The Effect Mechanism of Fragmented Green Space in High-Density Urban Residential Areas on the Foraging Behavior and Diversity of Pollinating Insects

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Abstract: During the process of high-density urban development, the green spaces in residential areas become fragmented, which has a profound impact on the urban ecosystem. As an essential part of the ecosystem, the foraging behavior and diversity of pollinating insects are closely tied to green spaces. Studying the mechanism of fragmented green space in high-density urban residential areas on pollinating insects is of great significance for maintaining urban ecological balance and promoting biodiversity conservation. The fragmented green spaces exhibit features like miniaturized areas, scattered distribution, and simplified plant communities. Ecological functions are limited due to reduced habitat connectivity and a discontinuous spatial and temporal supply of resources. Pollinating insects have a demand for food resources and suitable habitat conditions, and plant traits and spatial perception influence their foraging behavior. Therefore, fragmented green space limits their resource accessibility, increases their behavioral adaptation and energy consumption, thus affecting their foraging behavior. It acts on pollinating insect diversity through the species screening effect, causing population isolation and barriers to gene exchange. In summary, an in-depth analysis of the mechanisms of the two can provide a scientific basis for optimizing the greening space of urban residential areas and protecting pollinating insects.

1. Introduction

1.1 Research Background

The land use pattern of high-density urban residential areas has undergone significant changes due to the acceleration of global urbanization, resulting in the obvious fragmentation of green spaces. As individual spaces have become smaller and more scattered, forming a continuous green network has become challenging. The change of spatial structure has further triggered a series of ecological problems. On the one hand, the continuous expansion of impervious surfaces (such as roads, buildings) has led to more than 38% of the habitat loss of pollinating insects; At the same time, the greening plant community tends to be simplified, the proportion of native species is usually less than 30 %, and it is often replaced by non-native ornamental plants, resulting in a decrease in the diversity of insect-pollinated plants. On the other hand, the weakening of habitat connectivity disrupts the foraging path of pollinating insects, limiting their range of activity to one-quarter of the native habitat and increasing energy consumption.

Additionally, the heterogeneity of the urban microclimate (a temperature difference greater than 5°C between day and night), light pollution, and air pollution significantly reduce the survival rate of pollinating insects. The species screening effect of fragmented greening space also directly changed the insect community structure: the number of omnivorous species increased, while dedicated species faced regional extinction due to a lack of resources.

Although some cities have attempted to compensate for the ecological function defects through artificial greening, there are still obvious deficiencies in landscape design: The loss rate of tubular flowers is as high as 75%, which makes it difficult to meet the diverse needs of pollinating insects. In short, the multi-dimensional influence mechanism of fragmented greening space on pollinating insects has become a key issue in current urban ecological research.

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1.2 Research Significance

Based on ecology and landscape design, this study expounds the influence of fragmented green areas in high-density urban areas on the functional mechanism of pollinators, which has high research value. The existing literature in this field focuses on how pollinator species composition responds to specific environmental factors. It lacks a systematic explanation of the linkage effect between "habitat connectivity, vegetation layout, and insect behavior." This paper quantifies the interaction between the landscape barrier effect and plant functional attributes, enhances the theoretical framework of urban biodiversity, and fills the research gap on the behavioral ecology of pollinators in the context of urbanization. At the application level, the research conclusions provide specific guidance for ecological restoration in high-density urban areas, assist in identifying the synergistic relationship between native plants and pollinators, optimizing the layout planning of green vegetation, enhance the continuous distribution of nectar plants in time and space, and establish a small habitat network according to the spatial perception limit of insects, to improve the efficiency of gene exchange of pollinators.

2. Characteristics of Fragmented Green Spaces and Urban Ecological Effects

2.1 Structural Characteristics of High-density Urban Green Spaces

2.1.1 Miniaturized Areas and Scattered Distribution

In high-density urban areas, land resources are scarce, and green areas are continuously occupied, leading to the miniaturization of these areas [1]. Its scale is usually limited, and it isn't easy to develop a large-scale ecosystem. Additionally, the distribution of these areas is uneven, and there is little effective connection between them. In some large residential areas, although there are green spaces surrounding the buildings, they fail to create a cohesive ecosystem due to the barriers posed by roads and buildings. As a result of the reduction in green spaces and the fragmentation of distribution, achieving complete ecological efficiency is challenging [2]. For pollinating insects, they need to migrate frequently between miniature green spaces, which undoubtedly increases the difficulty of their foraging and survival.

