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Herbaceous Planting for Ecological Restoration of Urban Brownfields Based on Mechanisms of the Assembly of Plant Communities

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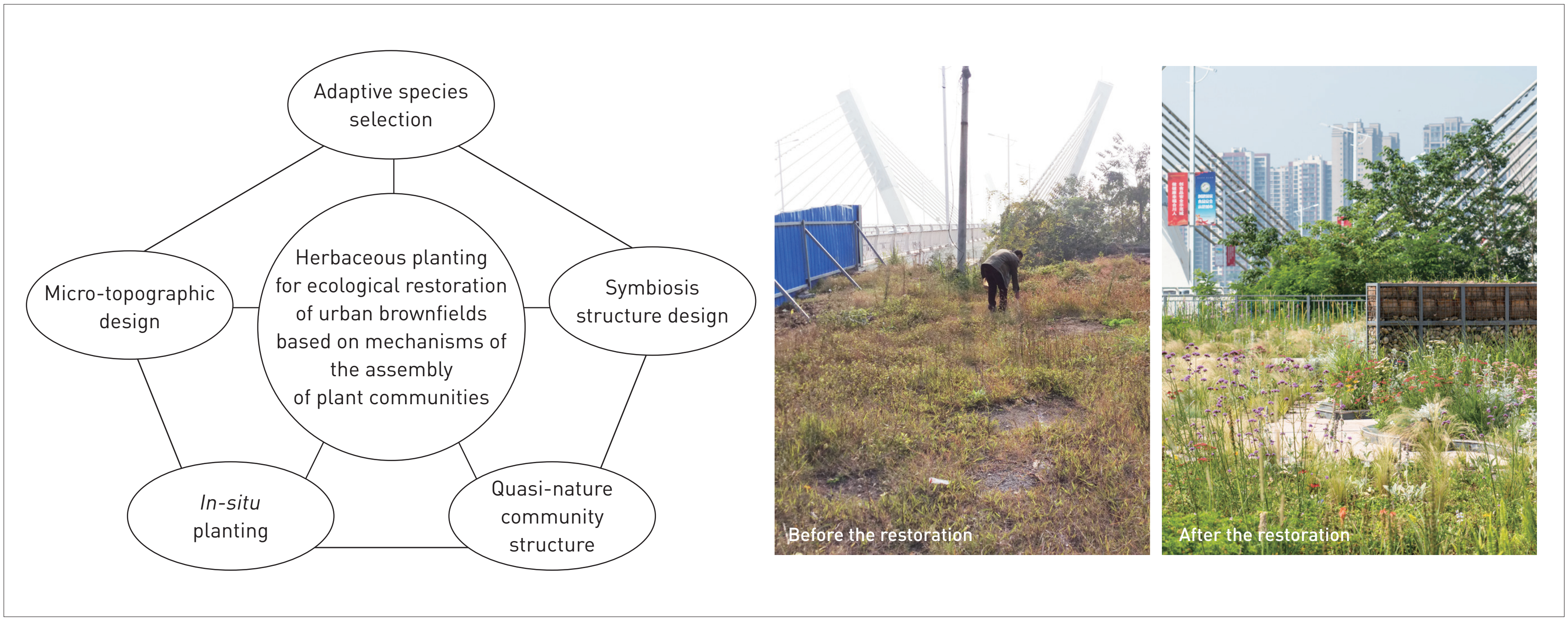
GRAPHICAL ABSTRACT



HIGHLIGHTS

- Proposes a novel technical framework of herbaceous planting for the ecological restoration of urban brownfields based on mechanisms of the assembly of plant communities
- Innovatively applies the above ecological planting technique in China and establishes health herbaceous communities with stable structure and ecological functions
- Provides scientific evidences and a referable technical paradigm for urban brownfield habitat restoration, biodiversity conservation, and enhancement of landscape aesthetic values

KEYWORDS

Urban Brownfields;
Ecological Restoration;
Herbaceous Communities;
Ecological Planting;
Mechanisms of the Assembly of Plant Communities;
Ecosystem Services

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ABSTRACT

Brownfield restoration has become a frontier topic in the research on urban ecosystem governance. Optimizing brownfield ecosystems through proper bioremediation approaches can provide urban landscapes and habitats with sound ecological potentials. Currently, the lagging theory and technique development of brownfield vegetation restoration, the species selection based on single causality, and the neglect of community structure and ecological functions formation have become major bottlenecks of brownfield restoration. Introducing the mechanisms of the assembly of plant communities for theoretical support, this paper proposes a novel technical framework of herbaceous planting for the ecological restoration of urban brownfields, which includes micro-topographic design, adaptive species selection, symbiosis structure design, building quasi-nature community structure, and *in-situ* planting. This research selected a brownfield site located in Hechuan District, Chongqing City for the application of the herbaceous planting, and evaluated the ecological benefits after restoration. Results showed that severely degraded brownfield vegetation has turned into an herbaceous community with a multi-species symbiosis and a stable structure, effectively optimizing its ecological functions such as stormwater retention and biodiversity conservation. This research can provide scientific evidence and a referable technical paradigm for urban brownfield restoration, and also contribute to the enhancement of urban ecological networks and ecosystem resilience.

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1 Introduction

Brownfields are previously developed lands that are currently being abandoned or unoccupied[1]. With the industrial restructuring and the decline of industrial areas, as well as the reform and relocation of heavily polluting industrial and mining enterprises under environmental policies, brownfields are commonly found in cities, and resulting in problems such as soil contamination, habitat degradation, and damage of ecosystem services. In recent years, brownfield remediation has been a hotspot in the research on urban ecosystem governance. Proper clean-up and bioremediation approaches to brownfields would allow to restore them into urban landscapes and habitats with sound ecological potential[2]. Internationally, there is research focusing on the restoration of ecological structures and functions of urban brownfields under the dominance of natural processes without human disturbance, offering opportunities for open mosaic habitats and urban rewilding[3].

In urban brownfield remediation practices, vegetation plays a key role in improving soil and habitat quality and enhancing purification function. However, due to the lagging research and application on vegetation restoration in urban brownfields, the deficiency of related techniques, and the severe growing condition in brownfields, researchers and practitioners are challenged with the following problems: 1) barren soil, severe contamination, and other problems often make urban brownfields have a low biodiversity and homogeneous structure of vegetation communities[4]; 2) because of the damage of existing vegetation community and the ruderal seed banks in the soil backfill, urban brownfields are often dominated by malignant weeds and even invasive species[5]; 3) existing research on adaptive plant selection for urban brownfields only measures the adaptability of different plant species to contamination and their capacities of heavy metal accumulation[6][7], lacking consideration about other ecological factors' (e.g., soil depth and drainage properties) impacts on plants; and 4) there are few studies on the eligible measures for the species assemblages and the configuration of vegetation communities in urban brownfields, offering little scientific guidance to promoting the symbiosis of multi-species and maintaining the structure of vegetation community and the biodiversity of native wild animals.

Currently, there are already a number of international studies utilizing herbaceous plants for brownfield remediation[8]~[10] to establish vegetation communities and improve habitat quality, due to their advantages including fast growths, high adaptability of built environment, low soil depth and nutrient requirements, and flexibility for use with multiple species[11][12]. In recent years, ecological planting techniques such as mixed sowing of herbaceous plants have been rapidly developed to establish urban vegetation communities by simulating community structures in natural meadows[13][14], as a potential strategy to improve soil quality, enrich biodiversity, and increase the aesthetic value of brownfields. Nevertheless, the lack of effective theoretical and scientific guidance for the composition of herbaceous communities and the preservation of biodiversity limits the practice of ecological restoration of urban brownfields.

This paper holds that a well comprehending of the formation and maintenance of plant communities and their diversity patterns (e.g. the processes of community assembly) is fundamental to the establishment of healthy herbaceous communities in urban brownfields. Mechanisms of the assembly of plant communities as one of the core research interests in community ecology studies play a key role in understanding the coexistence patterns of species and the maintenance of biodiversity. They are also crucial in understanding how can plant communities effectively sustain ecological performances[15][16]. Community assembly is mainly shaped by ecological filtering (including environmental filtering and biological filtering) which selectively letting species adaptive to a certain type of environment pass through in order to become part of a stable local community[17][18]. Environmental stress factors in urban brownfields, including soil nutrient, moisture, and contaminants, can act as environmental "filters" to select species with certain adaptive characteristics, and significantly impact the future establishment, survival, and growth of vegetation communities[19]. Therefore, increasing the heterogeneity in abiotic conditions to provide more niches for diverse types of vegetation and selecting the species of high adaptability to environmental stress is key to the assembly of plant communities for brownfields. When environmental conditions and site resource availability are improved, interspecific competition (e.g. biological filtering) will become the dominant process in shaping plant community assembly. Therefore, promoting interspecific facilitation and coexistence of species is of great significance for the long-term maintenance of community structure and function of vegetation communities in urban brownfields[20].

