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Urban Botany: Plant Diversity and Adaptation Strategies in Urban Environments

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Abstract:
Urban ecosystems experience notable shifts in species composition and functional diversity due to human disturbances. Understanding urban plant biodiversity and its drivers is crucial for predicting future changes and promoting resilient systems that provide essential services and mitigate climate impacts. Urbanization modifies plant communities by favoring species ill-suited to new environments, influenced by city-specific factors such as habitat availability and land use. Disturbance patterns and life-history strategies also affect species establishment, offering insights into ecological processes. For many people, urban flora is the only nature they encounter, yet the ability of urbanized areas to preserve biodiversity while delivering services remains unclear. The introduction of exotic species complicates the relationship between biodiversity and ecosystem services, necessitating careful assessment to align with societal goals. Understanding species replacement and coexistence can enhance the development of urban infrastructure that addresses aesthetic and conservation needs. Major cities are expected to face significant climate pressures, including extreme weather, erratic conditions, and prolonged droughts within dense urban areas. These changes impact food chains relying on urban plants for connectivity, influencing species movement and exotic species spread—some of which may provide services like water extraction during droughts but could also harm local vegetation and create pathways for invasive species.

Keywords: Urban ecosystems, biodiversity, Plant Diversity, Urban Environments.

1. Introduction

Urbanization has notable negative ecological impacts, like increased temperatures and reduced species richness, but it also introduces new species. Urban areas create distinct habitats, differing from typical open fields, and can offer greater ecosystem services. Certain urban plants thrive in drier, hotter, and more disturbed conditions than their native counterparts. These urban habitats often feature fewer competitors, allowing some native species to flourish. Additionally, urbanization introduces disturbances, attracting native plants that prefer such conditions, while city-native species may favor specific urban microhabitats. Urban plants benefit from unique growth tolerances and may supplement ecosystem services to adjacent areas. Our research explores plant diversity and adaptation strategies to climatic and anthropogenic pressures through global urbanization data. Approach 1 examines basic urban diversity, while Approach 2 assesses adaptation strategies and the decomposition of new ecosystem services related to pollinators, temperature, precipitation, disturbance, and nutrient availability. We address the urgent need for urban microhabitat and ecosystem service frameworks through the first multi-city global study and a focused adaptation analysis. (W. Dolan et al., 2017)

2. Conceptual Frameworks and Methodologies

Urban systems are complex environments influenced by various physical, chemical, and biological factors. In these landscapes, important elements include local climate, building structures, pollution, vegetation, and noise. Urban ecology studies the interactions among organisms in these ecosystems, while urban climate examines how city forms impact microclimates. Urban areas significantly alter ecosystem structures and functions, affecting plant-environment interactions, and leading to changes in plant compositions. Urban plants face disturbances and resource loading due to urbanization. They are vulnerable to invasive species and possess traits favoring adaptation, such as tolerance to disturbances and pollution, shorter life spans, and high reproductive capacity. These species thrive in diverse habitats and provide essential ecosystem services, making up a considerable part of urban flora. However, research on urban plant diversity is limited and lacks systematic inquiry, often focusing only on certain species or locations. Most studies center on urban biodiversity related to animals, leaving the unique characteristics, functions, and contributions of urban plant assemblages largely unexplored. Additionally, urban species, especially in higher plant taxa, are underrepresented in global trait databases. (W. Dolan et al., 2017)(Aronson et al., 2016)