2.1.2 Single Plant Community and Non-native Species Domination

In the green areas of urban high-density residential areas, one of the problems of plant communities is the lack of diversity. People pursue a quick greening effect and reduce maintenance expenses, so they often prefer only a few plants that are easy to manage, resulting in a relatively limited number of plant species. In addition, non-native species play a significant role in greening projects, and many cities introduce a large number of exotic plants to create unique landscape effects. The ecological connection between non-native species and local pollinating insects is not compatible, as it cannot provide suitable food sources and habitats for pollinating insects. The flowering period and nectar composition of some exotic flowers differ from the demands of local pollinating insects, which affects their survival and reproduction [3].

2.2 The Ecological Function Limitations of Fragmented Green Spaces

2.2.1 Decreased Habitat Connectivity and Microclimate Heterogeneity

Fragmented green spaces obviously weaken the connectivity of pollinating insects' habitats. The originally continuous ecological habitat is divided into several isolated areas, which leads to many obstacles in the migration of pollinating insects among various green patches. Artificial structures, such as roads and buildings, have become obstacles that they can't cross, limiting their scope of activities and gene exchange. Moreover, the fragmentation of green spaces caused an increase in microclimate heterogeneity [4]. There are differences between various green spaces and their surrounding environments, each of which has formed its own unique microclimate conditions. The green space near the building typically experiences higher temperatures and lower humidity, while the green space farther from the building exhibits the opposite characteristics. Microclimate

differences have adversely affected the activities of pollinating insects, forcing them to adapt to the changing environment and intensifying the pressure on their survival.

2.2.2 Spatio - temporal Discontinuity of Resource Supply

From the time dimension, the flowering period of nectar plants is relatively concentrated. At certain times, pollinated insects can obtain sufficient food, while at other times, they face a food shortage. For the greening of some residential areas, most flowers bloom in spring, and nectar plants are relatively scarce in summer and autumn, leading to a lack of food for pollinators due to seasonal changes. From the spatial dimension, the distribution of nectar plants in different green patches is uneven; some green patches have an abundance of nectar, while others have almost none. In short, an insufficient resource supply forces pollinators to spend more time and energy searching for food, which has a negative impact on their foraging efficiency and survival.

3. Ecological Requirements and Behavioral Characteristics of Pollinating Insects

3.1 The Essential Ecological Requirements for Pollinating Insects

3.1.1 Food Resources

The survival and reproduction of pollinating insects depend largely on food supply, so the richness of nectar plants and the continuity of the flowering period are crucial. Diversified nectar plants can provide a wide range of nutritional choices for pollinating insects. The nectar and pollen components of various nectar plants differ, which enables them to meet the nutritional requirements of pollinators at varying growth stages and under different physiological conditions. Bees require high-protein pollen during their larval stage for proper growth, and as adults, they prefer nectar to meet their energy needs [5].

It is the continuity of the flowering period that ensures a stable food source for pollinating insects throughout the year. In the natural ecosystem, the flowering period of plants is interconnected, forming a food supply chain. However, in high-density urban residential areas, green spaces are fragmented, and the plant community is relatively homogeneous, with a flowering period that is usually concentrated in a specific period. As a result, food shortages at certain times will affect the survival and reproductive abilities of pollinating insects.

3.1.2 Habitat Condition

Pollinating insects require a suitable habitat to thrive, which constitutes the foundation of their survival. Such habitat conditions specifically involve the nest-building medium and refuge spaces. Nest-building medium is a necessary element for pollinating insects to build nests and reproduce. There are different needs for nesting media of pollinating insects. Bees tend to nest in tree holes and rock crevices, while some solitary bees use soil and dead leaves to build nests on the ground or plant stems [6].

The shelter that pollinating insects rely on to avoid natural enemies and adverse weather conditions is a key factor in their survival. In urban residential areas, the scattered green spaces are often small and monotonous in structure, leading to a general lack of nesting materials and safe shelters. In addition, the continuous expansion of man-made structures, such as buildings and roads, has invaded the habitats of pollinating insects, preventing them from finding suitable nesting sites and shelters, which poses a severe challenge to their population reproduction.

