Postprint: Analysis of Potential Erosion-Resistant Plants in the Loess Hilly and Gully Region

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Abstract

Based on the collation and analysis of multi-year (2003-2014) vegetation survey data in the Yanhe River basin of the Loess Hilly and Gully Region, potential erosion-resistant plants in this area were screened according to the definition of erosion-resistant plants and the Braun-Blanquet phytosociological method, and the distribution characteristics and survival/reproduction abilities of different erosion-resistant plants were elucidated. The results showed that: 1) A total of 42 potential erosion-resistant plant species were screened out, belonging to 18 families and 33 genera, with the most species from Poaceae, Fabaceae, Asteraceae, and Rosaceae, accounting for 66% of the total species number. 2) Among the 42 plant species, 85% had life forms of phanerophytes, chamaephytes, and hemicryptophytes; 76% had growth forms of shrubs/small shrubs and perennial herbs; and 78% had water ecological types of xerophytic and mesophytic species. Combined with the climatic conditions of this basin and the distribution ranges of the 42 plant species, they could be divided into three types: eurytopic species, mesotopic species, and stenotopic species. 3) Fifty-five percent of the species had maximum coverage exceeding 50%, and could become constructive species or single dominant species in communities; other species with maximum coverage less than 50% mostly became co-dominant species in communities. These species had relatively high coverage and aboveground biomass, indicating that the plants could adapt to the erosional environment of this area and grow well. 4) Almost all of the 42 plant species had soil seed banks and seedling banks; 60% of the species had canopy seed banks; except for annual plants, other plants could all undergo vegetative reproduction, indicating that the potential erosion-resistant plants could all maintain their own survival and reproduction. 5) Among the 42 plant species, 13 were main-stem type plants, whose relatively large crown width could protect the soil at the base; 8 were loose-tussock type plants with strong abilities to protect soil mass and intercept sediment; and 6 aggregated-tussock type and 7 clustered-tussock type plants could effectively

intercept sediment. In summary, the potential erosion-resistant plants, which accounted for only 13% of the total recorded species number in the study area, possessed seed banks and seedling banks; perennial plants mainly relied on vegetative reproduction and could maintain their own survival and reproduction; due to the protection of the soil beneath the plant canopy and the interception of sediment by stems at the plant base, soil mounds could form at the plant base, which could effectively control soil erosion.

Full Text

Preamble

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Potential Erosion-Resistant Species Analysis in the Hill-Gully Region of the Loess Plateau

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Abstract

The Loess Plateau is well known for its severe soil erosion, which severely interferes with plant development and succession. However, plants do survive in regions with very serious soil erosion. These individuals can overcome stress and disturbance caused by soil erosion through various breeding strategies, as well as through morphological and physiological compensation. Therefore, a plant is considered erosion-resistant when it not only survives and adapts to the soil erosion environment, but can also protect and improve soil, prevent further erosion, regenerate itself, and maintain community stability and sustainable development. This study was based on vegetation survey data from the Yan River basin in the hill-gully region of the Loess Plateau collected over several years (2003–2014). The research objective was to select potential erosion-resistant species and subsequently illustrate their distribution characteristics and survival and propagation abilities. Using the definition of erosion-resistant species and Braun-Blanquet phytosociology methods, we selected potential erosion-resistant species. The main results were as follows: (1) A total of 42 potential erosion-resistant species were selected, belonging to 18 families and 33 genera. Gramineae, Leguminosae, Compositae, and Rosaceae accounted for 66% of the total potential erosion-resistant species. (2) Phanerophytes, chamaephytes, and hemicryptophytes were the main plant life forms, accounting for 85% of the total erosion-resistant species. Shrubs or small shrubs and perennial herbs were the main plant growth forms, accounting for 76% of the total erosion-resistant species. Xerophyte and mesophyte plants were the main water ecological types, accounting for 78% of the total erosion-resistant species. Furthermore, combined with the climatic conditions of the study area, the 42 potential erosion-resistant species could be divided into three types: eurytopic species, medium amplitude species, and stenotopic species. (3) Overall, 55% of the species were erosion-resistant, having a maximum cover over 50%, and could be the structural or single dominant species in a community. Maximum cover of the other species was less than 50%, and these species usually were the co-dominant species. All potential erosion-resistant species had high cover and aboveground biomass, indicating that these species could adapt to different erosion environments and grow adequately. (4) Almost all 42 potential erosion-resistant species had a soil seed bank and seedling emergence, and 60% of erosion-resistant species had a canopy seed bank. Except for annual plants, all species were able to reproduce asexually. This result indicated that the potential erosion-resistant species could maintain their own survival and reproduction. (5) From the 42 potential erosion-resistant species, 13 had a basal stem-shoot architecture, with a large crown that can protect the base soil. Furthermore, eight species have an expanding shoot architecture, which displays a strong ability to protect the soil and intercept sediments. In addition, six species have dense shoot architecture, and seven have a tussock-forming shoot architecture. Both types can effectively intercept sediments. In conclusion, the potential erosion-resistant species, which only occupied 13% of the total species recorded, had a seed and seedling bank. Furthermore, the perennial plants mainly employed vegetative reproduction, and could maintain their own survival and reproduction. Because plant crowns can protect the soil surface and plant base stems can intercept sediments, a mound can be formed in the plant base, which will effectively control soil erosion.

