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22

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22

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Introduction

Urban vegetation harbors abundant plant species and urban wildlife. This chapter explores the ways to manage urban vegetation to preserve and enhance urban biodiversity. Management actions can be taken to conserve plant biodiversity in natural and semi-natural vegetation and cultivated vegetation guided by knowledge of forces driving the vegetation dynamics in urban areas. Urban vegetation can also be managed to support urban wildlife biodiversity. A key lesson from existing projects is that long-term planning and management consistency are necessary to achieve desired results. Furthermore, regular monitoring and assessment should be in place to ensure that vegetation management works for urban biodiversity.

The shaping forces of biodiversity in urban vegetation

Urban vegetation is the total assemblage of plants within and on the perimeter of cities and towns (Carne 1994). Urban vegetation serves multiple functions, including critical habitats for threatened and endangered species (Ives et al. 2016), food and shelter for wildlife species (Hostetler et al. 2011), and ecological structure for producing ecosystem functions (Bolund and Hunhammar 1999). Active management and monitoring are required to maintain these functions. However, urban vegetation management is not a simple task since myriad natural and anthropogenic forces influence urban vegetation (Knapp and Zipperer, this volume). These forces include regional climate and biogeography, human-mediated biotic interchange, urban form and development history, socioeconomic and cultural influences, local human facilitation, and species interactions (Aronson et al. 2014; Williams et al. 2015; Aronson et al. 2016). The interaction effects of these forces shape the composition, abundance, and distribution of plants that form urban vegetation and wildlife that depend on urban vegetation. Management actions based on a sound understanding of those forces can preserve, restore, and increase urban vegetation biodiversity and the wildlife that relies on it.

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Managing urban vegetation for biodiversity

The overall goal and strategies

Urban vegetation management should improve the biodiversity of plants and animals as a system rather than focusing on a particular species. The concept of "Biodiversity quality" (Jalkanen et al. 2020), which evaluates biodiversity comprehensively from the aspects of species richness, biomass, population density, evenness, rarity, support for specialist species, and regional representativeness of the species assemblages in an area, provides an anchoring point for setting up the overall goal. Management strategies include five principal components: (1) implement citywide planning; (2) preserve and restore existing natural and semi-natural vegetation; (3) create an ecological network of corridors; (4) reduce degradation of existing vegetation; and (5) be creative in finding solutions.

First, citywide plans need to incorporate all types of urban nature, including cultivated, and novel habitats that might not be in the focus of classic nature conservation approaches. This plan includes biodiversity-friendly and cost-effective vegetation management in cultivated green spaces such as yards or parks (Friedman 2021; Aronson et al. 2017), for example, by reducing mowing intensity. Beyond, citywide plans should involve various stakeholders and decision-makers to include public and privately owned lands across the metropolitan area. A comprehensive approach to citywide management reduces risks of piecemeal, uncoordinated, and ineffective approaches, particularly for biophysical systems that may occur with local-scale planning (Bush et al. 2020). Tools such as the Institutional Analysis and Development Framework (IAD) can be used to understand the roles of stakeholders in inhibiting or supporting biodiversity conservation in urban vegetation to make better plans (MacKenzie and Gibbons 2019). Nevertheless, it should be noted that having a citywide biodiversity conservation plan itself is meaningless if no savvy political and governance measures exist to enact funding and policies that support the implementation of the plan.

Second, preserving natural or semi-natural vegetation needs to be made a top priority (Friedman 2021). Natural or semi-natural vegetation has a higher biodiversity value than cultivated vegetation (Barrico et al. 2018). They also support a higher diversity of insects, birds, and other wildlife (Müller et al. 2018).

Third, areas occupied by urban vegetation needs to be increased in cities. As a first step, cities should know the amount of existing urban vegetation. Data on vegetation types and extant at fine resolution (<10 m) can be collected through field surveys or interpretation of remotely sensed data. Furthermore, urban vegetation should be connected through a network of corridors that spread across urban-rural landscapes. This network can help decrease the detrimental effects of the small size of many inner-urban vegetation patches on species. It has been found that the impact of patch size and corridors on biodiversity is more important than vegetation structure and local management. Large areas of habitats (>50 ha) are essential for preventing rapid loss of area-sensitive species (Beninde et al. 2015).

Fourth, policies should be created to guide the design and construction of developments to reduce the impact on nearby natural vegetation and enhance the biodiversity of vegetation in developed lands (Hostetler et al. 2011). For example, biodiversity-friendly designing practices such as preserving vegetation on the development sites or using native species in planting should be encouraged.