3.2 Key Factors Affecting the Foraging Behavior of Pollinating Insects

3.2.1 Plant Traits and Insect Preference

Plant traits have a significant effect on the foraging behavior of pollinating insects, evident in factors like flower color, flower shape, and aroma. Flower color, a key visual signal for attracting pollinators, plays a prominent role—pollinators exhibit distinct color preferences: bees are more sensitive to yellow and blue flowers, while butterflies favor red and purple ones [7].

Flower shape also affects the visit of pollinating insects. Some plants with unique flower shapes,

such as lip-shaped or tubular flowers, permit only specific pollinating insects with particular mouthparts to effectively gather nectar and pollen.

Additionally, aroma acts as a chemical signal: many plants emit unique fragrances to attract pollinators. However, urbanization has led to reduced diversity in plant species, flower colors, shapes, and aromas in fragmented green spaces. This limits pollinators' foraging options, impairing their foraging efficiency and survival.

3.2.2 Spatial Perception and Limitation of Activity Range

Pollinating insects' spatial perception and activity range often limit their foraging behavior. Insects possess a specialized spatial perception, enabling them to distinguish their surrounding environment and food sources through both visual and olfactory senses [8]. However, in the fragmented green spaces in high-density urban residential areas, complex buildings and road structures often hinder the spatial perception of pollinating insects.

Therefore, the range of activities of pollinating insects is constrained. The scattered distribution and small area of green spaces force pollinating insects to spend more time and energy shuttling between different green blocks. The limited activity radius of some pollinating insects hampers their foraging opportunities, as scattered green spaces reduce their living range, negatively affecting population reproduction and growth.

4. Influence Mechanism of Fragmented Green Spaces on Pollinating Insects' Foraging Behavior

4.1 Resource Accessibility

4.1.1 Dietary Specialization Caused by the Reduction of Insect-Pollinated Plant Species

In densely populated urban communities, the number of plants that rely on insect pollination has decreased significantly. Pollinating insects usually rely on one type of food source. Urban development takes up extensive areas of land, fragments green spaces into smaller sections, and often makes plant species uniform. The previously rich and diverse insect-pollinated plant communities were destroyed, which led to a sharp decline in the food resources obtained by pollinating insects.

Pollinating insects have specific choices and needs for food. When the species of insect-pollinated plants they depend on decrease, bees can only obtain nectar and pollen from a limited number of plants. Some bee species originally rely on a variety of wildflowers to maintain their health and nutrition. However, in the fragmented green area, they are exposed to limited flower species. Long-term consumption of one food source will cause nutritional imbalance, affect their growth and development, reproductive capacity, and immune level, and ultimately bring adverse consequences to their population size and diversity.

4.1.2 Interference of Landscape Barrier Effect on Foraging Path

The fragmentation of green spaces exerts a profound influence on the foraging paths of pollinating insects, with the landscape barrier effect being the key driver. In urban environments, structures such as buildings, roads, and parking lots divide green areas into scattered, isolated units—effectively forming insurmountable physical barriers. When pollinating insects forage, they frequently need to move between these green patches, and such obstacles directly disrupt their flight paths.

Wide roads with heavy traffic pose a danger to pollinating insects: the insects may get disoriented or waste energy avoiding vehicles. Additionally, high-rise buildings alter airflow patterns, which impairs the flight stability of pollinating insects. In summary, these factors collectively contribute to the landscape barrier effect, making it harder for pollinating insects to locate optimal foraging paths. It not only increases foraging difficulty and time costs, and reduces foraging efficiency, but also decreases their access to other plants and limits their availability of food resources.

4.2 Behavioral Adaptation and Energy Consumption

4.2.1 Long-distance Flight Leads to Energy Loss

In fragmented green spaces, pollinating insects usually need to fly long distances to obtain

abundant nutrients. The distribution of green patches is scattered and the scale is limited. Pollinating insects can only shuttle between patches, and their flight path is obviously longer than that in a complete natural ecosystem.

Pollinating insects expend a great deal of energy when flying long distances, which puts a severe strain on their physical reserves. For example, bees need to burn a lot of nectar to gain energy during flight. Once the flight distance is too long, they will run out of energy before finding the next food source, and even die in serious cases. Excessive energy consumption threatens the survival of pollinating insects, and also affects the reproduction of the whole population. In other words, insufficient energy reserves may lead to the reduction of reproductive efficiency.