Keywords: erosion-resistant species; soil erosion; perennial herbs; runoff prevention; sediment interception

Introduction

The Loess Plateau is well known for its severe soil erosion. Soil erosion severely interferes with the process of plant development and succession. However, plants do survive in this region of very serious soil erosion. These individuals can overcome stress and disturbance due to soil erosion through various breeding strategies, as well as through morphological and physiological compensation. Therefore, a plant is considered erosion-resistant when it not only has survived and adapted to the soil erosion environment, but it can also protect and improve the soil, prevent further soil erosion, regenerate itself, and maintain the plant community' s stability and sustainable development.

Soil erosion's stress and interference on plants is an important limiting factor for vegetation development and restoration succession, affecting plants from seed formation through the entire growth process and thereby influencing vegetation restoration succession. Despite soil erosion limiting vegetation development and succession, plants still survive in severely eroded areas. These plants can adapt to and resist various stresses and disturbances caused by soil erosion through different survival strategies and can develop into erosion-resistant plant communities.

In studies related to soil erosion and vegetation restoration, the concept of "erosion-resistant species" has been proposed. In eroded sandy areas of northern Spain, *Carex rostrata* and *Salix phylicifolia* showed high survival rates (80%) and were considered erosion-resistant species in that region. In northern Spain, *Erucastrum nasturtiifolium*, *Lithodora fruticosa*, and *Santolina chamaecyparissus* appeared frequently in both highly eroded marl areas and lightly eroded clay areas. Plants can effectively control soil erosion depending on their own characteristics. Albala dejo et al. used plant species' germination and establishment capabilities, improvement of soil stability and fertility, and consideration of ecological conditions and landscape aesthetics to select suitable plant species. Quinton et al. created a list of potentially relevant species' ecological and bioengineering characteristics for Mediterranean abandoned land vegetation restoration to select species that could effectively control soil erosion. Some studies suggest that plants can effectively control soil erosion depending on their own plant configuration and mechanical characteristics. De Baets et al. established a methodological system for plant configuration and mechanical characteristics to screen erosion-resistant plants in typical semi-arid degraded areas of southeastern Spain.

Building on previous research, Zou Houyuan and Jiao Juying provided a definition of erosion-resistant plants: plants that can adapt to soil erosion environments, protect and improve soil, prevent soil erosion, have reproductive renewal capabilities, and can maintain community stability and sustainable development. They analyzed the change characteristics of different erosion-resistant plants during vegetation restoration in the Loess Plateau hill-gully region. However, this was only a qualitative description based on years of research experience. This study will take the vegetation restoration ecosystem under different erosion environments in the Yan River basin of the Loess Plateau hill-gully region as the research object to screen potential erosion-resistant plants in this area, analyze their distribution characteristics under different erosion environments, and clarify the survival, reproduction, and renewal capabilities of different erosion-resistant plants during vegetation restoration, as well as their ability to improve erosion environments. This will provide a theoretical basis for reasonable species selection and configuration in natural vegetation restoration and artificial vegetation reconstruction.

