions, vegetation status, surface soil roughness, soil erodibility, and soil crusting, and is used to quantitatively estimate regional soil wind-erosion amounts. Because changes in regional windbreak and sand-fixing functions are affected by many factors, such as land use, management measures, and meteorology and hydrology, most current research focuses on identifying the effects of climate change and human activities on windbreak and sand-fixing functions[4,47]. However, such work is concentrated on macro-scale analysis and can easily neglect the influence of plant functional-trait configuration at the micro scale. It is therefore necessary to reduce the research scale and combine sample-plot surveys to improve the accuracy of research results[18].

Second, factors in RWEQ such as soil erodibility, surface crusting, surface roughness, and vegetation cover change in large-scale remote-sensing image data.

Table 1 Common wind erosion prediction models and their applicable conditions

Tab. 1 Common wind erosion prediction models and their applicable conditions

Model name	Applicable situations	Advantages	Limitations
Wind Erosion Equation (WEQ) [40]	Can be applied to prediction of annual average soil loss at the cropland scale; suitable for long-term wind-erosion risk assessment and planning	An empirical model that is easy to apply through lookup tables and is widely used	Applicable only to specific regions (e.g., the central Great Plains of the United States); has a single spatial scale; inaccurate for forecasting extreme weather; some input data are difficult to obtain
Revised Wind Erosion Equation (RWEQ) [41]	Comprehensively considers key variables such as wind speed, precipitation, and vegetation, and has been widely applied in studies of northern arid regions of China	Incorporates the influence of process factors (e.g., climate-factor dynamics), can predict erosion at the daily scale, and input data are easy to obtain	Partly relies on empirical relationships; estimates of suspension loss are insufficient; some parameters require calibration (e.g., the soil crust factor) or field validation; performance is relatively poor on non-sandy soils or under high vegetation cover

Model name	Applicable situations	Advantages	Limitations
Wind Erosion Prediction System (WEPS) [42]	Suitable for multi-temporal and spatial-scale prediction ranging from field to regional and daily to sub-hourly scales; can calculate saltation + creep, suspension, and PM_{10} emissions	Modular process design (models for hydrology, soil, management, etc.); can output multiple components of loss (by direction and particle size)	High requirements for input data (e.g., weather generator); limited handling of hilly terrain; may underestimate small dust-storm events or spatial heterogeneity; high computational load during operation
Texas Erosion Analysis Model (TEAM) [43]	Applicable to different types of land (e.g., cropland or contaminated sites) and single-event wind-erosion prediction; can evaluate dust emissions and visibility	Integrates wind-erosion and water-erosion processes; can output horizontal flux and the vertical distribution of dust concentration	Insufficient treatment of dynamic changes in soil erodibility (e.g., freezing and thawing); limited validation on heterogeneous surfaces, restricting its application

Model name	Applicable situations	Advantages	Limitations
Wind Erosion Stochastic Simulator (WESS) [44]	Specifies erosion amounts at multiple point distances (DPS) within a field plot; applicable to prediction of single wind-erosion events; integrated into the EPIC policy assessment model	Comprehensively considers parameters such as soil texture, water content, and crop residue; can accurately predict moderate erosion events; is a mechanistic model based on physical processes	It is prone to systematically underestimate large erosion events while overestimating small erosion events; prediction fails near sheltered surfaces (DPS $<$ 60 m); requires manual calibration of the static wind-speed disturbance factor
Single-event Wind Erosion Evaluation Program (SWEEP) [45]	Can predict wind erosion under specified surface conditions for a single event (( )24 h) (e.g., disturbed sites or construction areas), and is suitable for real-time control-measure assessment	Based on the WEPS erosion submodel; user-friendly interface; can output detailed results for saltation, suspended particles, PM_{10}, etc.	Relies on user-specified surface parameters (e.g., moisture and roughness); may underestimate the influence of low-wind-speed events; and does not consider long-term climatic effects

Note: EPIC is the Environmental Policy Integrated Climate model.