4.2.2 Foraging Time Adjustment

The foraging time of pollinating insects may need to change due to the fragmentation of green spaces. Under natural conditions, these insects typically establish a relatively fixed foraging period based on the flowering cycle of plants and their own biological rhythms. In contrast, in the scattered green areas of the city, the plant species are scarce and the flowering time is concentrated, so it is difficult for pollinating insects to find enough food resources in its usual time.

Foraging during unusual times usually involves greater risk; high temperatures lead to dehydration, while nighttime brings increased threats from natural predators. Changing the foraging duration disrupts their biological clock, affects their physiological functions and reproductive activities, and poses increased survival challenges for pollinating insects.

5. Influence of Fragmented Green Spaces on Diversity of Pollinating Insects

5.1 Species and Community Changes

5.1.1 Dominance of Omnivorous Species and Decline of Specialized Species

In densely populated urban residential areas and scattered green belts, the living conditions of omnivorous species and specialized species are significantly different. Omnivorous pollinating insects have strong adaptability to food resources, and they can get enough food even in an environment with limited plant species. They do not rely on specific plants, but use nectar and pollen from many insect-pollinated plants, so they have obvious survival advantages in the environment.

Specialized species have a highly selective food preference, typically restricted to a small number of specific plants. The fragmentation of green spaces lead to the sharp decline or even extinction of plants, so the foraging path of specialized species is blocked. For example, some butterflies only feed on certain wild flowers, while wild flowers are becoming scarce in cities, so their population size is gradually shrinking. In the long run, the regional extinction of specialized species leads to the decline of species diversity of pollinating insects.

5.1.2 Influence of Exotic Plants Introduction

The introduction of exotic plants is another key factor affecting the composition of pollinating insect community in fragmented green spaces. In order to optimize the urban landscape or adapt to specific ecological purposes, some exotic species have been introduced into the residential areas.

Some exotic plants quickly occupy the niche and compete with indigenous plants for resources, resulting in a decline in the number of indigenous plants. Pollinating insects have certain adaptability and dependence on indigenous plants, and the decrease in the number of indigenous plants will lead to the loss of food sources and habitat for pollinating insects. Some exotic plants will also attract specific exotic insects and change the original community composition of insects. Subsequently, the remodeling of community structure will destroy the original ecological balance and have many effects on the diversity of pollinating insects.

5.2 Population Isolation and Gene Exchange Barriers

The fragmented green spaces is a common phenomenon in high-density urban residential areas, which is characterized by patchy distribution of habitats, resulting in the clustering of pollinating

insects being divided into scattered subgroups. Every patch is distanced from one another, with physical obstacles like roads and structures in between. The movement of pollinating insects among patches is greatly obstructed.

In small, isolated populations, the choice of mates among individuals is restricted, raising the likelihood of inbreeding. The inbreeding depression will result in several adverse traits in offspring, such as genetic abnormalities, reduced fertility, and diminished immune resistance. Taking honeybees as an example, inbreeding can lead to incomplete wing development and shortened life span, which has a negative impact on the health and survival of the population.

6. Conclusion

This paper focused on the green spaces in high-density urban residential areas and explored the mechanism of its influence on the diversity of pollinating insects' foraging behavior. In densely populated urban areas, green spaces are typically small and scattered. The plant community structure is often simplified and dominated by non-native species, which limits ecological functions and weakens habitat connectivity.

Food resources and habitat conditions are essential for pollinating insects, and their spatial perception and plant traits influence their foraging behavior. Fragmented green spaces limit the availability of resources, resulting in a decrease in the species of insect-pollinated plants. The landscape barrier effect disrupts their foraging paths, and long-distance flight increases their energy consumption. Additionally, changes in foraging time create survival pressure, which ultimately impacts their foraging behavior.

In terms of diversity, green space fragmentation promotes the dominance of omnivorous species through the species screening effect, while specialized species gradually decline. Moreover, the introduction of exotic plants has reconstructed the plant community structure: exotic plants often outcompete native nectar plants, which causes specialized insect populations to shrink and become geographically scattered. This scattered distribution of insect populations further leads to population isolation and obstructed gene exchange, eventually inducing inbreeding depression.

Future urban planning and greening projects should focus on connecting green spaces and promoting diverse plant communities. These projects should also create suitable habitats for pollinating insects to maintain their diversity and enhance the urban ecological environment.

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