1. Study Area Description

This study selected the Yan River basin in the Loess Plateau hill-gully region (36°23 -37°17 N, 108°45 -110°28 E) as the research area. The basin is located in northern Shaanxi Province, covering an area of 7,687 km² with elevations ranging from 495 to 1,795 m. The basin has a warm temperate continental semi-arid monsoon climate, with average annual precipitation of about 500 mm and average annual temperature of 8.8–10.2°C. More than 50% of monthly rainfall occurs in July–September. The Yan River basin climate shows obvious gradient changes, with precipitation decreasing from southeast to northwest. Vegetation changes along the environmental gradient are also evident, with forest, forest-steppe, and steppe zones from south to north.

The southern part of the basin is the forest zone margin, with mainly loess soil. The main constructive species are *Quercus liaotungensis* and *Platycladus orientalis*. Shrubs include *Rosa xanthina*, *Ostryopsis davidiana*, and *Syringa pekinensis*. Herbs include *Carex lanceolata*. The central part is the forest-steppe zone, with mainly artificial *Caragana intermedia* and *Sophora viciifolia*. Trees are mainly *Robinia pseudoacacia* and *Populus simonii*, with natural recovery of *Rosa xanthina* and *Stipa bungeana* after enclosure. Herbs mainly include *Artemisia gmelinii*, *Lespedeza davurica*, *Artemisia giraldii*, and *Bothriochloa ischaemum*. The northern part is the steppe zone, with temperate arid steppe vegetation. The main species are *Artemisia scoparia* and *Thymus mongolicus*. Soils are mainly yellow-brown soil and yellow-cinnamon soil.

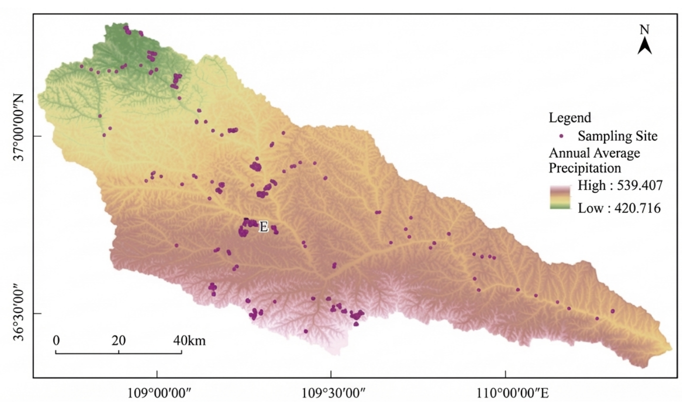

Figure 1: Figure 1

Location of Yan River basin and sampling plots

2. Methods

2.1 Plot Selection and Survey

This study collected and organized all vegetation survey data from the Yan River basin conducted by the research group from 2003 to 2014. Sample plot sizes were determined according to vegetation type: tree plots were 10 m × 10 m, shrub plots were 5 m × 5 m with at least 2 replicates, and herb plots were 2 m × 2 m with at least 5 replicates. Vegetation surveys recorded species abundance, coverage, and height, and aboveground biomass of herb and shrub layers was collected and measured.

2.2 Screening of Potential Erosion-Resistant Plants

Based on the definition of erosion-resistant plants, plants must have certain coverage under soil erosion conditions, indicating good growth and development status and dominant position in the community to maintain community stability and sustainable development. According to the Braun-Blanquet phytosociology method and Jin Zhenzhou' s approach, community dominant species were determined by community characteristic species and constant companion species. Species with fidelity degrees of 3–5 were considered community characteristic species. If companion species had presence greater than 60%, they were called constant companion species. Species with maximum coverage greater than 50% or presence greater than 60% were considered potential erosion-resistant plants, regardless of individual numbers. Species with maximum coverage of 5–50% or presence of 20–60% were considered companion species. Species presence was determined by the percentage of sample plots where each species occurred.

2.3 Growth Characteristics Investigation and Analysis

Growth characteristics of potential erosion-resistant plants, including plant coverage, were obtained from all sample plot vegetation surveys. Data on species seed banks, seedling banks, and vegetative propagule characteristics were obtained through literature review and plant flora consultation. The investigation and analysis of branch architecture were based on survey data from the Zhifanggou watershed, with specific experimental methods detailed in references [13, 18–20].