The changes are not obvious, and the role of climate factors is easily overemphasized [17]. In addition, the parameters of the RWEQ model are derived from statistical values for cropland on the U.S. Great Plains and are highly regional. In the practical use of the model, problems are often encountered, such as conversion of soil-texture data, downscaling of wind speed, and setting the threshold friction velocity [48]. Moreover, the vegetation-cover factor does not reflect the weakening effect of withered vegetation on wind erosion, and it is mainly a mathematical expression of vegetation cover (for example, calculation based on a normalized vegetation index). It does not involve structural indicators of vegetation communities, such as plant height, form, or dominant species, which can easily lead to the misunderstanding that the windbreak and sand-fixing function of vegetation depends only on vegetation cover. For example, Zhu et al. [4] found that changes in the windbreak and sand-fixing function of desert grasslands in Inner Mongolia based on the RWEQ model were mainly affected by climatic factors rather than vegetation factors. The reason is that only four factors—land-use type, precipitation, wind speed, and vegetation cover—were considered. If the effects of factors such as vegetation canopy structure and soil properties are additionally considered, the evaluation results may differ. Therefore, studying and clarifying the intrinsic relationships between vegetation conditions and windbreak and sand-fixing functions, identifying the key factors by which desert-grassland vegetation influences windbreak and sand-fixing functions, and integrating them to form new vegetation factors for incorporation into soil wind-erosion models can have important application value in monitoring and evaluating the effectiveness of ecological-function governance and restoration in desert grasslands.

The windbreak and sand-fixing effects of vegetation are achieved mainly by increasing surface roughness and absorbing the downward momentum of surrounding airflow [49]. Compared with bare land, soil under vegetation cover increases soil strength through mechanical reinforcement by roots [5]. Therefore, there is a positive correlation between vegetation cover and the amount of sand fixation [50], and vegetation cover has long been used as a quantitative indicator for mitigating and reducing wind erosion [51–52]. However, under the same vegetation cover, differences in the canopy structure of different vegetation types have significant effects on the ability to control soil erosion [53]. Differences in surface roughness and soil physicochemical properties caused by different vegetation types also affect the magnitude of the windbreak and sand-fixing capacity [54]. For example, shrub and woodland vegetation with low-hanging branches can reduce near-surface wind speed and capture deposited material, but shrub and woodland vegetation that is sparsely distributed in tall patches may increase wind erosion because of the "leakage effect," making their sand-fixing capacity lower than that of grassland with high cover [4]. Wang et al. [55] found that, although increased vegetation cover in the Beijing–Tianjin sand-source control project area improved the overall windbreak and sand-fixing function, 13% of the area still did not show relatively high synergy. Therefore, simply increasing vegetation cover is already insufficient to further enhance the windbreak and sand-fixing function in arid and semi-arid regions [17,55–56]. How to scientifically configure vegetation community structure is therefore crucial for wind-erosion control in northern arid regions of China [57].

3 Research on the influence of plant functional traits on windbreak and sand-fixing functions

Appropriate vegetation conditions are a key element in realizing windbreak and sand-fixing functions. Plant functional traits refer to plant characteristics that are formed during long-term adaptation to the environment and coevolution, can respond to changes in the external environment, and have certain effects on ecosystem functions [16]. In recent years,

Moreover, plant functional traits have become an important tool for exploring responses of ecosystem services to changes in environmental management[^14,^58-^59]. For example, a plant' s specific leaf area reflects, to a certain extent, the capacity of leaves to capture light and controls the net primary productivity of an ecosystem; it is a key indicator for evaluating the level of community productivity and its structural composition, and is also related to hydrological regulation and temperature-regulation services[^60]. The aboveground parts of vegetation can intercept rainfall and weaken the kinetic energy of raindrop impact, while the belowground parts can improve soil shear strength and resistance to erosion through root penetration and soil reinforcement. Thus, multiple functional traits—such as canopy density, leaf traits and size, and root length density—affect soil-retention services[^61]. Plant functional traits have been widely applied in simulating the effects of climate change on ecosystem service functions and in ecological planning assessments[^62-^63]. For instance, the diversity of functional traits in grassland communities on the Loess Plateau can influence the rate of soil erosion, while specific functional traits can alleviate soil-water erosion[^64]. Plants can adapt to changes in external environmental conditions by altering functional traits such as height and leaf area. For example, differences in the vertical spatial distribution of plants lead to differences in the ability of plants with different growth forms to capture light resources. Studies of the functional traits of desert plants in the Ebinur Lake region have confirmed that plants of different life forms in arid areas exhibit different trade-off adaptation strategies in carbon-storage functions. Functional traits such as crown width, plant height, and leaf nitrogen and phosphorus content of desert plants have good indicative value for carbon-sequestration capacity[^65]; crown width, leaf length, number of leaves, and leaf area can contribute up to 72.93% of aboveground biomass[^66]. Pan Ying et al.[^67] found that grassland shrub height and edible species, together with all shrub heights, were respectively related to three ecosystem services: soil organic carbon, organic nitrogen, and water content. Because desert plants show convergent integrated adaptation in nutrient-absorption functions, significant positive correlations also occur among functional traits within plant communities, such as plant height, crown area, specific leaf area, and dry-matter content[^68]. An experiment in a typical Inner Mongolian grassland confirmed that plant functional traits such as plant height, leaf length, and leaf area had positive effects on aboveground community characteristics and ecosystem services under light grazing conditions[^69]. It can be seen that, by taking plant functional traits as the entry point, optimizing the allocation of attributes in vegetation-community structure is an effective pathway for improving the windbreak and sand-fixing capacity of grasslands.