Based on the above theories of mechanisms of the assembly of plant communities, this research, differing from existing studies that simply focus on single causality, proposes a novel technical framework of herbaceous planting for the ecological restoration of urban brownfields, which includes micro-topographic design, adaptive species selection, symbiosis structure design, building quasi-nature community structure, and *in-situ* planting. This framework would facilitate the maintenance of species coexistence and the performance of ecosystem services such as biodiversity conservation. With a case study on the ecological restoration of the brownfield in Chongqing City, China, this research demonstrates the application of the technical framework, and conducts follow-up ecological performance evaluation. It aims to provide scientific evidence and a referable paradigm for the practice of urban brownfield remediation and improvement of ecosystem services, and for the enhancement of urban ecological networks and ecosystem resilience.

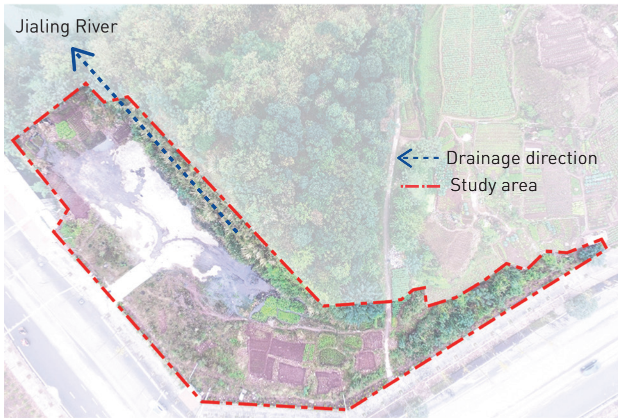
2 Study Site and Design Objectives

The studied brownfield site is located at the northwest side of Senkai Road and the north bank of Jialing River in Hechuan District, Chongqing City (Fig. 1). This area has a humid subtropical monsoon climate, with relatively low solar abundance throughout the year and frequent summer storms[21]. Covering an area of 3,600 m^2, this vacant site was a typical urban brownfield piled with construction wastes and scraped vehicle parts. The site was roughly flat, and the soil was barren and only 30 ~ 40 cm in depth, under which was the backfilled construction debris. Due to the poor moisture retention capacity of the soil and construction wastes layers, runoffs frequently occurred on the site during rainfalls, which washed and carried pollutants and heavy metal contaminants into the 90-centimeter-wide ditch near the northwest boundary of the site, and finally flowed into the Jialing River, causing pollution problems. The site also suffered from poor vegetation coverage and biodiversity, where invasive species such as *Alternanthera philoxeroides*, *Humulus scandens*, and *Conyza Canadensis* were dominant (Fig. 2).

As the study site is located at the intersection of the historic downtown and new urban development areas and close to the Jialing River, it is urgent to establish a sustainable vegetation community through restoration approaches, and to create a buffer zone from the river with functions of runoff retention, pollution prevention and control, and biodiversity improvement, aiming at optimizing the landscape effect and providing recreational places for surrounding residents.

3 Technical Framework of Herbaceous Planting for Urban Brownfields

Based on mechanisms of the assembly of plant communities and considering the environmental stress factors such as barren soil, pollution, invasive species propagation, and poor moisture retention capacity, this research concentrated on micro-topography design (to increase spatial heterogeneity and ecological niches) and adaptive species selection (by the tolerance of barren soil and contaminants, adaptability to varied soil moisture levels, etc.). Thereby, this research proposed a vegetation assembly pattern to promote the



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1. Site location plan
2. Site conditions before ecological restoration

symbiosis of plants and animals by simulating natural community structure, and utilized the *in-situ* mixed-seed sowing combined with seedlings planting to establish a well-coexistent and self-maintained herbaceous community with improved biodiversity and appealing landscapes. All the design strategies synergize and supplement each other, thus can form an effective technical framework of herbaceous planting for the ecological restoration of urban brownfields (Fig. 3). The planting on the study area was implemented spanning from October 2017 to March 2018.

3.1 Micro-topography Design

Urban brownfields usually suffer from harsh soil and pollution problems and see homogeneous habitats due to the previous landform construction, making the sites difficult to maintain biodiversity and retain runoffs and vulnerable to invasive plants propagation[22]. Since the variety of topography largely defines the spatial heterogeneity of the site[23], micro-topography design is the key to enriching the biodiversity of urban brownfields.

Enriching continuous topographic variation through design would help create diverse niches and varied habitat conditions and facilitate runoff retention[24]. Sunken areas are suitable for hygrophilous plants, among which deeper ones (often in forms of ponds and ditches) can retain runoffs, provide water to surrounding habitats, and lower the micro-environment temperature while creating favorable growing conditions for moisture-tolerant species[25]. At the same time, the slopes of elevated areas would help with drainage and provide favourable growing conditions for drought-tolerant species; mounds and ridges can provide not only higher places for heliophilous species but also shelters for shade-tolerant species. Such rich micro-topographic changes can buffer runoffs and gather propagules of spontaneous plants to increase the biodiversity of vegetation community, which can be particularly realized by creating a certain amount of gentle slopes (< 15°) that would have moderate and varied humidity. Since south-facing slopes have better thermal and light conditions for herbaceous plants, increasing the slope length will also help enhance the biodiversity of vegetation community[26].

In addition, to enrich the diversity of micro-topography, this research also formed a complex mosaic of micro-topography with diversified forms, sizes, heights, and depths. Materials like gravels, coarse sands, and wood chips were used to improve the soil texture, enhance infiltration, and the impermeability of a small part of sunken areas are improved with clay to create micro-wetlands that are suitable for hygrophytes and can be used for runoff retention.

3.2 Adaptive Species Selection

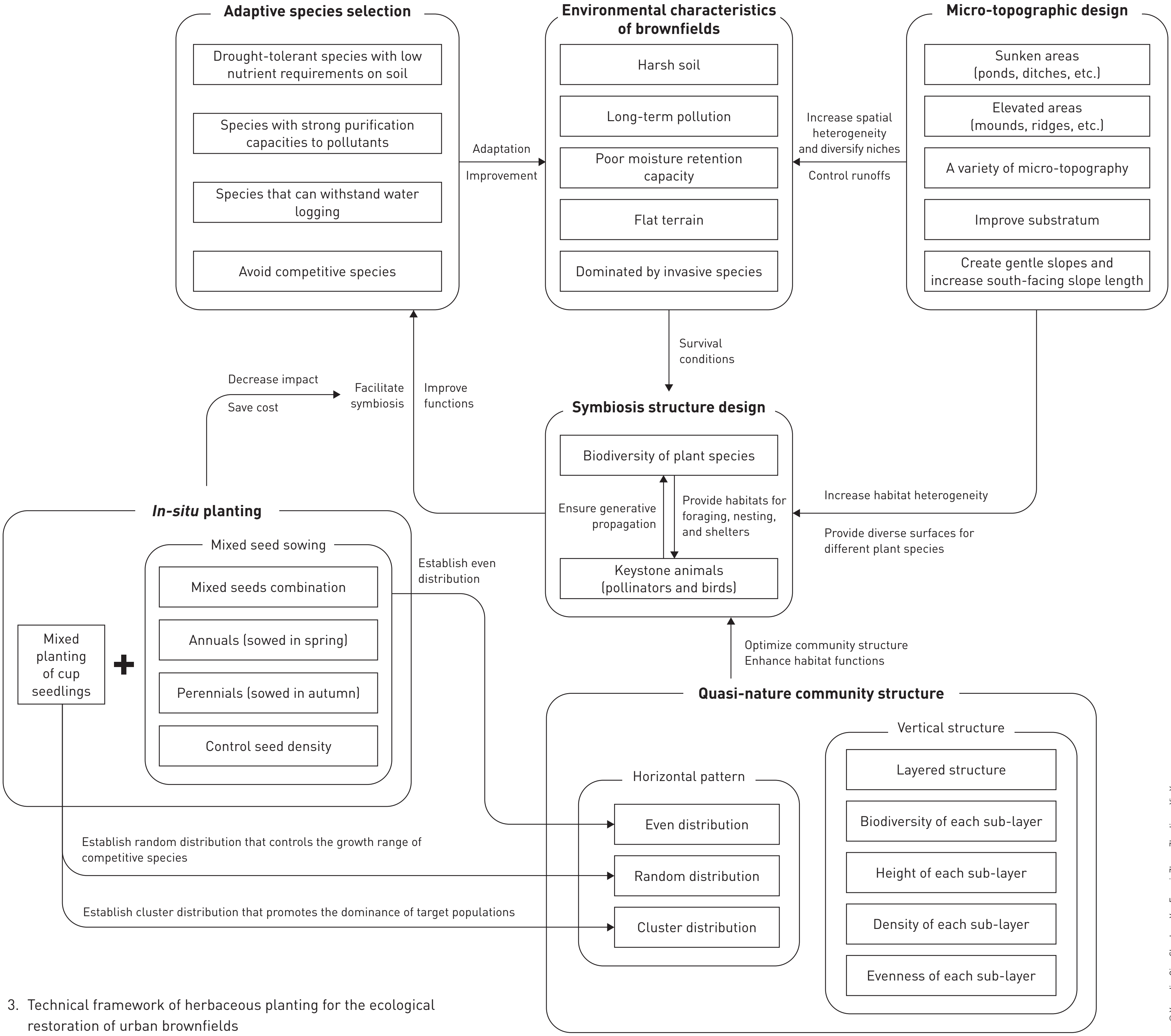
Adaptive species selection is determinant to the establishment of resilient vegetation community and its sustainability and low-maintenance. The following adaptive species selection principles are determined according to the specific site conditions.