3. Patterns of Plant Diversity in Urban Systems

Urban areas display distinctive patterns of plant diversity due to limited space and diverse land covers. Research on species richness, evenness, compositional turnover, and occurrence patterns of urban flora indicates the influence of urban development and environmental factors. Urban habitats often contain many non-native species, revealing ongoing species replacements and invasions. Species turnover in urbanization gradients results from abiotic filters, socio-economic influences, or human dispersal. Understanding native and exotic species dynamics and their coexistence mechanisms is vital for conserving urban biodiversity. Elements of green infrastructure, such as street greenery, parks, green roofs, and façades, are proposed as biodiversity corridors. Richness and compositional variability increase from streets to parks and green roofs. Connectivity assessments indicate larger parks enhance species exchange, while bylaws protecting water bodies improve natural vegetation connectivity. The role of urban green infrastructure in connectivity is debated. Urban structures create unique microhabitats that shape biological assemblages. Life strategies in managed parks evolved over two decades of urbanization in Saskatoon. Street and ornamental vegetation influence ecological differences related to adjacent land uses, with classifications emerging based on street patch size, spacing, and functions. Global urban assemblages show patterns linked to urban functions, exotic species growth, and life-form distributions, with soil seed banks reflecting ongoing changes post-vegetation alterations. (W. Dolan et al., 2017)

3.1. Native versus Exotic Species in Cities

Flora inhabiting cities all over the world is a mixture of native and exotic plant species. The historic introduction of a variety of exotic plants emphasises the notion that urban ecosystems are designed to differ from their surrounding landscapes. Many studies show that exotic species not only occupy vacant ecological niches within the urban systems but also diversify and expand significantly. Various authors address the increase in non-native species and their growing importance to city flora as a research topic. Qualitative investigations increasingly focus on native and exotic species simultaneously and reflect the notion of cohabitating normalisation. These studies claim that native species are replaced by exotic counterparts because of preference for similar traits and environmental characteristics. Though a significant number of exotic plants were introduced to urban habitats, native species are the dominant urban flora across many countries. Exotic species reliance and parallel development between exotic and native plant communities evidently associate to the urbanisation level of a country. (M. et al., 2019)

3.2. Green Infrastructure and Biodiversity Corridors

In many cities, urban green infrastructure and other vegetation connectivity improvements are promoted to enhance community plant species diversity. The prioritization of such measures has been driven by the theory that green infrastructure can act as a biodiversity corridor. Green infrastructure includes parks, gardens, cemeteries, and non-motorised transport routes; yet, the potential of these features in cities where patch size and connectivity are already large remains uncertain. Several habitat quality and species connectivity metrics are evaluated to assess whether urban green infrastructure features, migratory pathways, or habitat quality have more influence on community plant diversity patterns across a city.

In fragmented urban landscapes, modifiable green infrastructure is the corridor class with the highest mean abundance of established non-native plants. Species composition and abundance were analysed across four cities (San Francisco, Barcelona, Vienna, Cape Town) using citizen-science data published via the gallery of urban flora, and linked remotely sensed landcover information. Green infrastructure may have acted as a macro-patch rather than a micro-corridor in the colonisation of San Francisco city centre; non-native Mediterranean taxa were favoured on human-modified surfaces, suggesting that associated island biogeographic theories may have limited applicability (Mantle, 2010).

3.3. Microhabitats and Spatial Heterogeneity in Urban Landscapes

In urban areas dominated by the built environment, plant distribution often depends on the presence of interspaced linear microhabitats such as roads, surfaces, walls, trees, and vegetation patches. On pavements, remnant vegetation survives along sidewalks, chinks between slabs and buildings, potholes and cracks in asphalt, above drainage grilles, and near closed storefronts. Such ruderal flora can harbor native species. In cities where strict bylaws control planted vegetation, naturally colonizing species disperse through channels formed by road curbs. The range of abiotic conditions under pavements—light intensity, water regime, and soil quality—bears resemblance to conditions found in many urban green spaces. Although imposed by human agency, paved patches remain outside parks and gardens, thus incorporating them into green-space inventories would obscure the distinction between habitats actually designed for vegetation and those that merely support spontaneous flora (Peng et al., 2020).

Spatial heterogeneity is the variety of distinct patches and components that together comprise a landscape, influencing ecosystem structure, process, and function (Young et al., 2009). The extent of spatial dissimilarity shapes the species–area relationship governing colonization of urban remnants by species inhabiting adjacent patches. Abandoned urban land and surfaces provide typical microhabitats created by human activity, yet spatial variability is often overlooked because the construction process renders the macrostructure uniform. Local substrate, geometry, and composition of the surrounding built environment dictate patch roughness, abundance, size, spacing, and configuration of potential sites.