3. Results

3.1 Screening of Potential Erosion-Resistant Plants

Statistical analysis of vegetation survey data from 42 sample plots in the Yan River basin of the Loess Plateau hill-gully region recorded 320 species. This study screened 42 potential erosion-resistant plant species, accounting for 13% of the total species recorded. These belonged to 18 families and 33 genera. Gramineae, Leguminosae, Compositae, and Rosaceae accounted for 66% of the total potential erosion-resistant species. According to Li Dengwu' s statistics, about half of the species in the Loess Plateau hill-gully region are composed of Compositae and Gramineae. These families are widely distributed in the region and are the main plant components in the vegetation restoration succession process of abandoned farmland. Leguminosae is a large family in the Loess Plateau region, accounting for 41.9% of total species. The large families in the regional species pool account for a large proportion of species composition, leading to a high proportion of species from these families in the screened potential erosion-resistant plants.

3.2 Ecological Composition of Potential Erosion-Resistant Plants

Using Raunkiaer' s life form classification system, which categorizes plants based on the position and protection of renewal buds or reproductive organs during unfavorable periods, the 42 erosion-resistant plants were divided into phanerophytes, chamaephytes, hemicryptophytes, annual plants, and geophytes. Phanerophytes, chamaephytes, and hemicryptophytes accounted for 85% of total species, reflecting the zonal characteristics of vegetation distribution in the warm temperate semi-arid region. Annual herbs included *Setaria viridis*. Geophytes included *Heteropappus altaicus*. Shrubs were mostly phanerophytes or chamaephytes, accounting for 24% of total species. Perennial herbs were mostly hemicryptophytes, accounting for 61% of total species.

Based on Whittaker's growth form system, which classifies plants by shape category, the 42 erosion-resistant plants were divided into trees, shrubs, sub-shrubs, and perennial herbs. Trees and shrubs accounted for 24% of total species, sub-shrubs accounted for 12%, and perennial herbs accounted for 64%. Annual herbs accounted for 7% of total species. Trees included *Platycladus orientalis* and *Quercus wutaishanica*. Shrubs included *Rosa xanthina* and *Ostryopsis davidiana*. Sub-shrubs included *Artemisia giraldii*. Perennial herbs included *Stipa bungeana*.

Water condition is the dominant and limiting factor affecting plant growth in semi-arid regions. Based on descriptions in references [23–24], the water ecological types of the 42 erosion-resistant plants were classified as xeromorphic, xero-mesomorphic, meso-xeromorphic, and mesophytic plants. Xeromorphic and xero-mesomorphic plants accounted for 78% of total species. Xeromorphic plants were mostly herbs, sub-shrubs, and small shrubs, accounting for 45% of total species. Mesophytic plants were mostly trees and large shrubs, accounting for 17%. Due to zonal climate conditions determining vegetation types, the main vegetation types in this study area are sparse forest steppe and shrub steppe. From southeast to northwest, temperature and rainfall gradually decrease. The southeastern part is dominated by sparse forest steppe, while the northwestern part is dominated by shrub steppe. There are fewer tree species, and all surveyed trees came from forest areas. The climate' s natural selection determines that vegetation growth forms are mainly shrubs and herbs, with water ecological types dominated by mesophytic and xeromorphic plants, though mesophytic species also occupy a certain proportion.

[FIGURE:2] Growth form, life form, and ecological type composition of 42 potential erosion-resistant species

3.3 Distribution Characteristics of Potential Erosion-Resistant Plants

Combined with the climatic conditions of the Yan River basin, the 42 plants were divided into eurytopic species, medium amplitude species, and stenotopic species. Eurytopic species are widely distributed throughout the Yan River basin with annual rainfall of 420–540 mm, including *Lespedeza davurica*, *Artemisia scoparia*, *Heteropappus altaicus*, and *Stipa bungeana*. Medium amplitude species account for 45% of potential erosion-resistant plants. They are distributed in the central-southern region of the basin with annual rainfall of 470–540 mm, mainly including *Robinia pseudoacacia*, *Carex lanceolata*, and other mesophytic trees and shrubs. They are also distributed in the central-northern region with annual rainfall of 420–500 mm, mainly including xeromorphic grasses such as *Cleistogenes squarrosa* and *Cleistogenes chinensis*, as well as *Ostryopsis davidiana* on shady slopes. Stenotopic species are distributed in the southern region with annual rainfall >500 mm, including *Platycladus orientalis* on sunny slopes and *Quercus wutaishanica* on shady slopes, as well as *Spiraea pubescens*. They are also distributed in the northern region with annual rainfall <450 mm, mainly including *Wikstroemia chamaedaphne* and *Thymus mongolicus* on sunny slopes, and *Artemisia frigida* on shady slopes.