1) Select drought-tolerant species with low nutrient requirements on soil, moisture retention capacity, etc., so as to reduce irrigation, fertilization, and other maintenance cost.

2) Select plant species with strong capture, adsorption, and purification capacities to pollutants and heavy metal contaminants, to alleviate soil pollution of the site.

3) Select plant species adaptive to the environmental conditions of the sunken areas and the rainwater retention ponds. Cyclic moisture fluctuation between water storage and drainage days will also require the species that can withstand 24 ~ 96 hours of water logging[27].

And 4) avoid competitive species, such as those with large



3. Technical framework of herbaceous planting for the ecological restoration of urban brownfields

size, excessive seeds, overgrown creeping stems, and propagative prolifically with rhizomes.

Based on the above principles, this study selected 39 herbaceous species (Table 1), among which 24 are perennials, 7 annuals, and 8 perennial ornamental grasses.

3.3 Symbiosis Structure Design

The research attempted to build symbiosis structures for the herbaceous community and keystone animals (which play an important regulatory role in the other species' distribution and community diversity), to promote the self-sustain and -maintain

Table 1: Plant species selected for the study site

Life form	Species	Adaptability		
		Barren- or drought-tolerant	Pollution-resistant/ purification	Water-tolerant/withstand 24 ~ 96 hours of water logging
Perennial	*Achillea millefolium*	●	●	
	Antirrhinum majus	●	●	
	Artemisia austriaca	●	●	
	Coreopsis grandiflora	●	●	
	Digitalis purpurea	●	●	●
	Echinacea purpurea	●	●	●
	Filipendula Palmata	●	●	●
	Gaura lindheimeri	●	●	●
	Hyacinthus orientalis	●	●	
	Hylotelephium spectabile	●	●	
	Iris ruthenica var. *nana*	●	●	●
	Iris tectorum	●	●	●
	Kniphofia uvaria	●	●	●
	Leucanthemum vulgare 'Short'	●	●	
	Liatris spicata	●	●	
	Linaria vulgaris	●	●	
	Lupinus micranthus	●	●	●
	Physostegia virginiana	●	●	
	Primula malacoides	●	●	●
	Salvia japonica	●	●	
	Senecio cineraria	●	●	
	Stachys lanata	●	●	
	Verbena bonariensis	●	●	●
	Veronica didyma	●	●	

Continued

Table 1: Plant species selected for the study site

Life form	Species	Adaptability		
		Barren- or drought-tolerant	Pollution-resistant/ purification	Water-tolerant/withstand 24 ~ 96 hours of water logging
Annual	*Centaurea cyanus*	●	●	
	Cosmos sulphureus	●	●	
	Eschscholzia californica	●	●	
	Gaillardia pulchella	●	●	
	Papaver rhoeas	●	●	
	Sanvitalia procumbens	●	●	
	Tarenaya hassleriana	●	●	●
Perennial ornamental grass	*Acorus gramineus*	●	●	●
	Calamagrostis × *acutifolia* 'Karl Foerster'	●	●	●
	Cortaderia selloana	●	●	●
	Festuca glauca	●	●	●
	Melinis repens	●	●	●
	Miscanthus sinensis	●	●	●
	Pennisetum alopecuroides 'Little Bunny'	●	●	●
	Stipa tenuissima	●	●	

capacity of vegetation community, and further facilitate the biodiversity conservation and low-cost maintenance. Nectar and pollen source species with different flowering seasons such as *Hylotelephium spectabile*, *Primula malacoides*, *Verbena bonariensis*, *Digitalis purpurea*, and *Gaura lindheimeri* were selected to provide adequate food for pollinators like butterfly, bee, and hoverfly. "Insect inns" (Fig. 4) were built with the scraped vehicle parts, construction wastes, and dead branches. Pebbles and blocks were piled up to provide nests and shelters for pollinators, such as bees that nested on the ground or bumblebees that cannot nest on their own. Some large rocks and gabions were randomly placed to form platforms above the plants for pollinators to bask in the sun (Fig. 5). Some gentle slopes were left unvegetated to provide a safe environment for insects (e.g. butterflies) to sip water after rainfall (Fig. 6). Ornamental tall grasses such as *Pennisetum alopecuroides* 'Little Bunny,' *Calamagrostis* × *acutifolia* 'Karl Foerster,' and *Miscanthus sinensis* were planted in clusters with wooden debris around (e.g. fallen trees, dead branches) to provide foraging, nesting, and shelters for small birds (Fig. 7). All these diversified micro-topographies can increase the "vegetation–pollinator–bird" symbiosis structures while physically forming a series of mosaic patterns on the site, to conserve keystone species,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4. Insect inn
5. Platform for pollinators to bask in the sun
6. Gentle slopes for insects to sip water
7. Tallgrass communities for small birds to nest, forage, and shelter.

among which pollinators can sustain the generative propagation and genetic vitality of vegetation communities and small birds can help seed spread[28].

3.4 Quasi-Nature Community Structure

Most artificial herbaceous communities in cities are planted in dense clusters and horizontally arranged by the height of plants to form a “low front, high back” landscape. Such planting not only lacks natural appearance, but also requires frequent maintenance because any end of flowering or dormancy will compromise the landscape effect or even lead to bare soil. In natural meadow, a combination of various herbaceous plants with different flowering seasons, heights, and leaf shapes ensures a higher vegetation coverage and a more complex layered structure, creating rich seasonal landscapes with long-lasting aesthetic values.

In this research, herbaceous community planting simulated the mosaic pattern in natural meadow community[29], forming three horizontal patterns (Fig. 8). Table 2 displays the selected herbaceous species and their corresponding patterns of an example site.

1) Even distribution: plants distribute in certain distances. Form even distribution through mixed seed sowing of species with various flower colours, small inflorescences, and different flowering seasons. Calculate each species’ percentage of seed weight in seed mixture according to thousand-seed weight to make the proportion of each species roughly the same. Greater species richness for this pattern is emphasized to effectively prolong the flowering and vegetation coverage period.

2) Random distribution: each plant randomly distributes horizontally in the community, and would not impact the distribution of the others. Select large plant species such as *Cortaderia selloana* and *Pennisetum alopecuroides* ‘Little Bunny,’ and species with distinct leaf and flower shapes such as *Artemisia austriaca*, *Senecio cineraria*, and *Kniphofia uvaria* to randomly scatter seedlings. This pattern can control the growth range of competitive species, and increase the aesthetic values by these ornamental species.

And 3) cluster distribution: plants densely distribute in groups, clusters, or blocks. Select species with strong environmental adaptability, long flowering season, and rich nectar and pollen sources. This can help promote the establishment and the dominance of target populations, create and sustain the expected landscape effects, and support pollinator foraging.

Natural meadow communities have layered structures, which can greatly increase plants’ utilization of environmental resources, and moderate the competence of nutrition. There are normally 3 ~ 5 sub-layers in a natural meadow community[30]. The highest sub-layer receives more sunlight, supports better photosynthesis, and will be easier to dominate; the medium sub-layer usually has a richer biodiversity; while the lowest sub-layer has higher shade-tolerance and earlier flowering seasons.