4. Physiological and Ecological Adaptations to Urban Conditions

Urban systems impose physiological and ecological stress and therefore disrupt the normal functioning of urban plants. Urbanization alters microclimates by modifying temperature, moisture, wind, and solar radiation. Pavement, buildings, and tree canopies influence temperature, interception of precipitation, and runoff. Urban structures obstruct and redirect wind movement, reducing ventilation and modifying humidity. Urban surfaces absorb, retain, and reradiate heat and alter moisture content urban-generated temperature differences and water scarcity, soil seal, and air pollution) and urban morphology disturb pollination interactions (e.g., fragmentation of plant-pollinator networks) (Pisman et al., 2020).

Global climate change and urbanization contribute to loss of biodiversity, ecosystem degradation, and poor resilience to perturbations and enhance the threat of sustainability to urban systems (M. Winchell et al., 2022). Urban flora provide critical functions in regulating weather, improving air quality, and supporting pollinators (M. et al., 2019). Biodiversity improves resilience to shocks such as extreme climatic events and pest invasions. Climate, landscape, and ecological modelling can help predict ecosystem approaches climate, landscape, and ecological considerations to predict ecosystem assembly, structure, and ecological functions in the Anthropocene.

5. Functional Roles of Urban Flora

Urban vegetation performs multiple functions and provides ecosystem services by regulating soil moisture, pollutant deposition, and microclimate (W. Dolan et al., 2017). Vegetation can also perform important service functions, including flood protection through storm-water retention, cooling to mitigate the urban heat island effect, noise suppression, and recreation. In addition to their physiological adaptations to cope with limited water supplies, urban plant species often possess functional traits (e.g. high leaf dry matter content) that enable the completion of their life cycles more rapidly than non-urban plants. Urban plant diversity is associated with the ecological resilience of urban systems towards disturbances and with shorter recovery trajectories in response to disturbances.

5.1. Ecosystem Services in Built Environments

Green infrastructure, such as trees, parks, and walls, is essential to sustainable, resilient, and healthy urban systems (Milliken, 2018). A straightforward approach to illustrate their numerous co-benefits is to estimate the economic value of certain key ecosystem services. Urban vegetation provides a wide range of economic benefits related to air-quality improvement; temperature-regulation; storm-water management (e.g., flood mitigation and aquifer replenishment); and pollination support (Gundimeda, 2017). Many green-infrastructure projects enable both economic and non-economic co-benefits, simultaneously meeting multiple objectives with the same infrastructure components. Among co-products, urban trees also play a crucial role for health, urban heat island mitigation, or enhancement of nature-based social cohesion. In many cases, community-based food production on private or public rooftops improves storm-water REGULATION, enhances biodiversity, and contributes to better physical, psychological, and nutritional health, while simultaneously fostering social cohesion. Urban morphology, such as fragmentation, density, and biomass variation, influences the to urban ecosystems: a nuanced analysis indicates that connectivity primarily addresses the capacity to link distinct clusters of vegetation or tree cover. In fragmented landscapes, small patches still tend to exhibit high, often previously under-grounded importance.

5.2. Biodiversity and Resilience to Disturbance

Biodiversity sustains urban ecosystem functioning despite disturbances such as extreme temperatures, precipitation events, and invasive species outbreaks. A resilient ecosystem rapidly returns to its prior state after a disturbance, while a fragile one is altered for a prolonged period and requires greater management inputs for restoration (W. Dolan et al., 2017). The rate of return to a former condition after disturbance defines recovery trajectories; rapid return implies moderate disturbance (N Spotswood et al., 2021). Biodiversity maintenance fosters both resilience and rapid recovery, primarily by supporting species functional complementarity.