Based on bibliometric methods, Pan Quan et al.[^14] and Zheng Hua et al.[^15] found that current research on the effects of plant functional traits on ecosystem services is mainly concentrated on four ecosystem-service indicators: forest and grass biomass, soil organic carbon content, soil fertility, and net primary productivity; by contrast, research on regulating services such as soil retention, Schematic diagram of the influence of plant functional traits on windproof and sand fixation function

Figure 1: Schematic diagram of the influence of plant functional traits on windproof and sand fixation function

biological control, and temperature regulation still needs to be strengthened. Windbreak and sand fixation is an important ecosystem-service function of the desert grassland belts of northern China. On the one hand, plant branches and leaves reduce airflow velocity through friction and increase surface roughness through withered branches and fallen leaves, thereby slowing near-surface wind speed; on the other hand, plant roots can penetrate deeply into the soil to fix sand particles and improve soil structure, thereby enhancing sand-fixing capacity (Fig. 1). At present, some studies have begun to focus on the influence of vegetation structural composition on windbreak and sand-fixing functions. For example, Roels et al.[^70] confirmed that plant biomass, its configuration pattern, and the structural characteristics of plant branches and leaves all influence windbreak and sand-fixing capacity. In a study of the structure of windbreak and sand-fixing forest systems in the Yulin wind-sand region of northern Shaanxi, Fu Yarui et al.[^71] found that the amount of sand fixation was closely related to afforestation density, the number of near-ground branches of trees, and herbaceous vegetation cover. In a comparative study of plant windbreak and sand-fixing functions in the Mu Us Desert, Chang Zhaofeng et al.[^72] found that *Caragana* had the best windbreak and sand-fixing effect, followed by *Hedysarum scoparium*; moreover, the vertical cross-sectional area of individual plants, the density of branches, stand density, and the height of aboveground parts above the ground were all affected. Zhang Lei et al.[^65] found that perennial herbaceous plants are more strongly adapted to arid, water-deficient desert ecosystems, whereas shrubs allocate more biomass belowground, resulting in more developed root systems; therefore, herb–shrub combinations have stronger windbreak and sand-fixing capacity. Although the above studies confirm that vegetation structural combinations have a relatively significant influence on windbreak and sand-fixing functions (Fig. 1), the interaction between plant functional traits and windbreak and sand-fixing functions still requires in-depth investigation[^16]. In particular, long-term positional monitoring of plant functional traits and windbreak and sand-fixing functions in arid regions, as well as studies of the feedback mechanisms between the two, remain weak, making it difficult to meet the urgent needs of major ecological-engineering construction and the advancement of sand-prevention and sand-control work in China.