Plant spatial distribution is a concentrated expression of plant response to different erosion environments. In this study area, topography and geomorphology affect water-heat distribution and historical human activity processes, thus determining zonal species distribution at a large scale. Different ecological species distributions determine community restoration succession stages and affect the probability of species migrating to restoration sites, thereby influencing aboveground vegetation composition. The distance between remnant patch seed sources and restoration sites, as well as species dispersal ability and lifespan, affect the speed at which these species disperse to abandoned farmland restoration sites and form populations or communities. In different habitats, annual weeds such as *Artemisia scoparia* in the early succession stage, perennial herbs such as *Lespedeza davurica* and *Heteropappus altaicus*, and sub-shrubs such as *Artemisia gmelinii* and *Artemisia giraldii* are distributed throughout the region, gradually appearing with succession time and basically unaffected by terrain conditions. As succession proceeds, vegetation types gradually differentiate by habitat, such as *Platycladus orientalis* on sunny slopes and *Quercus wutaishanica* on shady slopes, which are mostly distributed on locally steep gully slopes. Historical data also show that before vegetation destruction by human activities, these species could form widely distributed and well-growing communities. *Thymus mongolicus* and *Artemisia frigida* are characteristic plants of desert steppe. Their appearance is the result of local microclimate and substrate aridification caused by intense water erosion, wind erosion, and overgrazing after the destruction of sparse forest steppe and shrub steppe vegetation. They are xeromorphic creeping sub-shrubs of steppe that generally do not enter forest areas.

Spatial distribution characteristics of potential erosion-resistant species

3.4 Survival, Reproduction, and Renewal Capacity of Potential Erosion-Resistant Plants

Statistical analysis of coverage of 42 potential erosion-resistant plants found that average species coverage ranged from 25% to 58%, with maximum coverage exceeding 50% for 55% of species, existing as community constructive or single dominant species. Some species such as *Clematis fruticosa*, *Lespedeza floribunda*, *Lespedeza juncea*, and *Heteropappus altaicus* had maximum coverage less than 50%, coexisting with other species as community co-dominants. When these species had high coverage in communities, their density and aboveground biomass were also high. High coverage and aboveground biomass indicate that plants can adapt to their environment and grow well, suggesting these plants adapt to the erosion environment of the study area, with good growth and strong survival capacity.

Plants maintain their survival through sexual reproduction and vegetative propagation. Most plants can renew through soil seed banks, which allow seeds to avoid various threats. Based on soil seed bank identification results from the Zhifanggou watershed and literature review, except for *Wikstroemia chamaedaphne*, all 42 plants had soil seed banks, with 26 species having persistent soil seed banks and 16 having transient soil seed banks. Most erosion-resistant plant seeds can rapidly germinate under suitable conditions. Some plants can store seeds in the canopy to delay shedding, forming canopy seed banks. Delayed seed dispersal allows propagules to avoid threats from predation and unpredictable disturbances, can supplement soil seed banks, and facilitates long-distance wind dispersal and spring germination, providing continuous supply for soil seed banks. Through field observation and literature review, canopy-retained seeds mostly shed in spring. A total of 25 potential erosion-resistant plant species have the potential to form canopy seed banks, including the tree *Platycladus orientalis*, shrubs *Rosa xanthina* and *Spiraea pubescens*, small shrubs *Syringa oblate* and *Clematis fruticosa*, sub-shrubs *Artemisia giraldii*, and herbs *Stipa grandis* and *Potentilla tanaecetifolia*.

Seedling survival is a critical stage in the transition from seed to plant and is the most sensitive period to environmental conditions. Through seedling surveys in the Zhifanggou watershed and literature review, except for *Wikstroemia chamaedaphne*, seedlings were observed for all 41 other species, indicating these species can achieve natural vegetation renewal through seed bank germination and seedling establishment.

