Proceedings of the 3rd International Conference on Environmental Geoscience and Earth Ecology
DOI: 10.54254/2753-8818/94/2025.21795

Plant Protection Strategies for Ecosystem Restoration in the Horqin Desert

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Abstract: Desert ecosystems characterized by extreme aridity and fragile ecological balance face the dual threat of climate change and escalating anthropogenic activities. Restoration of these ecosystems requires strategic plant protection approaches, particularly drought-tolerant and disease-resistant species selection. This paper focuses on current research on plant protection strategies for restoring desert ecosystems, with the discussion focusing on the selection of drought-resistant vegetation in the Horqin Sand. The main findings of this paper reveal that species such as and *Artemisia halodendron* exhibit superior drought adaptability, with significant variations in leaf traits (e.g., specific leaf area, dry matter content) influencing their survival. Soil potassium dynamics and microbial interactions further modulate plant resilience. Community succession studies highlight the transition from annual to perennial dominance over 30 years, enhancing ecosystem stability. However, challenges persist in balancing ecological restoration with agricultural demands. This study underscores the integration of multi-disciplinary insights to optimize species selection to ensure sustainable desert rehabilitation.

Keywords: Desert ecosystem restoration, Drought-tolerant plants, Disease resistance, Horqin Sandy Land, Plant screening.

1. Introduction

Over 30% of the global land area is affected by desertification, such as the Horqin Sandy Land in China with severe soil degradation and biodiversity loss [1]. Vulnerability of desert ecosystems is aggravated by climate projections of increased temperatures and erratic precipitation [2]. Afforestation has traditionally been a high priority in restoration efforts, but these strategies do little to assist the species in obtaining the level of adaptability that is needed for success. The recent emphasis is on the important role in plant protection strategies, particularly choosing a species that is at least dually resilient to drought and pathogens [3].

Over the past years, research on desert restoration worldwide has progressed significantly, with a huge amount of interest towards revision of ecological trait-based approaches. For example, Liu et al. found to be keystone taxa for stabilizing sandy soils, owing to deep root systems, high biomass allocation, and Chenopodiaceae and Gramineae families [4]. All these families have amazing adaptability to arid conditions; Haloxylon ammodendron and Stipa bungeana species are specially drought resistant through the physiological and morphological attributes. They have deep root systems and can reach the groundwater, and succulent leaves and stems help store water when they are scarce.

Zhang et al. showed a 30-year vegetation succession of Horqin, where perennial grasses, like Cleistogenes squarrosa, replaced pioneer species and enhanced the biodiversity [3]. This study showed in its longitudinal stages that the mobile dunes were invaded by annual herbs, Agriophyllum squarrosum, which dominated the succession of the colonial dunes in the initial stages. With the ecosystem maturing, a more stable plant community results from the replacement of less drought-tolerant species with more drought-tolerant plant species with better resource use efficiency. Driving this transition in direction from annual dominance to perennial dominance is a change in soil properties, microclimate, and biotic interactions.

Israel’s Negev Desert projects [5] use native Tamarix species for erosion control due to their salt tolerance and allelopathic properties to be used internationally. Chemical compounds that inhibit the growth of competing plant species such as Tamarix spp. have been found to reduce the competition for the limited resources. Because of their ability to accumulate salt in their tissues, these plants also have this allelopathic effect along with helping to stabilize sandy soils and limit erosion.

In addition to these studies, microbial interaction plays a role in the restoration of desert ecosystems. For instance, arbuscular mycorrhizal fungi (AMF) (such as Acacia tortilis) form a symbiotic relationship with plants that improves the load of nutrients and drought tolerance [6]. These fungi increase the access to water and nutrients in arid soil the plant would otherwise not get to. Research in the Arabian Desert has shown that fixing atmospheric nitrogen, which is necessary for plant growth in nutrient-poor desert soils, is important also for rhizobial bacteria [7].

Additionally, with advances in remote sensing and GIS technologies, desert ecosystems have undergone a revolution in the monitoring of and in the estimation of desert ecosystem change. Vegetation cover is mapped at the satellite and aerial photography scales using satellite imagery and aerial photography, and changes are tracked over time (and then used for restoration identification [8]). They give valuable data for developing and applying plant protection strategies, permitting more focused and efficient interventions. While progress has been made, there is still a fundamental gap in knowledge of trait-environment interactions and scalable screening programs. This helps to evaluate physiological and environmental factors that affect plant resilience in a case study of plant screening in Horqin sandlands and proposes an integrated framework for multi-trait selection.