Fig. 1 Schematic diagram of the influence of plant functional traits on windproof and sand fixation function

4 Research on Improvements in Techniques for Assessing Windbreak and Sand-Fixing Functions

Under the new situation of ecological construction, models for evaluating windbreak and sand-fixing functions need to be integrated and improved. Territorial spatial ecological restoration is an important task in China' s ecological-civilization construction, and it has shifted from a single pursuit of vegetation quantity targets toward the coordinated restoration of ecosystem structure, pattern, and function[^73]. However, how to integrate the functional traits of plants into studies of ecosystem functions remains a major challenge at present[^74]. Although the ecological and environmental benefits brought by a series of major ecological-engineering projects are obvious—for example, the Beijing–Tianjin sandstorm-source control project has significantly improved water-use efficiency[^75]—some studies have also argued that vegetation restoration in arid and semi-arid regions mainly depends on the positive effects of climate change, while the influence of ecological-engineering measures is limited[^76]. This is chiefly manifested in the fact that, in arid regions where water availability is severely constrained, large-scale tree planting cannot be supported; furthermore, artificial afforestation activities may damage surface vegetation, leading to increased soil evaporation and reduced soil water content, thereby limiting their windbreak and sand-fixing functions[^77]. Therefore, the construction of major ecological projects urgently needs to fully consider the laws of natural factors, differences in geographical zonality, and the impacts of climatic factors on ecosystems[^18]. Improvement of windbreak and sand-fixing functions in arid regions should, under the constraints imposed by local water-resource carrying capacity, be achieved through optimization of the spatial pattern of plant communities and adaptive improvement of windbreak and sand-fixing measures. Emphasis should be placed on exploring the potential for improving windbreak and sand-fixing functions from the perspective of plant-community trait allocation in project areas. Accordingly, it is necessary to propose dynamic monitoring tools for windbreak and sand-fixing functions that integrate plant functional traits.

Multi-scenario simulation based on remote sensing and climate models is the principal means of predicting future changes in ecosystem services, but it is necessary to clarify scientifically the driving mechanisms under the interaction of multiple factors[^10]. Although RWEQ can fairly well reflect the effects of multiple factors such as vegetation, climate, soil, and management measures, and has already been widely applied in fields such as ecological-asset accounting, assessment of ecological-environmental impacts, and evaluation of ecological-engineering effectiveness[^55], vegetation-cover factors calculated from normalized vegetation indices are difficult to use to truly represent vegetation structural characteristics[^30]. Therefore, in practical application it is necessary to overcome the locality and simplification of the model parameters in order to satisfy the needs of multi-scenario simulation and assessment of windbreak and sand-fixing functions (Table 2). To improve the accuracy of meteorological factors in soil wind-erosion estimation, Xian Guoli et al.[^80] used a two-parameter Weibull distribution function, daily mean wind speed, and daily maximum wind speed to improve the algorithm for the RWEQ wind factor. To address the insufficiency of the soil-moisture factor in temporal and spatial continuity, Meng Jian et al.[^17] selected four remote-sensing indicators of soil moisture and improved the soil-moisture factor algorithm in RWEQ. To reflect the enhancement of windbreak and sand-fixing functions brought about by optimization of vegetation structure, it is necessary to develop an improved algorithm for the vegetation factor in RWEQ. By introducing trait indicators such as leaf-area index, vegetation biomass, dominant species, and morphology, the differences and enhancement potential of windbreak and sand-fixing functions under different plant-community structural combinations can be simulated, thereby providing technical tools for vegetation-construction strategies in desert-grassland ecological-engineering areas.

Table 2 Correction of parameter factors in the revised wind erosion equation (RWEQ)

Tab. 2 Correction of parameter factors in the revised wind erosion equation (RWEQ)

Correction factor	Correction method	Application area
Soil moisture factor	MODIS evaporative ratio method, remote-sensing moisture index, visible–shortwave infrared drought index, SMAP soil-moisture ratio method, etc.	Northwestern Liaoning[^17]
Wind-force factor	Use of the exponential equation to partition and correct windward and leeward slopes	Zhangjiakou[^78]
Wind-force factor	Conversion methods for wind-speed data from different time periods	Agro-pastoral ecotone of northern China[^79]
Wind-force factor	Two-parameter Weibull distribution function, daily mean wind speed, and daily maximum wind speed to fit wind speed	Northern China[^80]

Correction factor	Correction method	Application area
Surface roughness	Use of NDVI and building contours to distinguish mat-surface correction under natural and urban landscapes	Zhangjiakou[^78]
Soil-texture factor	Use of a lognormal distribution model to improve soil-texture parameters	Inner Mongolia, Jilin, Shaanxi, etc.[^48]
Soil-texture factor	Use of fractal-model transformation of soil-texture data among standards for different soil particle-size grades	Agro-pastoral ecotone of northern China[^79]

Note: MODIS is the Moderate Resolution Imaging Spectroradiometer; SMAP is the Soil Moisture Active Passive microwave remote-sensing satellite; NDVI is the normalized difference vegetation index.