Vegetative propagation is widespread in natural ecosystems, especially in highly competitive and stressful habitats, where it plays an important role. Through field surveys and flora consultation, except for annual plants, all other 38 potential erosion-resistant plants can reproduce vegetatively. There were 13 species with root sucker types, 8 with rhizome types, and 9 with stolon types. The 8 Gramineae species are tillering types. In harsh environments, clonal plant offspring are supported by the mother plant, making it easier to safely pass the juvenile period and facilitating rapid population diffusion and spread to achieve successful establishment. These vegetative propagation species are more adaptive than sexual reproduction in harsh environments and help improve individual survival and competitiveness.

3.5 Capacity of Potential Erosion-Resistant Plants to Improve Erosion Environments

Because plant crowns protect the underlying soil and plant base stems intercept sediments, mounds can form at plant bases. This microtopography can intercept and concentrate nutrients and moisture lost to erosion, and plant roots absorb nutrient elements from the soil around the plant base, improving the soil erosion environment. Plant branch architecture plays a mediating role in plant mound formation. Mounds are mainly formed by asymmetric splash erosion inside and outside plant crowns, with stronger splash erosion outside the crown than under the crown. Under extremely steep and dangerous slope conditions, mound formation is mainly due to surface runoff erosion outside the plant crown causing surface decline, while soil under the plant crown is protected. Meanwhile, sediment and litter from the upper slope accumulate at the plant base due to stem interception, forming a micro-mound. On gentle and steep slopes, plant crown size and base branch quantity play important roles in plant mound formation.

Based on plant crown and base morphology, potential erosion-resistant plants can be divided into four branch architecture types: (1) Main stem type: single-axis branched perennial deciduous trees and shrubs, usually with one or two main stems at the base, branching at mid-height, with large crowns protecting base soil but weak rainwater interception capacity, so mound area rapidly decreases with slope increase, such as *Robinia pseudoacacia* and *Platycladus orientalis*. (2) Expanding type: sympodially branched perennial deciduous shrubs forming new shoots and dense branches expanding outward at the base, with many closely arranged branches that effectively intercept sediments in different erosion environments, such as *Spiraea pubescens* and *Caragana korshinskii*. (3) Dense type: perennial deciduous herbs or small shrubs with small crowns but high branch density, such as *Carex lanceolata*. (4) Tussock type: perennial grasses with well-developed underground rhizomes that can produce buds and expand laterally to occupy relatively large areas, usually forming ring-shaped grass clumps in the study area, such as *Bothriochloa ischaemum*, *Cleistogenes chinensis*, and *Stipa bungeana*.

Sparse clump-type plants such as *Heteropappus altaicus* and *Cleistogenes hancei* have many well-developed branches that can extend to larger areas and effectively intercept sediment sources such as sand from upper slopes and litter, thus having strong capacity to protect soil bodies and intercept sediments. Tussock-type plants such as *Lespedeza davurica*, *Lespedeza juncea*, and *Artemisia giraldii* have well-developed underground rhizomes. The amount of sediment sources increases with slope gradient, and their formed mound area increases continuously with slope gradient. In erosive environments, the 42 potential erosion-resistant plants can not only adapt to soil erosion environments by maintaining certain coverage and biomass, but also prevent soil erosion through soil seed banks, canopy seed banks, and unique branch architectures, and survive and reproduce through seedling establishment and vegetative propagation.

Growth characteristics of potential erosion-resistant species

4. Conclusion

This study screened a total of 42 potential erosion-resistant plants belonging to 18 families and 33 genera. Large families with worldwide distribution and containing over a thousand species dominate in the study area. The climate's natural selection determines that regional plant growth forms are dominated by shrubs and herbs, life forms are dominated by phanerophytes, chamaephytes, and hemicryptophytes, and water ecological types are dominated by mesophytic and xeromorphic plants. Gramineae, Leguminosae, Compositae, and Rosaceae are the main plant components in the vegetation restoration succession process of abandoned farmland. Shrubs are mostly phanerophytes or chamaephytes, while perennial herbs are mostly hemicryptophytes. Although the 42 potential erosion-resistant plants only account for 13% of the total recorded species, these plants combine to become the dominant species of main community types in the region. These species have soil seed banks and seedling banks, and most species' soil seed banks can be supplemented by canopy seed banks. Perennial plants mainly employ vegetative reproduction and can maintain their own survival and reproduction. Because plant crowns protect the underlying soil and plant base stems intercept sediments, mounds can form at plant bases, improving the soil erosion environment and effectively controlling soil erosion. Future research should further reveal how plants adapt to and resist soil erosion through their own physiological and root architecture characteristics, in order to utilize vegetation measures to control soil erosion.