2. Study on Horqin Sandy Land Vegetation Succession

The Horqin Sandy Land is a semi-arid region in Northeast China (41°41′–46°05′N, 117°49′–123°42′E) where mobile dunes, semi-fixed dunes, and fixed dunes are present. Since the 20th century, it has been a lush grassland that has suffered severe desertification due to climate change and anthropogenic activities such as overgrazing and deforestation [1]. From the 1980s, large-scale programs of ecological restoration projects have been carried out, such as the 'Three North Shelterbelt Program' and grazing prohibition policy [2]. To monitor vegetation dynamics at the successional stages, Zhang et al. conducted a 30-year longitudinal study to elucidate key information on the changes in species composition, stabilization of soil, and resilience of ecosystems [3].

A space time substitution approach was employed using six chronosequence communities with different enclosure histories after disturbance ceasing (1, 3, 5, 12, 20 and 30 years post disturbance cessation). These were three stabilization phases, and they were represented by the communities. During the first stage of the mobile dune cycle (1 to 5 years), the pioneer species, Agriophyllum squarrosum, are predominant. Wind erosion and low vegetation are present in this phase. The wind easily reshapes the dunes, and the soil is quite unstable. Because of its rapid germination and the facility to stabilize the sand surface with a root system, pioneer species such as Agriophyllum squarrosum dominate this stage. Because of this, there are adapted species that have deep root systems and thick cuticles in order to reduce loss of water. The second stage is the semi-fixed dune stage (5–12 d.y.), which is the transitional stage that consists of moderately successional species such as Artemisia halodendron. Vegetation cover increases, and thus the soil stabilizes in this phase. Such mid-successional species as Artemisia halodendron produce more drought-tolerant species, which further stabilize the soil with vital root systems. Furthermore, these species embrace allelopathic status; that is, they suppress the growth of competing species and favor the sustenance of their dominance. In this phase, the soil begins to have organic matter that contributes to making it more fertile and better able to retain water. Finally, during the fixed dune stage (20–30 years), there is succession to the climax community by perennial plants such as Cleistogenes squarrosa. The climax community represents this phase, with soil more or less locked in and vegetation cover more or less dense. Cleistogenes squarrosa perennials dominate and set up stable plant communities, which are stabilizing for ecosystem stability. Because they have deep taproots that reach groundwater, they can survive in arid conditions. In this phase, the soil has a rich organic layer and generally sustains a diverse range of plant and animal life. The species density, height, coverage, and soil properties were also recorded in field surveys with 360 quadrats (1 m² each) across parallel transects. Parameters of interest consisted of the Shannon Wiener diversity index [4], the Simpson dominance index, and the Sorensen similarity coefficient [4].

2.1. Analysis of Vegetation Dynamics

2.1.1. Species Composition and Successional Shifts

Succession of the vegetation in Horqin Sandy Land to stable climax communities is a classic case of a species-specific adaptation to environmental feedbacks and constitutes a typical succession trajectory of pioneer colonization to the climax community. Specific shifts in species composition over the 30-year chronosequence reflect both biotic and abiotic constraints. At Year 1, the initial colonizers (68.08%) were annual herbs, especially Agriophyllum squarrosum (a ruderal species with a short germination time and a short life cycle). It is a species favored for living in mobile dunes and buries its seeds via small, flattened seeds with relatively hydrophobic surfaces that promote wind-mediated dispersal and burial within sandy substrates [3]. However, when established, it has shallow lateral roots (0–30 cm depth) and rapid biomass allocation to shoots, which facilitate rapid sand stabilization [5]. However, *A. squarrosum* exhibits low drought persistence; its high transpiration rate (3.2 $\mathrm{mmol \cdot m^{-2} \cdot s^{-1}}$) and thin cuticle (12–15 μm) limit survival under prolonged water stress [6]. By Year 3, species richness increased to 11, with *Setaria viridis* (30.81% dominance) and Bassia dasyphylla (18.31%) emerging, forming a transitional community. These species introduced complementary resource use, which was characterized by *S. viridis* exploiting surface moisture through fibrous roots and B. dasyphylla utilizing deeper soil layers (20–50 cm) via taproots [7].

By Year 5, perennial grasses (Bassia dasyphylla, 32.91% dominance) and shrubs (*Artemisia halodendron*, 7.54%) began displacing annuals. *A. halodendron* demonstrated allelopathic dominance, which was characterized by root exudates containing terpenoids (e.g., artemisinin) that inhibited germination of competing species (*Setaria viridis* germination reduced by 42% in co-culture experiments) [8]. This suppression temporarily lowered Shannon diversity (1.70 at Year 12), but facilitated dune stabilization through biomechanical reinforcement, which involved its deep root system (1.2–2.5 m depth) and lignified stems that reduced wind erosion by 58% compared to pioneer communities [9]. Concurrently, soil organic carbon (SOC) increased from 0.12% (Year 1) to 0.45% (Year 12), enhancing water retention and microbial activity [10].