6. Urban Management and Policy Implications

Urban management, governance, and policy are critical elements influencing urban biodiversity, the configuration of green spaces, and equitable access to nature. Urbanization generally reduces biodiversity by transforming or degrading natural habitats—especially under uncontrolled sprawl. Yet, some cities have maintained or enhanced their urban flora despite significant urban expansion over long time periods. Urban planning policies that incorporate plant diversity as a multiscale objective at the city, neighborhood, and microhabitat levels contribute to our understanding of the interactions between plant diversity and urbanization processes, and they reveal the potential of urban systems to be biodiversity hotspots (W. Dolan et al., 2017).

In the city of Haikou (China), for example, intentionally planned green spaces have been found to preserve species richness across residential areas with different building and population densities. Research institutes contain the highest plant diversity—likely due to the presence of botanical gardens and sustainable landscaping—whereas governmental organizations show the lowest diversity, a reflection of limited green space. Commercial urban functional units, in turn, support slightly more species than industrial areas, which have minimal greenery and consequently very low plant diversity. Integrating additional green space into industrial districts is thus critical for enhancing local biodiversity; convincing stakeholders of the benefits, however, is often a prerequisite for implementation. Urban green spaces provide habitats, food, and shelter, and therefore play an important role in sustaining biodiversity and supporting related ecosystem services. Nonetheless, management practices such as pesticide application, combined with the introduction of nonindigenous species, pose significant threats and curtail positive influences on urban biodiversity (Zhang et al., 2023).

7. Case Studies from Global Cities

Cities worldwide are facing notable changes in environmental conditions due to urbanization. The removal of natural vegetation and the introduction of exotic species significantly alter species diversity, impacting ecosystem sustainability and essential services for humans and wildlife. Vegetation is now crucial in planning sustainable, energy-efficient cities, prompting research into improving bio-ecosystem resilience. Some cities benefit from revitalization strategies for vacant areas, while others establish protected wilderness for complex biodiversity. Preservation efforts involve restoration strategies with both bottom-up and top-down controls. Programs like “Green City, Clean City” and “BiodiverCities” are actively pursued. Multi-purpose vegetation systems in streets, parks, rooftops, and under-walks enhance urban ecology, supporting species survival and increasing greenery. A case study in Haikou, China, explores urban green space patterns using remote sensing and social data, examining the interplay between rapid development and green settlement. Size and habitat variety serve as indicators, revealing that rarer species thrive in urban zones balancing biota and eco-social functions, underscoring the value of multifunctional green spaces. Green infrastructure connects open patches and enhances social-functional signals. Habitat diversity is assessed through a remote-sensing vegetation map, with urban green space complexity measured by metrics such as patch number and shape index. Additionally, Valencia, Spain, is analyzed for biodiversity changes over 120 years. Tree lines, small parks, and irrigated areas near the historical center enhance landscape heterogeneity, supporting a diverse range of flora, while the introduction of alien species in the twentieth century markedly increased biodiversity.

7.1. Case Study A

Urbanization profoundly impacts biodiversity, converting natural systems to impervious surfaces and affecting ecosystem processes and services. Human disturbances and pollutants alter physical, chemical, and biological properties, threatening organism survival. Beyond global species loss and reduced biodiversity from climate change and habitat destruction, cities present unique challenges and selective pressures on biological communities. The specific influences on urban plant diversity and composition differ based on local policies and socio-economic contexts. Global guidelines to safeguard urban biodiversity are in development. India, with 1.4 billion people, is undergoing rapid urbanization, expected to exceed 900 million in urban areas by 2050. The city of Pune, despite its natural surroundings, has witnessed significant urban expansion over 200 square kilometers, diminishing its green cover, which is around 12% on formal properties, while informal areas remain largely unassessed. (W. Dolan et al., 2017)(Zhang et al., 2023)

7.2. Case Study B

The municipality of Madrid, a city of 3.1 million inhabitants in the center of Spain's Iberian Peninsula, has seen considerable increase in vascular plant diversity since 1850, with a higher proportion of exotic species than in other cities (M. et al., 2019). Measures aimed at ameliorating the urban climate and enhancing the city's green-blue structure and greenery connectivity have contributed to changes in the city's floral composition, and various responses have been observed across different groups of species. The increase continues and requires prediction of which species will likely remain in the urban environment and the extent of filtering by ecology. Overall, Madrid's vascular flora has changed since 1850 and, although exotic species remain most abundant, the trend positions it within a biodiversity-extinction scenario.