References

[1] Fu BJ, Liu Y, Lü YH, He CS, Zeng Y, Wu BF. Assessing the soil erosion control service of ecosystems change in the Loess Plateau of China. Ecological Complexity, 2011, 8(4): 284–293.
[2] Guerrero-Campo J, Montserrat-Martí G. Comparison of floristic changes on vegetation affected by different levels of soil erosion in Miocene clays and Eocene marls from Northeast Spain. Plant Ecology, 2004, 173(1): 83–93.
[3] Bochet E, García-Fayos P, Poesen J. Topographic thresholds for plant colonization on semi-arid eroded slopes. Earth Surface Processes and Landforms, 2009, 34(13): 1758–1771.
[4] Wang N, Jiao JY, Lei D, Chen Y, Wang DL. Effect of rainfall erosion: seedling damage and establishment problems. Land Degradation & Development, 2014, 25(6): 565–572.
[5] Guerrero-Campo J, Montserrat-Martí G. Effects of soil erosion on the floristic composition of plant communities on marl in northeast Spain. Journal of Vegetation Science, 2000, 11(3): 329–336.
[6] Zou HY, Jiao JY. Preliminary study on erosion-resistant plants in the Loess Plateau hill-gully region. Science of Soil and Water Conservation, 2010, 8(1): 22–27.

[7] Hellsten S, Riihimäki J, Alasaarela E, Keränen R. Experimental revegetation of the regulated lake Ontojärvi in northern Finland. Hydrobiologia, 1996, 340(1/3): 339-343.
[8] Albaladejo J, Castillo V, Roldan A. Rehabilitation of degraded soils by water erosion in semiarid environments // Rubio JL, Calvo A, eds. Soil Degradation and Desertification in Mediterranean Environments. Logroño: Geoforma Ediciones, 1996: 265-278.
[9] Quinton JN, Morgan RPC, Archer NAL, Hall GM, Green A. Bioengineering principles and desertification mitigation // Geeson NA, Brandt CJ, Thornes JB, eds. Mediterranean Desertification: A Mosaic of Processes and Responses. Chichester: John Wiley and Sons, 2002: 93-105.
[10] Bochet E, Poesen J, Rubio JL. Runoff and soil loss under individual plants of a semi-arid Mediterranean shrubland: influence of plant morphology and rainfall intensity. Earth Surface Processes and Landforms, 2006, 31(5): 536-549.
[11] De Baets S, Poesen J, Reubens B, Muys B, De Baerdemaeker J, Meersmans J. Methodological framework to select plant species for controlling rill and gully erosion: application to a Mediterranean ecosystem. Earth Surface Processes and Landforms, 2009, 34(10): 1374-1392.
[12] Jiao JY, Wang DL. Change processes of different erosion-resistant plants in ecological restoration lands of Loess Plateau hill region. Bulletin of Soil and Water Conservation, 2009, 29(4): 235-240.
[13] Kou M. Study on seed source limiting factors of natural vegetation restoration in Loess Plateau hill-gully region [D]. University of Chinese Academy of Sciences, 2013.
[14] Yin QL. Prediction and mapping of potential vegetation distribution in Yan River basin of Loess Plateau region [D]. Northwest A&F University, 2013.
[15] Jiao JY, Wang N, Lei D. Community ecological characteristics of plants improving soil erosion environment in Loess Plateau hill-gully region. Chinese Journal of Applied Ecology, 2008, 19(9): 1897-1904.
[16] Song YC. Vegetation Ecology. Shanghai: East China Normal University Press, 2001.
[17] Jin ZZ. Phytosociology Theory and Methods. Beijing: Science Press, 2009.
[18] Kou M, Jiao JY, Yin QL. Adaptation of dominant plants to different erosion environments in Loess Plateau hill-gully region: from tissue to physiology [D]. University of Chinese Academy of Sciences, 2013.
[19] Begon M, Harper JL, Townsend CR. Ecology: Individuals, Populations and Communities. Oxford: Blackwell Scientific Publications, 1986: 122-156.
[20] Wang N. Plant reproductive strategies in Horqin Sandy Land. Beijing: Meteorological Press, 2010.
[21] Li DW. Floristic geographical study of wild plants on Loess Plateau in northern Shaanxi. Yangling: Northwest A&F University Press, 2009.
[22] Chinese Vegetation Editorial Committee. Chinese Vegetation. Beijing: Science Press, 1980.
[23] Zhang Q. Water ecological types and life form spectrum characteristics of understory vegetation in *Robinia pseudoacacia* forests. Science of Soil and