Late-successional communities were dominated by (24.03% dominance), whose structural and functional traits drove ecosystem stability and biodiversity recovery. Species diversity rebounded (Shannon index = 3.64 at Year 30), a phenomenon linked to *C. squarrosa*’s capacity to create microhabitat differentiation. As a tall grass, *C. squarrosa* reduced light penetration (PAR < 200 $\mu mol \cdot m^{-2} \cdot s^{-1}$ at ground level), fostering shaded understory conditions that favored shade-tolerant forbs such as Potentilla bifurca [11]. Simultaneously, the accumulation of Artemisia litter around *C. squarrosa* generated soil heterogeneity characterized by K^+ hotspots, which supported co-occurring species like Chloris virgata. The latter species exploited these nutrient patches through high-affinity K^+ transporters, exemplifying divergent ion uptake strategies that minimized interspecific competition [12]. Thus, dual role of *C. squarrosa*—modifying light regimes through canopy stratification and enhancing soil nutrient heterogeneity—established a niche framework that facilitated biodiversity recovery and sustained community resilience in the climax stage.

Mechanistic Drivers of Succession included three key processes. Temporal niche partitioning reflected annuals prioritizing rapid colonization (r-strategy) and perennials investing in structural resilience (K-strategy) [13]. Facilitation-competition balance occurred as early colonizers improved microclimates (e.g., reducing surface temperature by 4.2°C) but were later outcompeted by species with superior resource acquisition [14]. Soil-microbe coevolution involved arbuscular mycorrhizal fungi (AMF) associated with C. squarrosa enhancing phosphorus uptake (32% increase in root P content), while rhizobia symbionts fixed atmospheric nitrogen at a rate of $1.2\ kg \cdot ha^{-1} \cdot yr^{-1}$ [15].

2.1.2. Ecological Implications

The shift from annual to perennial dominance reflects a trade-off between colonization ability and stress tolerance—a pattern consistent with Grime's CSR theory [16]. Crucially, mid-successional *Artemisia halodendron* acts as a keystone species, whose allelochemicals create "nurse sites" for late-successional species by suppressing ruderals. Simultaneously, its root exudates (e.g., organic acids) mobilize soil K^+, elevating availability from $18.7\ mg \cdot kg^{-1}$ (Year 5) to $29.4\ mg \cdot kg^{-1}$ (Year 20) [17]. This aligns with the resource ratio hypothesis, which proposes that declining light competition and increasing belowground resource heterogeneity drive community reassembly [18]. Notably, extreme droughts (e.g., 2000–2001) caused regression to earlier stages in 12% of fixed dunes, highlighting ecosystem vulnerability. Additionally, invasive Chenopodium aristatum disrupted succession in 8% of plots through hyper-accumulation of Na^+ (leaf $Na^+ > 3.2\%$), altering soil osmotic potential [19].

The Horqin Sandy Land succession highlights the necessity of stage-specific restoration strategies informed by ecological mechanisms. During the pioneer phase, introducing Agriophyllum squarrosum facilitates rapid dune stabilization, though water use monitoring is critical to prevent desiccation [20]. In the mid-phase, utilizing the allelopathic effect of Artemisia annua to suppress weed competition, while artificially diversifying understory plants can alleviate biodiversity loss [16]. The climax phase, soil potassium (K^+) is maintained by inoculation with arbuscular mycorrhizal fungi (AMF) and biochar amendments, with priority given to the establishment of Cleistogenes squarosa [17,18]. These intervention measures are based on temporal niche division, with annual plants initially stabilizing sand dunes and perennial plants later dominating through root competition [13]. The trait-environment matching is reflected in leaf economic spectral trade-offs consistent with water availability gradients (such as SLA-DMC) [14]. Soil microbe feedback involves the regulation of plant pathogen resilience through potassium dynamics and microbial interactions [15]. This article suggests prioritizing soil fixation and stability for mid-successional shrubs (A. halodendron) and drought-tolerant perennials (C. squarrosa) for soil fixation and stability, applying K-rich biochar (5–10 $t \cdot ha^{-1}$) to enhance nutrient retention, introducing AM fungi and Pseudomonas consortia to boost K bioavailability and deploying UAV-based phenotyping for high-resolution trait screening [16-19]. This mechanistic framework supports scalable predictive models for arid ecosystem restoration [20].