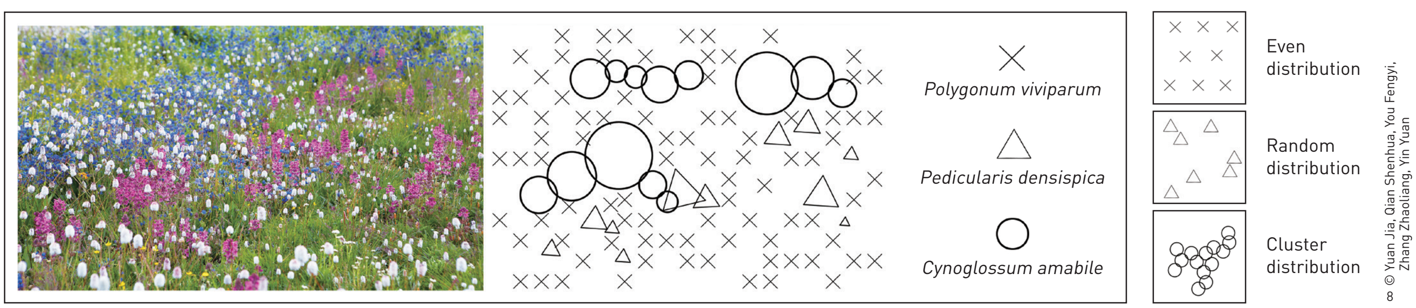
Based on the above theory, the research designed a three-sub-layer vegetation community (Fig. 9). Plant species that have higher leaves (50 ~ 90 cm), small leaves, and tall flower stalks (90 ~ 120 cm) were set in the first sub-layer to provide more sunlight for the plants below and ensure a layered effect during flowering seasons. Species with a medium height (30 ~ 50 cm), a longer flowering season, and colourful head or raceme inflorescence in the second sub-layer. Shade-tolerance species with lower leaf arrangement (10 ~ 30 cm), shorter flower stalks (20 ~ 30 cm), and earlier flowering season were planted in the third sub-layer; in addition, this sub-layer needs to include species with a larger cover to ensure the vegetation coverage and landscape effects in early spring.

3.5 *In-situ* Planting

Compared with seedling planting, mixed seed sowing and utilization of native seed bank can greatly save cost, and reduce resource consumption and greenhouse gas emissions[31][32]. Based

Table 2: Plant assembly patterns that simulate the structure of natural plant communities

Even distribution				Random distribution		Cluster distribution	
Mixture of annuals	**Percentage of seed weight (%)**	**Mixture of perennials**	**Percentage of seed weight (%)**	**Mixture of different life forms**	**Planting density (stem/m^2)**	**Mixture of different life forms**	**Planting density (stem/m^2)**
Centaurea cyanus	1.5	*Achillea millefolium*	0.2	*Artemisia austriaca*	2 ~ 4	*Digitalis purpurea*	2 ~ 4
Cosmos sulphureus	60.8	*Antirrhinum majus*	0.3	*Hyacinthus orientalis*	1 ~ 2	*Filipendula Palmata*	2 ~ 4
Eschscholzia californica	9.1	*Coreopsis grandiflora*	3.0	*Kniphofia uvaria*	1 ~ 2	*Gaura lindheimeri*	2 ~ 4
Gaillardia pulchella	15.2	*Echinacea purpurea*	2.5	*Liatris spicata*	1 ~ 2	*Hylotelephium spectabile*	2 ~ 4
Papaver rhoeas	0.9	*Iris ruthenica* var. *nana*	10.0	*Senecio cineraria*	2 ~ 4	*Physostegia virginiana*	4 ~ 6
Sanvitalia procumbens	1.5	*Iris tectorum*	10.0	*Cortaderia selloana*	1 ~ 2	*Primula malacoides*	2 ~ 6
Tarenaya hassleriana	11.0	*Leucanthemum vulgare* 'Short'	0.6	*Festuca glauca*	2 ~ 4	*Stachys lanata*	4 ~ 6
		Linaria vulgaris	0.2	*Melinis repens*	2 ~ 4	*Verbena bonariensis*	2 ~ 4
		Lupinus micranthus	72.0	*Pennisetum alopecuroides* 'Little Bunny'	1 ~ 2	*Acorus gramineus*	2 ~ 6
		Salvia japonica	0.6			*Calamagrostis* × *acutifolia* 'Karl Foerster'	2 ~ 4
		Veronica didyma	0.6			*Miscanthus sinensis*	2
						Stipa tenuissima	4 ~ 6



8. An example of horizontal patterns in the natural meadow community in northwest Yunnan, China.

9. Vertical structure of herbaceous community
10. Diagram of a sample plot of the restored herbaceous community (surveyed in June 2018)

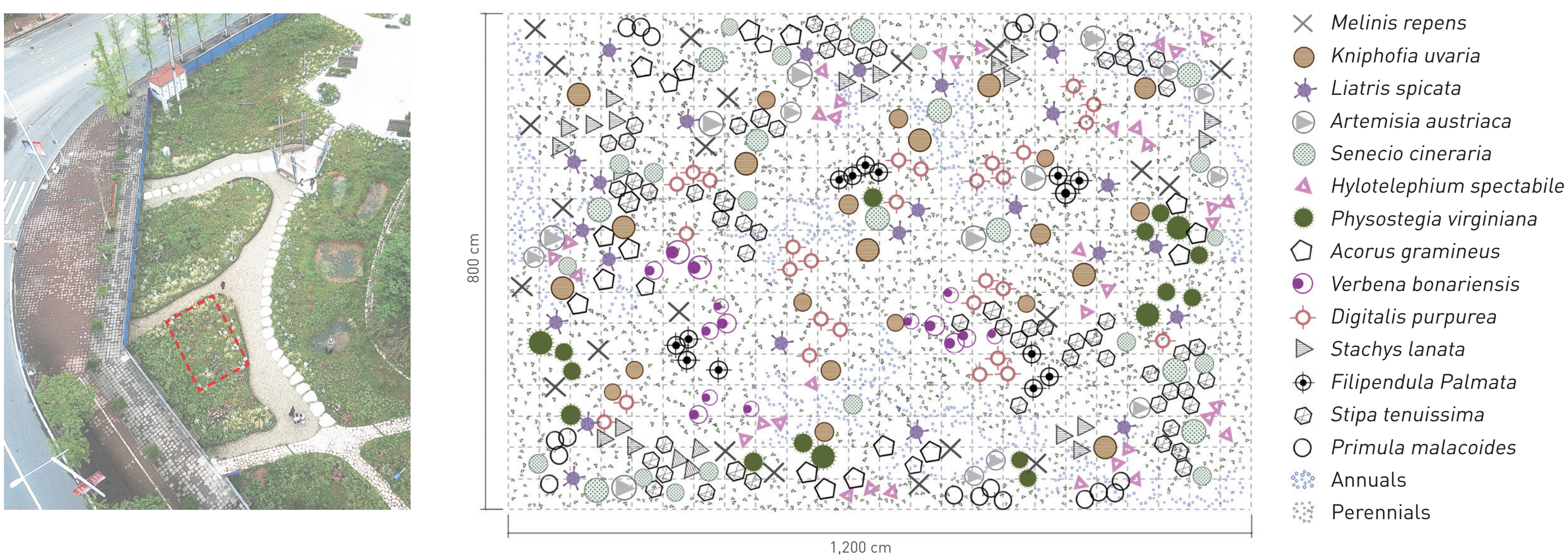
on the consideration of cost, low-impact development, and specific establishment of the even, random, and cluster distribution patterns, this research implemented mixed seed sowing together with seedling planting. Before sowing, manual removal of weeds and mixing the topsoil (2 ~ 3 cm in depth, which was rich of ruderal seeds) with humus are required. During the sowing, seeds need to be fully mixed with coarse sands, fine river sands, and vegetation fibers (2 ~ 5 mm long, 0.2 ~ 0.8 mm in diameter) made by reeds. Then, 60% of the area was sown with mixed seeds, including perennials (sowed in October to November 2017) and annuals (sowed in March 2018), with a seed density of 5 g/m^2. Random and cluster distribution patterns were established using 15 cm cup seedlings, which helps form the small clusters for dominant species and control the growing range of the larger plants.

4 Ecological Performance Evaluation

4.1 Community Structure and Landscape Effect

After the implementation of ecological planting techniques, the previously infertile and ruderal species dominated site turned into a dynamic plant community that is highlighted with aesthetic of nature. Researchers conducted a random sampling on the restored site (8 m × 12 m) in June 2018 (Fig. 10) to monitor and evaluate the horizontal distribution of different plant species in the community. The results show that the biodiversity of the restored herbaceous community substantially increased, presenting even, random, and cluster distribution patterns as expected and witnessing a sound symbiosis among various species. Meanwhile, the vegetation coverage of the cultivated community increased to 96.3%, effectively inhibiting the growth of malignant weeds such as *Alternanthera philoxeroides* and *Humulus scandens*.