Water Conservation, 2008, 6(2): 95-99.
[24] Zou HY. Discussion on ecological basis for vegetation restoration on Loess Plateau. Journal of Soil and Water Conservation, 1995, 9(4): 1-4.
[25] Zhang Q. Plant community types in forest-steppe zone of northern Shaanxi. Acta Phytoecologica et Geobotanica Sinica, 1982, (2): 1-8.
[26] Wang N, Jiao JY, Lei D. Composition structure and numerical classification of natural recovery vegetation on abandoned land in Loess Plateau hill-gully region. Acta Ecologica Sinica, 2008, 28(7): 2981-2997.
[27] Zou HY. Range of forest-steppe zone on Loess Plateau in northern Shaanxi. Acta Phytoecologica et Geobotanica Sinica, 1983, 7(2): 122-131.
[28] Shi YF. Vegetation and its changes on Loess Plateau in historical periods. Geography, 1994, (2): 9-12.
[29] Zou HY. Preliminary study on vegetation restoration succession in forest-steppe zone of Loess Plateau in northern Shaanxi. Journal of Shanxi University (Natural Science Edition), 1993, 16(1): 94-100.
[30] Wang N, Jiao JY, Lei D. Aboveground biomass of vegetation and its influencing factors in wind-water erosion crisscross region of Loess Plateau. Chinese Journal of Applied Ecology, 2011, 22(3): 556-564.
[31] Rotundo JL, Aguiar MR. Vertical seed distribution in the soil constrains regeneration of *Bromus pictus* in a Patagonian steppe. Journal of Vegetation Science, 2004, 15(4): 515-522.
[32] Yang Y. Soil seed bank and natural regeneration of fragmented evergreen broad-leaved forest [D]. Zhejiang Normal University, 2008.
[33] Wang N, Jiao JY, Lei D. Characteristics of soil seed banks during natural vegetation restoration in Loess Plateau hill-gully region. Agricultural Research in the Arid Areas, 2009, 27(6): 215-222.
[34] Van Oudtshoorn KVR, Van Rooyen MW. Dispersal Biology of Desert Plants. Berlin Heidelberg: Springer, 1999.
[35] Wang N. Plant seed life history strategies and seed sowing restoration research in Loess Plateau hill-gully region [D]. Northwest A&F University, 2014.
[36] Harper JL. Population Biology of Plants. New York, USA: Academic Press, 1977.
[37] Wang N, Jiao JY, Lei D. Characteristics of seedling banks and seedling survival under different erosion environments in Loess Plateau hill-gully region. Acta Botanica Boreali-Occidentalia Sinica, 2009, 29(7): 1387-1393.
[38] Price EAC, Marshall C. Clonal plants and environmental heterogeneity—An introduction to the proceedings. Plant Ecology, 1999, 141(1/2): 3-7.
[39] Buis E, Temme AJAM, Veldkamp A, Boeken B, Jongmans AG, Van Breemen N, Schoorl JM. Shrub mound formation and stability on semi-arid slopes in the Northern Negev Desert of Israel: A field and simulation study. Geoderma, 2010, 156(3): 363-371.
[40] El-Bana MI, Nijs I, Khedr A-HA. The Importance of Phytogenic Mounds (Nebkhas) for Restoration of Arid Degraded Rangelands in Northern Sinai. Restoration Ecology, 2003, 11(3): 317-324.
[41] Bochet E, Rubio JL, Poesen J. Relative efficiency of three representative

matorral species in reducing water erosion at the microscale in a semi-arid climate (Valencia, Spain). Geomorphology, 1998, 23(2/4): 139-150.
[42] Du HD, Jiao JY, Jia YF, Wang N, Wang DL. Phytogenic mounds of four typical shoot architecture species at different slope gradients on the Loess Plateau of China. Geomorphology, 2013, 193: 57-64.