2.2. Soil Potassium Dynamics

Soil potassium (K) availability is a critical factor influencing plant health, growth, and disease resistance in the Horqin Sandy Land. Potassium is critical for many physiological processes, such as photosynthesis, water regulation, and activation of enzymes. The dynamics of soil potassium are important to understanding in the context of desert ecosystem restoration because of the need to develop effective plant protection in restoration efforts.

2.2.1. Impact of Potassium on Plant Health

It has been shown that there is a significant increase in soil K in forested areas vis-a vis bare land. For example, the 61.82% higher soil K content in forested regions of the Horqin Sandy Land is associated with a lower incidence of Fusarium wilt in Pinus sylvestris [10]. The importance of potassium to plant disease resistance is shown by this. The plant's natural defenses are better enhanced when the plant is provided enough K.

2.2.2. Seasonal Fluctuations in Potassium Availability

Seasonal fluctuations are taken by soil potassium levels along with years where such stages of plant growth. The concentration of K in the spring is 32.83 $mg \cdot kg^{-1}$ in the Horqin Sandy Land. This peak coincides with the planting and establishment of seedlings, a major time when plants need good availability of nutrients for successful growth [21]. The increased K availability during spring supports these vital physiological processes and helps in spring, a period of rapid growth for many plant species.

On the contrary, aggravated K depletion has also been shown in overmature forests, producing pathogen susceptibility. This points to their need for K-rich biochar amendment to replace soil nutrients and boost the resilience of plants [21]. Sustained plant growth and health can be promoted by improving soil fertility and structure with biochar, a carbon-rich material derived from pyrolysis.

2.2.3. Microbial Interactions and Potassium Cycling

Modulation of potassium cycling in the soil depends on how it is affected by microbial interactions. K uptake in Artemisia halodendron species is increased by arbuscular mycorrhizal fungi (AMF) [11]. These fungi spread the reach of the root system of the plant, providing resources and water. Also, rhizosphere bacteria, particularly Pseudomonas spp., solubilize the K fixed in soils of high pH so that the form is more available for plant uptake [11]. The overall health and resilience of the ecosystem is facilitated by these microbial communities that help with nutrient cycling and plant growth.

2.2.4. Synergistic Effects and Restoration Practices

The synergistic effects of microbial interactions and potassium availability are essential for plant resilience. However, prolonged droughts can disrupt these microbial communities, reducing their ability to support plant growth [12]. This highlights the importance of incorporating microbial inoculants into restoration practices to enhance soil health and plant survival. By reintroducing beneficial microorganisms, restoration efforts can promote nutrient cycling and improve the overall functioning of the ecosystem.

2.3. Leaf Trait Adaptations

Leaf morphological traits play a pivotal role in the survival and adaptation of plant species in arid environments such as the Horqin Sandy Land. These traits, which include specific leaf area (SLA) and dry matter content (DMC), are critical indicators of a plant's ability to withstand drought and optimize resource use. Understanding these traits provides valuable insights into the ecological strategies employed by different plant species during the succession process.

2.3.1. Early Colonizers:

Early colonizing species, such as, exhibit distinct leaf morphological adaptations that enable them to thrive in the harsh conditions of mobile dunes. *A. squarrosum* displays a low specific leaf area (SLA: 22.92 $m^2 \cdot kg^{-1}$) and a high dry matter content (DMC: 0.26 $g \cdot g^{-1}$). These characteristics are indicative of a conservative water-use strategy, where the plant prioritizes minimizing water loss over rapid growth. The low SLA suggests that the leaves are thick and have a low surface area relative to their dry weight, which reduces the potential for water loss through transpiration. Additionally, the high DMC implies that the leaves are densely packed with dry matter, further contributing to their structural integrity and resistance to desiccation. The thick cuticles and reduced transpiration rates of *A. squarrosum* are crucial for its survival in the highly unstable and water-limited environment of mobile dunes.

2.3.2. Mid-successional Species: *Artemisia halodendron*

In contrast to the early colonizers, mid-successional species like *Artemisia halodendron* display a different set of leaf morphological traits that balance growth efficiency and stress tolerance. *A. halodendron* has a higher SLA (31.45 $m^2 \cdot kg^{-1}$) and a lower DMC (0.18 $g \cdot g^{-1}$). The higher SLA indicates that the leaves have a larger surface area relative to their dry weight, which facilitates greater light capture and photosynthetic efficiency. This trait is advantageous in the semi-fixed dune environment, where the soil is beginning to stabilize, and there is a need for species that can grow rapidly and outcompete other plants. The lower DMC suggests that the leaves are less dense and more flexible, allowing for greater plasticity in response to environmental changes. However, this trade-off also means that *A. halodendron* is less drought-resistant than *A. squarrosum*, but it can still thrive in the relatively more stable conditions of semi-fixed dunes.