In the first year after restoration, the herbaceous community was observed a 5-month of flowering attractiveness (from early March to late August), which greatly enhanced the aesthetic value of the site (Fig. 11). Plants in the third sub-layer such as *Leucanthemum vulgare* 'Short,' *Iris ruthenica* var. *nana*, *Primula malacoides*, *Eschscholzia californica*, and *Achillea millefolium* began to cover the ground in early spring, and started their



11. The rich aesthetic value of the restored herbaceous communities

blossom from March to April while the other two sub-layers started to grow. Entering May, plants in the second sub-layer such as *Hylotelephium spectabile*, *Melinis repens*, *Kniphofia uvaria*, *Digitalis purpurea*, *Liatris spicata*, *Sanvitalia procumbens*, *Gaillardia pulchella*, *Centaurea cyanus*, *Senecio cineraria*, *Papaver rhoeas*, and *Lupinus micranthus*, and the ones in the first sub-layer such as *Verbena bonariensis*, *Pennisetum alopecuroides* 'Little Bunny,' and *Calamagrostis* × *acutifolia* 'Karl Foerster,' blossomed one by one and covered the third sub-layer, presenting a beautiful layered structure with diverse inflorescence types (e.g., spike, panicle, umbel, and head), which distinctly contrasted with rosette herbaceous and ornamental grasses such as *Stipa tenuissima* and *Miscanthus sinensis*. Grass species would last the landscape effect after August.

4.2 Runoff Management

The research used Guelph permeameter to measure the soil permeability of the topsoil (10 ~20 cm in depth) in August 2017 (before restoration) and June 2018 (six-months after restoration), which has significantly increased from 3.96 ± 0.305 cm/h to 6.22 ± 0.259 cm/h . The restored herbaceous community increased the complexity of root system architecture, which would be beneficial for the improvement of soil porosity and permeability and further to the strengthening of water retention capacity of the site[24][33].

The enlarged vegetation coverage and the layered structure help improve the stormwater management on site by detaining and reducing runoffs. In 2018, the site experienced 31 times of storm (24-hour precipitation up to 50.0 ~ 99.9 mm), 24 torrential rain (24-hour precipitation up to 100.0 ~ 249.9 mm), and 6 raging storms (24-hour precipitation exceeds 250 mm). The research team surveyed the site every time 24 hours after the end of each rainfall event, and found that there was no obvious water logging except for the ponds and sunken areas with impermeable treatment. The results proved that the designed micro-topography enhanced the efficacy of rainwater retention, preventing Jialing River from the runoffs and carried pollutants.

4.3 Biodiversity Conservation

Monthly survey of pollinators, which was used as indicator taxa for biodiversity in this research, was conducted during the summers of 2018 and 2019. The results showed that the restored herbaceous community had an enriched species in pollinators (Fig. 12). There were 37 observed butterfly species during research period, increased 32% compared with 28 species before the implementation. Those species with colourful head or raceme flowers and rich in nectar and pollens, such as *Hylotelephium spectabile*, *Eschscholzia californica*, *Verbena bonariensis*, *Achillea millefolium*, *Liatris spicata*, *Centaurea cyanus*, *Papaver rhoeas*, *Lupinus micranthus*, and *Echinacea purpurea*, have attracted pollinators (e.g., butterflies, bees, bumblebees) most and formed a sound symbiosis. It was demonstrated that the "pollinator–nectar plants" symbiosis structures and the structural characteristic of nestedness are vital to sustaining the number of insects, the community structure, and the stability of community ecosystem services, which also promote the sustainability of the ecological performance of the site and the minimum management and maintenance cost.

5 Conclusions and Prospects

The ecological planting design of the brownfield in Senkai Road, Hechuan district, Chongqing City in this paper is an exploratory research addressing complicated environmental challenges in brownfields, including infertile soil, pollution, and malignant weeds. After restoration, the site that was vulnerable to environmental stress, overgrown with invasive species, and severely declined in species richness and ecosystem services now has turned into a healthy herbaceous community that provides functions such as runoff retention and biodiversity conservation with optimized structure and landscape aesthetics. The proposed technical framework of herbaceous planting for the ecological restoration of urban brownfields—steps as micro-topographic design, adaptive species selection, symbiosis structure design, building quasi-nature community structure, and *in-situ* planting—is an innovative application case in China. This research aims to provide scientific evidences and a referable technical paradigm for brownfield habitat restoration, biodiversity conservation, and aesthetic promotion, in order to contribute to the improvement of urban ecological network and ecosystem resilience.

In future, more quantitative analysis for the dynamics of species composition and interspecific competition within urban brownfield vegetation communities, as well as mechanisms for plant community's response and modification to the brownfield environment are needed. Research efforts can focus on the exploration of design parameters such as the plant composition proportion in different horizontal/vertical structures, to provide more empirical studies for the optimization of community structure and ecological functions of urban brownfields. It is also necessary to conduct quantitative monitoring to assess the long-term adaptability of constructed plant communities to polluted soil and its purification capacity, combined with *in-situ* tests to further select hyperaccumulator plants, which can provide reference to the species selection and composition of herbaceous community. Scholars and practitioners are expected to explore new models of herbaceous planting in urban brownfields with high land-use conversion rates and under different climatic and flora conditions. There also needs more attention on urban brownfield herbaceous landscape ecological processes (including species flow, nutrient flow, and hydrological flow), and on the role of spontaneous plants and potential vegetation in ecological planting, to create communities with a better adaptability and a higher self-sustain and –maintain capacity.

12. Pollinators in the restored herbaceous community

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基于群落构建机制的城市棕地草本植物生态种植研究

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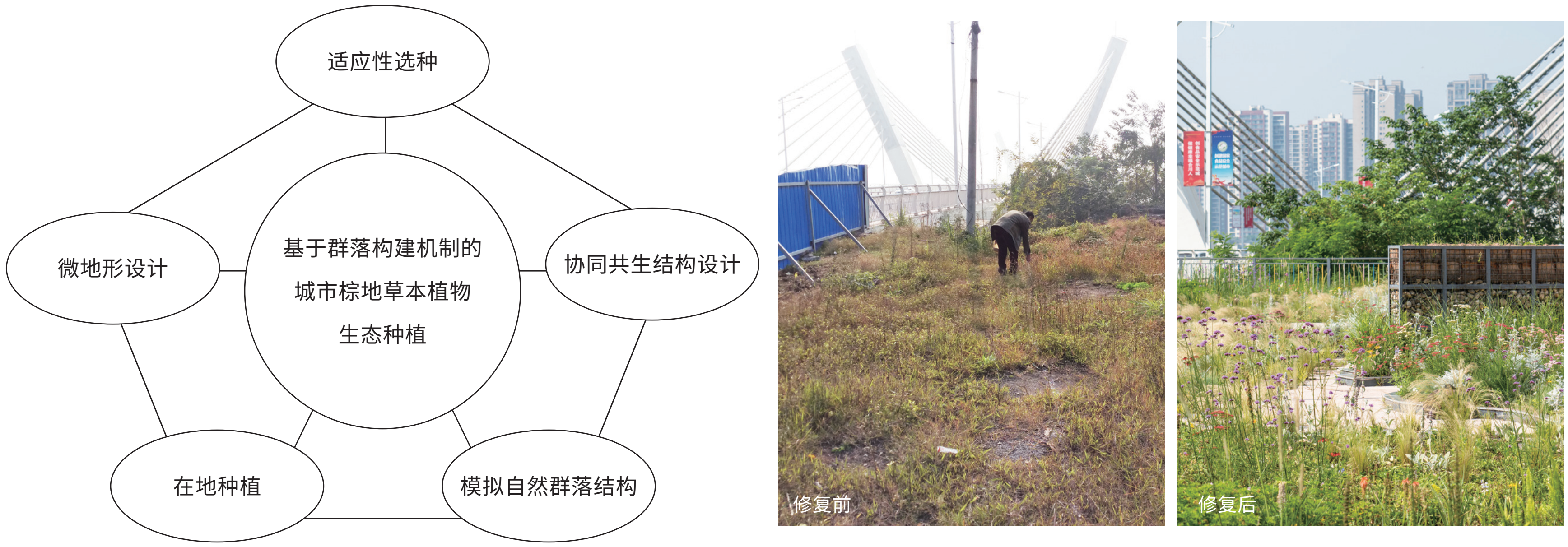
图文摘要



文章亮点

- 基于群落构建机制的科学理论，创新构建了城市棕地草本植物群落生态种植技术框架
- 在国内城市棕地修复实践中创新性集成运用上述生态种植技术，修复后的草本植物群落结构及生态功能稳定
- 为棕地生境优化、生物多样性保育及景观美学价值提升提供了可参考的技术范式