Urban flora have become an important issue in addressing metropolitan urban heat islands and climate change mitigation. To alleviate and control these problems the Madrid city council developed a specific Plan Verde y Biodiversidad in 2009 to enhance green-blue connectivity and urban have diverse plant species distributed in multiple areas. Responses to management measures adopted under this plan have revealed that urbanisation does not always decrease biodiversity by favouring native or exotic species; indeed, under socio-ecological analysis conditions, native plants can spread even more.

7.3. Case Study C

Indianapolis, the capital of Indiana, USA, experienced significant population growth between 2000 and 2010. Despite this increase, municipal parkland continued to exist within the city limits. Parks and green spaces serve several important functions, but the inherent structural complexity of urban vegetation can also confer benefits. The city and surrounding areas were classified according to the US National Vegetation Classification System, offering a systematic means of assessing floristic changes over time. A comparison between a historical survey (Breene, 1965) and a contemporary (2017) survey, which entailed sampling 253 sites and cataloguing 581 taxa, indicates that the municipal inventory lost 147 taxa but gained 130 during the study period (W. Dolan et al., 2017).

8. Synthesis and Future Directions

Sustainable adaptation to climate change presents a major global challenge, particularly for cities, which are proposed as resilience magnifiers. By 2050, nearly 80% of the global population is expected to inhabit urban areas, increasing vulnerability to extreme events such as heat waves, floods, vector-borne diseases, and social unrest. Cities generate about 70% of greenhouse gas emissions, highlighting their crucial role in climate responses. Urbanization offers opportunities for adopting ecosystem approaches; for instance, urban vegetation can reduce temperatures by an average of 8°C near water bodies and filter air pollutants by up to 82%. Urban botany now explores the interplay between urban landscapes and biodiversity globally, providing insights for various disciplines. Issues like Urban Ecology and Urban Climate are intertwined, reflecting contemporary dynamics. Urban species face unique deterministic filters based on environmental factors such as temperature and moisture. Effective urban governance and management are essential to combat biodiversity loss and environmental degradation. Research must address spatial and temporal aspects of Urban Ecology, focusing on urbanization effects on biodiversity over various time scales. Initial urban expansion often intersects existing bioregions, creating biogeographical filters that influence urban flora assemblages. These ecosystems develop through interactions with native species challenged by urban conditions like pollution and altered water availability, shaped further by global trade and tourism. The interaction of past and present environmental influences results in diverse urban flora assemblages, especially at intermediate and high urbanization levels. (Aronson et al., 2016)(W. Dolan et al., 2017)

9. Conclusion

Urban areas represent an extreme environment and evolutionary laboratory for plants. Urban plant diversity has been solely related to alien plants, while natives appear as collateral damage affected by urban isolation. Instead of limiting urbanization to the introduction to scientific niche, a historical evolutionary sense applied to historical buildings could recast the value of urbanism to an Urban Evolution, the fourth evolutionary force after Natural Selection from the outside and Artificial Selection from the inside of the Natural Environment (M. et al., 2019). Thanks to the improvement of the living environment, native flora has been recolonizing urban distribution fully and not only those destroyed by urbanization; a native plant community network preserved as much as possible could assist both process and urban management (W. Dolan et al., 2017). Reassessing scientific knowledge acquired from the Metro-plant Project on native plant responses to other evolution and eco-evolutionary aspects of abandoned distribution through time of vegetation vacant by Urban Sprawl performed acquisition and management helps step back 130 years before urban formation, ensuring that the original natural environment tangled full of never introduced alien flora could be directly remedied.

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