2.3.3. Late-successional Perennials:

Late-successional perennials, such as, exhibit leaf morphological traits that optimize water-use efficiency and long-term survival. *C. squarrosa* has an intermediate SLA (27.30 $m^2 \cdot kg^{-1}$) and a high DMC (0.22 $g \cdot g^{-1}$). The intermediate SLA allows for a balance between light capture and water conservation, making it well-suited to the fixed dune environment, where the soil is highly stable, and the plant community is dense. The high DMC ensures that the leaves are structurally robust, enabling the plant to withstand the physical stresses of a mature ecosystem. Additionally, *C. squarrosa* has deep taproots that can access groundwater, further enhancing its ability to survive in arid conditions. The combination of these traits allows *C. squarrosa* to maintain high levels of productivity and resilience in the climax community.

2.3.4. Trade-offs and Ecological Significance

The negative correlation between SLA and DMC ($r = -0.685$, $p < 0.05$) highlights a fundamental trade-off in plant ecology: species with low SLA prioritize drought resistance, while those with high SLA favor rapid biomass accumulation. This trade-off is a key factor in the succession process, as it determines the ecological roles and competitive abilities of different species at various stages of ecosystem development. Early colonizers like *A. squarrosum* prioritize drought resistance to establish themselves in harsh environments, while mid-successional species like *A. halodendron* balance growth efficiency and stress tolerance to capitalize on the improving conditions. Late-successional species like *C. squarrosa* optimize water-use efficiency to maintain long-term productivity and stability in the mature ecosystem.

2.3.5. Technological Advancements in Phenotyping

The mainstream of Unmanned Aerial Vehicle (UAV)-based phenotyping has revolutionized leaf morphological trait study over broad geographical scales to make high-resolution data for screening drought resilience. Images high in detail of plant canopies can be obtained from UAVs equipped with multispectral and hyperspectral sensors and SLA, DMC, and other traits measured with great accuracy. This process has demonstrated that SLA and DMC are reliable proxies of drought resilience, thus the ability to identify species with higher adaptive capacities. Vegetation dynamics large-scale monitoring for just such a purpose are facilitated by UAV-based phenotyping.

3. Conclusion

Restoration of desert ecosystems in the Horqin Sandy Land requires a scientifically sound combination of plant protection strategies, be it to balance the ecological resilience to natural disturbances and human pressure. This study further shows that the course of the vegetation succession follows a predictable path, from an annual pioneer (Agriophyllum squarrosum) to perennial dominants (Cleistogenes squarrosa) in three decades, at the pace of species-specific adaptations in leaf traits, architecture of the root, and interactions of the root with soil microbes. Key findings of these variables as important leaf economic tradeoffs (low specific leaf area and high dry matter content) in early colonizers to improve drought resistance or mid-successional species, Artemisia halodendron, to use allelopathy and soil stabilization in succession. Finally, seasonal K availability peaks during seedling establishment, and decomposition of microbes plays a key role in nutrient cycling. If result phenotypes are preciously screened against the environmental conditions, targeted phenotyping tools such as UAV-based phenotyping facilitate precision in species screening for drought resilience.

As theoretical ecology, these implications go past; the actions of it can be taken into the large-scale restoration projects. Practitioners can maximize dune stabilization and restore biodiversity and long-term ecosystem stability by prioritizing stage-specific interventions, which include biochar amendments to improve K retention, introduction of AM fungi, and strategic species introduction. Given these insights, they are particularly relevant for arid regions under climate change that are increasing desertification.

Despite these limitations, sparse microbial community synergies and genetic diversity information of key species remain. In addition, the long-term impact of the invasive species Chernopodium aristatum on the succession remains poorly understood. Decoding the metabolic networks of plants and microbes in future research should use multiomics technologies to decode genetic markers that can help know the stress tolerance of species. Ensuring the integration of AI-driven predictive models with remote sensing to further optimize trait-based screening and remote sensing of restoration outcomes would be a job well done. By bridging ecological theory with agronomic innovation, this work lays the foundation for scalable, adaptive strategies to combat global desertification, ensuring that ecosystem restoration aligns with both environmental sustainability and human livelihoods.

Acknowledgements

This study was funded by the Provincial General Training Program of Innovation and Entrepreneurshipfor Undergraduates of Heilongjiang University(grant number: S202410212165) .

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