关键词

城市棕地；生态修复；草本植物群落；生态种植；群落构建机制；生态系统服务

摘要

棕地修复已成为城市生态治理的前沿热点，通过生物修复技术整治棕地生态系统，能够提供具有巨大生态潜力的城市景观与生物栖息地。当前，国内外棕地植被修复理论及技术发展较为迟滞、植被选种多关注单一要素，以及忽视群落结构与生态服务功能构建成为城市棕地植被修复的关键瓶颈。本文依据群落构建机制的基础理论，创新性提出“微地形设计－适应性选种－协同共生结构设计－模拟自然群落结构－在地种植”的城市棕地草本植物生态种植设计技术框架。研究选择重庆市合川区一处棕地地块开展草本植物群落生态种植实践，并在修复后对其生态效益进行评估。结果表明，原本生态功能严重衰退的地块在修复后形成了多物种共生、结构稳定的草本植物群落，场地的径流管理与生物多样性保育等生态服务功能与景观美学价值得到了有效提升。研究成果可为城市棕地生境修复提供科学依据与可参考的技术范式，对完善城市生态网络与增强城市生态系统韧性具有重要意义。

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1 引言

棕地是曾被开发且处于荒废、闲置状态的土地[1]。随着城市产业结构调整、工业区衰退，以及环保政策影响下一些重污染工矿企业的转产或区位调整，棕地在城市中大量形成，并产生土壤污染、生境退化与生态系统服务衰减等问题。近年来，棕地修复成为城市生态治理的前沿热点，适当清理并结合生物修复技术整治受损棕地，能够提供具有巨大生态潜力的城市景观与生物栖息地[2]。国际上已有研究关注城市棕地在终止人为干扰和自然过程主导下逐渐恢复的生态结构与功能，并将其视为开放栖息地斑块及城市再野化的机遇性空间[3]。

在城市棕地再生实践中，植被发挥着土壤改良、污染净化与生境质量提升等关键作用。然而，由于国内外城市棕地植被修复研究与应用较为迟滞、相关技术积累不足，且城市棕地生境条件严苛，当前存在如下突出问题：1）城市棕地普遍存在土壤贫瘠、污染富集等不利条件，对植物生长形成胁迫，导致群落物种贫乏、结构单一[4]；2）由于原生植被破坏与客土回填所携带的杂草种子库等原因，棕地植被往往由恶性杂草甚至入侵植物占据优势地位[5]；3）已有的棕地适生植物选种研究往往单一考虑不同植物种类对污染土壤的适应能力及其重金属积累能力[6][7]，缺乏对其他生境因子（如土层厚度、土壤排水性能）的综合考虑；4）鲜有研究提供城市棕地植物群落的物种组成及其空间布局等配置技术，缺乏促进多物种共存、维持棕地植物群落结构及乡土野生动物多样性的科学指导。

目前，国际上已有较多案例使用草本植物进行棕地修复[8]-[10]，利用草本植物生长快速、适应人工环境、对土壤厚度及养分需求较低、配置灵活等优势[11][12]，建立棕地植物群落并改善生境质量。近年来，以草花混播为例的生态种植技术快速发展，通过模拟自然植物群落结构建立城市植被[13][14]，可被视为修复棕地土壤、提升生物多样性与增加棕地美学价值的潜在策略。然而，由于缺乏有效的理论及科学指导，草本植物群落的物种组成及物种多样性维持常常成为棕地植被修复实践的关键瓶颈。

本文认为，构建结构及功能稳定的城市棕地草本植物群落的前提，是理解植物群落及其多样性的形成和维持机制，即群落构建机制。群落构建机制是群落生态学的核心研究问题之一，对解释群落中物种的共存格局和物种多样性的维持，并高效发挥生态功能有重要意义[15][16]。群落构建机制主要体现在通过生态过滤（包括环境过滤和生物过滤）使适应某一类型环境的物种进入该环境中，并形成物种稳定共存的群落[17][18]。城市棕地内较强的环境胁迫（如土壤养分、水分、污染等非生物环境因子）作为“过滤器”，筛选特定性状物种进入局域群落，并显著影响植物的定植、存活和生长[19]。因此，增加场地内部环境的空间异质性以产生更多生态位，从而筛选并容纳更多类型植物，同时选择对环境胁迫因子具有良好适应性的植物物种，是棕地群落配置的关键基础。当环境条件得以改善、资源相对充沛时，植物群落的主要构建机制则转变为植物种间的竞争排除（即生物过滤）；因此，通过有效设计使棕地植被内各物种产生种间促进作用并达到良好共存，对群落结构与功能的长期稳定维持具有重要意义[20]。

本文依据群落构建机制的理论基础，突破以往城市棕地植被选种关注单一要素、难以维持多物种共存，以及忽视生物多样性保育等生态功能的瓶颈，创新性地提出“微地形设计—适应性选种—协同共生结构设计—模拟自然群落结构—在地种植”的城市棕地草本植物生态种植技术

框架。研究选择重庆市的一处棕地地块实施棕地修复，并进行修复后生态绩效评估，旨在为城市棕地生境修复及其生态服务功能优化提供科学依据和可参考的应用范式，对完善城市生态网络与增强城市生态系统韧性具有重要意义。

2 研究场地与设计目标

研究场地位于重庆市合川区森楷路西北侧、嘉陵江北岸（图1）。研究区域属亚热带湿润季风气候，全年日照较少，夏季暴雨频繁[21]。研究场地占地面积约3 600m^2，该地块常年闲置，堆放着建筑废弃物、报废车辆零部件等，具有典型的城市棕地特征。场地内部土壤瘠薄、土层厚度仅30~40cm，土层以下为回填建筑弃渣。场地地形平整，由于土壤及建筑弃渣蓄水保墒能力差，降雨时极易形成大量径流，冲刷并携带场地内富集的污染物及重金属元素汇入靠近场地西北边界的一条宽度约90cm的冲沟，最终流入场地下方的嘉陵江，对河流水体造成污染。场地内植被覆盖度较小，现状植被中以空心莲子草（*Alternanthera philoxeroides*）、葎草（*Humulus scandens*）、小蓬草（*Conyza canadensis*）等入侵植物占绝对优势地位，生物多样性极为贫乏（图2）。

由于研究场地位于重庆合川区旧城与新城建设区域的交汇处，且紧邻嘉陵江河道，亟需建立可持续性良好的植物群落，通过植被修复，在场地与下方嘉陵江之间建立一个具备地表径流调蓄、面源污染防控、生物多样性提升等功能的生态缓冲区，优化场地景观效果，为附近居民提供良好的游憩场所。

3 城市棕地草本植物生态种植技术框架

基于植物群落构建机制，研究针对场地存在的土壤瘠薄、污染富集、入侵植物扩繁、蓄水保墒能力差等限制植物生长的环境胁迫因子，重点考虑了微地形设计（以形成空间异质性及空间生态位）和适应性选种（综合考虑物种对于贫营养环境的耐受性、不同土壤水分条件的适应性、污染物的耐受和富集特性等）两个方面。在此基础上，提出促进动植物协同共生、模拟自然植物群落结构的植物配置模式，并利用种子混播结合工程苗混栽的在地种植技术，构建物种间良好共存、能够自组织、自维持的草本植物群落，同时提升棕地景观的生物多样性及观赏效果。所有设计策略耦合协同，从而组织起有效的棕地草本植物生态种植技术框架（图3）。研究团队于2017年10月至2018年3月间，对场地实施了草本植物生态种植项目。

3.1 微地形设计

城市棕地普遍土壤瘠薄、污染元素富集，加上经历过开发建设时期的土地平整与土壤夯实，往往形成极为均质的生境条件，既无法满足生物多样性维持需求，又导致入侵植物进入定居并快速扩繁[22]，也难以有效调蓄地表径流。地形变化是形成空间异质性的重要原因[23]，因此，微地形设计是提升城市棕地生物多样性的关键。

通过设计增加连续的凹凸地形变化，有利于创造多样化的空间生态位、提供多样化的植物生长条件，也有利于地表径流的生态调蓄[24]。构建凹地形能够为喜湿植物创造所需生长空间，其中，池、塘和沟槽等深度较大的凹地形则能发挥拦截蓄滞地表径流的功能，适宜耐水湿植物生长，且可为周边生境提供水分并有效降低微环境温度[25]。凸地形的坡面有利于排水，适宜耐旱或喜旱植物生长；小丘与土垄等凸地形既能为喜光植物提供可获得更多光照的高点，又可以形成遮荫，为低矮的喜荫植物提供生长条件。制造凹凸地形组合，则能利用地表的小微起伏实现径流的缓冲，同时获取并富集随径流传播的自生植物繁殖体，有利于提高植物群落生物多样性。由于平缓坡面（坡度<15°）湿度适中且水湿变化较为丰富，因此在凹凸地形中设置一定量的平缓坡面，有利于增加植物群落的物种丰富度；南向坡面利于聚热采光，因此增加南向缓坡的坡长能为更多草本植物提供适宜的生长环境[26]。

此外，研究还注重微地形配置的多样性，在水平空间上形成形态、大小、高度、深度各异的凹凸地形的复杂镶嵌；同时，利用碎石、粗砂、木屑等材料改善土壤质地、加强渗透，并对小部分洼地进行以黏土为主的生态防渗处理，形成适宜湿生植物生长并蓄滞污染径流的小微湿地结构。