5 Conclusions and Prospects

The windbreak and sand-fixing function of desert grasslands is an important manifestation of the northern ecological-security barrier. However, under the dual constraints of limited water resources and restricted vegetation coverage, how to restore and maintain this windbreak and sand-fixing function through scientific allocation of vegetation structure has become an urgent issue requiring breakthroughs. This paper systematically summarizes research on the windbreak and sand-fixing functions of China' s desert grasslands and finds that current ecological-engineering-area construction emphasizes restoration of vegetation quantity, while insufficient attention is paid to improvement of ecosystem functions under optimization of vegetation-community structure. Although wind-erosion models such as RWEQ have already been widely used in monitoring and assessing windbreak and sand-fixing functions in desert grasslands, under the background of the continuous advancement of territorial spatial ecological construction, it is necessary to synthesize and integrate new vegetation factors so as to dynamically monitor the effectiveness of optimized vegetation communities in improving windbreak and sand-fixing functions. A large body of existing research has confirmed that trait characteristics such as vegetation canopy density, leaf shape and size, and root length density can influence regional windbreak and sand-fixing functions. Under the constraints of water-resource carrying capacity, the trait characteristics of plant communities in arid regions···

Optimization of configuration is an important direction for tapping and enhancing the potential of windbreak and sand-fixation functions. Developing monitoring and evaluation tools for windbreak and sand-fixation functions that integrate plant functional traits has become an important task in advancing the implementation of ecological engineering. To this end, it is recommended that, with major ecological-engineering regions such as the northern sand-control belt, the "Three-North" Project, wind-sand source control areas, and ecological security barriers as focal areas, the relationship between windbreak and sand-fixation functions and plant functional traits be used as the entry point. Satellite remote-sensing data and the RWEQ model should be used to reveal the spatiotemporal variation patterns of windbreak and sand-fixation functions, and to identify the effects of climatic factors as constraints for optimizing vegetation structure and improving models. Surveys of plant functional traits and observational experiments on soil wind erosion in typical sample plots should be conducted to clarify the mechanisms by which plant functional traits affect windbreak and sand-fixation functions, and to obtain key plant functional-trait parameters for windbreak and sand-fixation functions. Vegetation-factor parameters in the RWEQ model should be improved, and a soil wind-erosion assessment model based on the configuration of plant functional traits should be constructed. This would enable simulation of differences in, and enhancement potential for, the windbreak and sand-fixation functions of plant species and community combinations under climatic constraints, thereby providing new understanding, new approaches, and new methods for China' s sand-prevention and sand-control projects and large-scale ecological construction.

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Review of research on sand fixation function of desert grasslands in China under the context of ecological engineering

ZHANG Biao[1], ZHU Jiashun[2], HE Xiaohui[1], XU Jie[3], LIU Hongyu[1], SUN Hailian[1]

(1. School of Ecology and Environment, Baotou Teachers' College, Baotou 014030, Inner Mongolia, China;
2. Institute of Geographic Sciences and Natural Resources Research, CAS, Beijing 100101, China;
3. School of Ecology and Nature Conservation, Beijing Forestry University, Beijing 100083, China)

Abstract: Desert grasslands are an important part of China' s northern sand control belt and provide a vital sand-fixation function. As key ecological protection and restoration projects advance, it is vital to elucidate the intrinsic relationship between plant traits and sand fixation functions for implementing precise measures. This paper summarizes the achievements in vegetation restoration research and sand fixation functional assessment across China' s desert grasslands, as well as the requirements for restoring vegetation structure and ecological function within the study region. Focusing on sand fixation in desert grasslands, this paper compares the applicability of varied assessment methods and indicates their ineffectiveness in revealing the impacts of the vegetative community on sand fixation. Based on the mechanisms by which sand fixation functions affect plant traits, the paper proposes directions for functionally improving sand fixation assessment models applicable to areas under ecological restoration projects, thereby providing a reference for decision-making in such major ecological and sand control efforts across China' s desert grasslands.

Keywords: ecological restoration; sand fixation; functional traits; desert grassland