3.2 适应性选种

针对生境条件进行适应性选种，是建立植物群落环境韧性的先决条件，对提高棕地植被的可持续性和降低养护成本起到关键作用。本文基于研究场地的棕地生境条件，确定如下适应性选种原则。

1）需选择对土壤养分需求较低、且有一定耐旱能力的种类，以适应场地土壤极为瘠薄、蓄水保墒能力差、土层以下为回填建筑废渣等严苛条件，并减少灌溉、施肥等人工养护的投入。

2）选择对污染物和重金属元素具有较强阻滞、吸附及净化能力的植物种类，以消减场地土壤污染富集。

3）针对微地形设计中增加的凹地形及部分积蓄雨水径流的湿塘进行适应性选种。在这些洼地结构中，受降水及土壤排水的综合影响，会产生“蓄水—排空”的周期性水湿变化，应当选择具有一定耐水湿能力、能够在24~96小时的积水环境中存活的种类[27]。

4）避免选择竞争力强的植物种类，如具有植株庞大、结籽量过大、匍匐茎发达、能够通过根茎大量繁殖等特征的种类。

根据上述原则，研究共筛选39种草本植物（表1），其中24种为多年生草本植物、7种为一二年生草本植物、8种为多年生观赏禾草。

3.3 协同共生结构设计

研究通过设计构建草本植物群落与动物关键种（即对其他动植物的分布和群落多样性具有重要调控作用的动物种类）的协同共生结构，以提升植被的自组织及自我维持能力，有效服务于区域生物多样性保育并降低养护成本。设计选用八宝景天、报春花、柳叶马鞭草、毛地黄、山桃草等蜜粉源丰富、覆盖不同开花期的草本植物，为蝴蝶、蜜蜂、食蚜蝇等传粉昆虫提供充足的食物。利用场地内留有的汽车金属部件、建筑弃渣及枯枝构筑“昆虫旅馆”（图4），并在地面堆砌一定量的卵石堆、块石堆，为部分地面筑巢的蜜蜂或无法自主营巢的熊蜂等传粉昆虫提供必要的巢穴和庇护生境。将一定数量的大体积岩石和石笼网随机置入场地，形成高出植物、供传粉昆虫接受光照的平台（图5）。少量平缓坡面上不种植任何植物，可在雨后为蝴蝶等昆虫提供啜饮泥浆的安全环境（图6）。将“小兔子”狼尾草、卡尔拂子茅、芒等观赏性高草进行集群栽植，并在附近置入倒木、枯枝等木质物残体，为小型鸟类提供觅食、筑巢、庇护与停栖场所（图7）。上述一系列多样化的小微生境，能够增加场地内“植物—传粉昆虫—鸟类”协同共生结构数量，并在立体空间上形成复杂嵌套，从而保障对传粉昆虫和鸟类等关键种种群的有效保育——传粉昆虫的授粉服务能够维持草本植物群落的有性繁殖与遗传活力，而小型鸟类则能通过传播种子等繁殖体帮助植物扩繁[28]。

3.4 模拟自然群落结构

城市内的大部分人工草本植被是将植物密集成团栽植，并按植物叶序或花序的高度排列成“前低后高”的植物组景，不仅缺乏自然野趣，而且任何一种草本植物花期结束或进入休眠都会导致观赏效果下降，甚至会出现土壤裸露现象，需要频繁的人工养护来维持景观效果。在自然草甸中，不同花期、不同高度和不同叶序形态的多种草本植物相互交错生长，既保证了植被覆盖度与更为复杂的分层结构，又能够形成丰富季相并延长观赏期。

草本植物群落配置模拟自然草甸群落中不同种群斑块相间的镶嵌式布局[29]，形成三种类型的水平格局（图8）。表2展示了研究所选草本植物种类及其对应的水平空间配置模式。

1）均匀式：植物个体按一定间距均匀分布。选择花色丰富、花序较小、开花时间交错的植物种类，通过混播种子形成均匀式布局；根据不同植物的种子千粒重，计算不同种类在种子混播组合中所占重量比例，使每种植物的种子数量所占比例接近。均匀式配置的物种数丰富，能够有效延长植被花期与覆盖地表的时间。

2）随机式：每种植物个体在种群所占水平空间中随机出现，任何个体的存在不影响其他个体的分布。选择蒲苇、“小兔子”狼尾草等植株较大，以及银蒿、银叶菊、火炬花等花序与叶序特征明显的种类，随机选点栽植形成随机式配置，既能有效控制竞争能力较强种类的生长范围，也能利用观赏效果独特的种类增加植物群落的美学价值。

3）集群式：植物个体成群、成簇、成块地密集分布。选择环境适应性强、花期长、蜜粉丰富的种类进行密集型栽植，形成集群式配置。集群式配置有利于建立种群优势地位，通过优势种提供并维持植物景观的主体观赏效果，同时更加便于传粉昆虫寻找和搜集蜜粉。

自然草甸群落的垂直结构呈现分层的基本特征，分层结构能够显著提高植物利用环境资源的能力，缓解不同种类对营养空间的竞争。自然草甸群落一般具有3~5个亚层[30]，最高亚层接受的光照强度更高、光合作用更充分，容易形成竞争优势；中间亚层通常具有较高的物种多样性；最低亚层则拥有更高的耐荫能力和最早的花期。

据此，研究设计了三个草本植物群落亚层（图9）。第一亚层选择叶序较高（50~90cm）、叶序量少的种类进行稀疏种植，使第二亚层植物获得更好的光照条件；同时，选择抽薹开花时花茎较高（90~120cm）的种类，以保证花期景观层次丰富。第二亚层选择中等高度（30~50cm）、花期长、头状花序与总状花序色彩鲜艳的种类。第三亚层选择叶序低（10~30cm）、花茎短（20~30cm）、花期早且耐半荫的种类，既能适应较高亚层植物形成的遮荫，又能保证早春观赏效果。此外，第三亚层需选择一些冠层面积较大的种类，以保证初春的植被覆盖度。

3.5 在地种植

利用种子混播和保护本地土壤种子库等在地方式，能够大幅节省成苗移栽的人力成本，并有效降低生产成苗所消耗资源和运输过程产生的温室气体排放[31][32]。研究基于成本控制、低影响开发，以及形成“均匀—随机—集群”水平配置的综合考虑，采取种子混播与种苗混栽相结合的复合种植技术。其中，场地中面积约60%的区域采用种子混播技术建立植被，种子组合包括多年生种类组合（秋播，2017年10~11月）与一二年生种类组合（春播，2018年3月），混播密度为$5g/m^2$。播种前对场地杂草进行人工拔除，并移除土壤种子库密度较大的2~3cm表层土；将少量腐殖土与表土混合，增加土壤养分；播种时将种子与粗砂、细河沙及由芦苇加工成的植物纤维（长度2~5mm、直径0.2~0.8mm）进行充分混合。随机式与集群式配置采用15cm杯苗混栽，有利于准确建立优势种的小集群，并有效控制高大植物种类的生长范围。

4 生态效益评估

4.1 群落结构与景观效果

生态种植实施后，原本土壤瘠薄且入侵杂草扩繁严重的场地内形成了结构丰富、充满自然野趣的草本植物群落。2018年6月，研究者对修复后地块进行了随机取样（8m × 12m）测绘（图10），以监测不同植物

表 1：研究场地适生植物种类

分类	物种名称	适应能力		
		耐瘠薄／耐旱	抗污染／净化	耐水湿／适应 24~96 小时积水
多年生草本	蓍（*Achillea millefolium*）	●	●	
	金鱼草（*Antirrhinum majus*）	●	●	
	银蒿（*Artemisia austriaca*）	●	●	
	大花金鸡菊（*Coreopsis grandiflora*）	●	●	
	毛地黄（*Digitalis purpurea*）	●	●	●
	松果菊（*Echinacea purpurea*）	●	●	●
	蚊子草（*Filipendula Palmata*）	●	●	●
	山桃草（*Gaura lindheimeri*）	●	●	●
	风信子（*Hyacinthus orientalis*）	●	●	
	八宝景天（*Hylotelephium spectabile*）	●	●	
	矮紫苞鸢尾（*Iris ruthenica* var. *nana*）	●	●	●
	鸢尾（*Iris tectorum*）	●	●	●
	火炬花（*Kniphofia uvaria*）	●	●	●
	矮滨菊（*Leucanthemum vulgare*‘Short’）	●	●	
	蛇鞭菊（*Liatris spicata*）	●	●	
	柳穿鱼（*Linaria vulgaris*）	●	●	
	羽扇豆（*Lupinus micranthus*）	●	●	●
	假龙头花（*Physostegia virginiana*）	●	●	
	报春花（*Primula malacoides*）	●	●	●
	鼠尾草（*Salvia japonica*）	●	●	

续表见下页

表 1：研究场地适生植物种类

分类	物种名称	适应能力		
		耐瘠薄／耐旱	抗污染／净化	耐水湿／适应 24~96 小时积水
多年生草本	银叶菊（*Senecio cineraria*）	●	●	
	绵毛水苏（*Stachys lanata*）	●	●	
	柳叶马鞭草（*Verbena bonariensis*）	●	●	●
	婆婆纳（*Veronica didyma*）	●	●	
一二年生草本	矢车菊（*Centaurea cyanus*）	●	●	
	黄秋英（*Cosmos sulphureus*）	●	●	
	花菱草（*Eschscholzia californica*）	●	●	
	天人菊（*Gaillardia pulchella*）	●	●	
	虞美人（*Papaver rhoeas*）	●	●	
	蛇目菊（*Sanvitalia procumbens*）	●	●	
	醉蝶花（*Tarenaya hassleriana*）	●	●	●
多年生观赏禾草	金钱蒲（*Acorus gramineus*）	●	●	●
	“卡尔”拂子茅（*Calamagrostis* × *acutifolia*‘Karl Foerster’）	●	●	●
	蒲苇（*Cortaderia selloana*）	●	●	●
	蓝羊茅（*Festuca glauca*）	●	●	●
	红毛草（*Melinis repens*）	●	●	●
	芒（*Miscanthus sinensis*）	●	●	●
	“小兔子”狼尾草（*Pennisetum alopecuroides*‘Little Bunny’）	●	●	●
	细茎针茅（*Stipa tenuissima*）	●	●	

表 2：模拟自然植物群落结构的植物配置模式

均匀式				随机式		集群式	
一二年生组合	种子重量百分比（%）	多年生组合	种子重量百分比（%）	种类组合	种植密度（株／平方米）	种类组合	种植密度（株／平方米）
矢车菊	1.5	蓍	0.2	银蒿	2 ~ 4	毛地黄	2 ~ 4
黄秋英	60.8	金鱼草	0.3	风信子	1 ~ 2	蚊子草	2 ~ 4
花菱草	9.1	大花金鸡菊	3.0	火炬花	1 ~ 2	山桃草	2 ~ 4
天人菊	15.2	松果菊	2.5	蛇鞭菊	1 ~ 2	八宝景天	2 ~ 4
虞美人	0.9	矮紫苞鸢尾	10.0	银叶菊	2 ~ 4	假龙头花	4 ~ 6
蛇目菊	1.5	鸢尾	10.0	蒲苇	1 ~ 2	报春花	2 ~ 6
醉蝶花	11.0	矮滨菊	0.6	蓝羊茅	2 ~ 4	绵毛水苏	4 ~ 6
		柳穿鱼	0.2	红毛草	2 ~ 4	柳叶马鞭草	2 ~ 4
		羽扇豆	72.0	“小兔子”狼尾草	1 ~ 2	金钱蒲	2 ~ 6
		鼠尾草	0.6			“卡尔”拂子茅	2 ~ 4
		婆婆纳	0.6			芒	2
						细茎针茅	4 ~ 6

种群在群落中的水平分布状况。结果显示，修复后草本植物群落的物种丰富度大幅提升，且不同种类协同共生，呈现出预期的“均匀—随机—集群”水平结构。同时，栽培群落良好覆盖了场地空间（植被覆盖度达96.3%），建立了竞争优势，有效抑制了空心莲子草、葎草等恶性杂草的生长。

修复后第一年，草本植物群落呈现了长达5个月的观赏花期（3月上旬至8月下旬），群落季相丰富，极大地提升了场地的美学价值（图11）。其中，第三亚层植物（如矮滨菊、矮紫苞鸢尾、报春花、花菱草、蓍等）在初春覆盖地面，并在3~4月进入花期；此时，其他两个亚层植物逐渐进入营养生长期，群落垂直结构优良。步入5月后，第二亚层的八宝景天、红毛草、火炬花、毛地黄、蛇鞭菊、蛇目菊、天人菊、矢车菊、银叶菊、虞美人、羽扇豆等，以及第一亚层的柳叶马鞭草、“小兔子”狼尾草、“卡尔”拂子茅等次第成熟开花，逐渐遮盖第三亚层植物，此时群落垂直结构更加错落有致，尖塔形花序、圆锥花序、伞形花序和头状花序等花序类型丰富，与具有莲座状叶丛的草本植物及细茎针茅、芒等观赏禾草形成了鲜明对比。8月后，群落观赏效果主要由禾草提供。

4.2 径流管理

研究采用Guelph渗透仪，分别于2017年8月（修复前）和2018年6月（修复半年后）对场地内10~20cm土壤层进行土壤渗透率测定。研究结果表明，修复后的土壤渗透率（6.22±0.259cm/h）相较修复前（3.96±0.305cm/h）显著提高。修复后的草本植物群落增加了根系结构的复杂性：浅根系种类能够增加表层土壤的孔隙度[24]，深根系种类则能够改善深层土壤的孔隙度和渗透率[33]；这些植物根系交错生长，有效提升了场地径流渗透和调蓄功能。

同时，修复后的草本植物群落具有更高的植被覆盖度和更丰富的分层结构，有利于降雨和地表径流的拦截、阻延与蒸腾，减少径流生成总量并延长径流的形成时间。2018年，研究场地共经历了31次暴雨（24小时降水量达50.0~99.9mm）、24次大暴雨（24小时降水量达100.0~249.9mm）和6次特大暴雨（24小时降水量≥250.0mm）。每次降雨结束24小时后对场地进行调研，结果表明除采用简单防渗处理的小型湿塘及较深的洼地结构以外，场地内其他区域均没有明显积水。此外，场地内形成的一系列形态、面积、深度、高度不同的、在空间上彼此连续的凹凸地形组合，能够形成对场地内地表径流及其携带污染物的及时拦截、缓冲和调蓄，对场地下方嘉陵江的水生态安全起到了保障作用。

4.3 生物多样性保育

本文以传粉昆虫作为场地生物多样性的指示类群，在2018、2019年夏季分别开展月度调研。结果表明，修复后的草本植物群落中分布有种类丰富的传粉昆虫（图12）：蝴蝶种类数量显著增加（研究期间共记录37种），相较修复前（28种）增加了32%；八宝景天、花菱草、柳叶马鞭草、蓍、蛇鞭菊、矢车菊、虞美人、羽扇豆、松果菊等具有头状花序和总状花序、色泽鲜艳且蜜粉源丰富的种类，最受访花昆虫喜爱，与蝴蝶、蜜蜂、熊蜂等重要传粉昆虫建立了良好的协同共生关系。场地内形成的“传粉昆虫—蜜源植物”协同共生结构及其在空间上的复杂嵌套，对维持传粉昆虫种群数量、植物群落结构及功能稳定性具有重要作用，也有利于提升场地生态绩效的可持续性、降低人工管理成本。

5 结语及展望

本文中显示的重庆市合川区森楷路棕地的生态种植设计是适应棕地土壤瘠薄、环境污染及杂草扩繁等复杂环境挑战的一项探索性研究。原本易受环境胁迫、入侵植物占据群落优势地位、结构单一、生态功能严重衰退的棕地植被，修复后成为了具有良好结构特性及景观效果的草本植物群落，有效提升了场地的地表径流管理与生物多样性保育等生态服务功能。本文基于群落构建机制提出的技术框架——微地形设计—适应性选种—协同共生结构设计—模拟自然群落结构—在地种植——属在国内城市棕地草本植物生态种植的创新性应用，可为棕地生境优化、生物多样性保育及美学价值提升提供科学依据与可参考的技术范式，对完善城市生态网络与增强城市生态系统韧性具有重要意义。

在今后的研究中，需要对城市棕地植物群落的物种组成变化、种间竞争关系，以及群落对棕地环境的响应与改造机制进行深入定量分析，进一步探索不同水平结构和垂直分层中植物种类的组成比例等设计参数，实现棕地植物群落结构及生态功能的科学优化；应对修复后土壤污染浓度及其重金属含量进行定量监测，评估生态种植营建的草本植被对棕地土壤的长期适应能力及其污染净化能力，通过原位试验进一步筛选超积累植物，为城市棕地草本植物群落的物种组合优化提供科学依据；应构建不同气候条件／植物区系下，土地利用类型高周转区域内城市棕地的草本植物群落生态种植模式；应加强城市棕地草本植物景观的生态过程（如物种流、营养流、水文流等）研究，并关注城市自生植物及潜在植被在生态种植中的功能及作用，使草本植物群落对环境变化和人类活动干扰具有更好的适应性与自组织、自维持能力。

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