Finally, the complex socio-ecological processes involved in urban vegetation management demand creative solutions. New ideas should be encouraged, tested, and duplicated if proved effective. Temporary conservation, which aims to maintain a spatiotemporal mosaic of different successional stages ranging from pioneer to pre-forest communities, may help cope with the highly dynamic urban landscapes (Kattwinkel et al. 2011). Another new idea is passive rewilding, that is, to allow for spontaneous ecological processes in urban landscapes, which can potentially reduce management intensity and achieve higher biodiversity in urban vegetation (Müller et al. 2018).

Managing natural and semi-natural vegetation

Natural and semi-natural vegetation include patches of remnant forests and other original vegetation types unaltered or moderately modified by human activities. They harbor higher shares of plant taxa with high conservation and ecological values than vegetation more strongly affected by humans (Barrico et al. 2018; Kowarik and von der Lippe 2018). Spontaneous species are the main components of natural and semi-natural vegetation. These areas also support a higher diversity of invertebrate and bird species than cultivated vegetation (Müller et al. 2018). Consequently, maintaining the structural and functional integrity of natural and semi-natural vegetation should be prioritized in urban vegetation management.

Intensive anthropogenic activities in urban landscapes frequently degrade the structure and function of natural and semi-natural habitats. Restoration is often required to revive the ecological integrity of native habitats (Johnson and Handel 2016). Restoration activities represent a continuum from passive to active management depending on site conditions and management objectives (Mostert et al. 2018). Passive restoration activities emphasize the need to facilitate the spontaneous natural dynamics of vegetation and are generally faster and less costly than active restoration measures (Capotorti et al. 2017). Active restoration requires extensive human interventions. Examples of active restoration methods include 'close-to-nature' silviculture techniques, such as creating small gaps to simulate gap-dynamics (Teobaldelli et al. 2020), restoration of seed sources, ways to enhance functional connectivity for biogeographically representative and ecologically coherent trees (Capotorti et al. 2017), and targeted seeding of native grassland species into urban wasteland sites (Fischer et al. 2013). In their restoration framework, Mostert et al. (2018) consider the extent of invasive species coverage, indigenous vegetation, and other biotic and abiotic factors to prioritize sites for different types of restoration.

No matter which restoration approach is taken, a reference condition or state is often the goal of restoring a habitat. The reference condition is normally the pristine condition of the habitat, a late-successional sere, or some historical condition. However, such conditions are often challenging to reach in urban landscapes because of the altered biophysical environment, landscape configuration, and disturbance regimes (Johnson and Handel 2019). Also, species and communities consistently recover, reassemble, adapt, and evolve in urban environments due to the complex interactions among different influencing factors (Kowarik 2011; McDonald et al. 2016). The urban landscape requires vegetation restoration to take a more dynamic, multidimensional approach than conventional restoration and realize that restored vegetation may not necessarily recover its former state (Johnson and Handel 2019). Recognizing the need to have a reference condition, McNellie et al. (2020) proposed a contemporary reference state framework to set goals and benchmarks for restoration activities in human-altered landscapes. The framework identifies the contemporary "Best-on-Offer" reference state based on a standardized assessment of the social and ecological context, providing a way for policymakers and practitioners to select a reference

state that maximizes conservation and restoration outcomes in contemporary ecosystems (McNellie et al. 2020). Moreover, when actively restoring the urban landscape, consistent management is necessary to achieve desired long-term outcomes such as maintenance of biodiversity and ensuring the structural and functional integrity of resident plant communities. It is unrealistic to expect an urban habitat fragment to quickly reach the original ecological status that took centuries to form (Johnson and Handel 2019).

The managing agency should also pay attention to preventing new damage to natural and semi-natural vegetation in cities. Urban residents frequently use natural and semi-natural vegetation sites for recreation, dumping yard waste and garbage, and excavation (Sharpe et al. 1986). Residents' unregulated use of informal trails in natural and semi-natural vegetation can degrade the vegetation structure (Ballantyne and Pickering 2015). Those activities should be regulated. Residents can be organized to serve as stewards of natural and semi-natural vegetation.

Management of cultivated vegetation

Cultivated vegetation in gardens, lawns, parks, streetscapes, and similar green spaces composes a major component of urban vegetation. Besides generating ecosystem services, which benefit people, cultivated vegetation can be managed to enhance biodiversity in cities. Aronson et al. (2017) point out that managing cultivated vegetation can significantly affect biodiversity in urban landscapes both negatively and positively. For instance, a homogeneous structure of vegetation dominated by lawns was created by homeowners, which at the same time are similar in cities across the globe (Ignatieva et al. 2020). Similarly, many cities focus on managing individual units rather than managing lands collectively for publicly owned green spaces. A high degree of habitat fragmentation and increased spatial heterogeneity potentially create multiple sinks for meta-population dynamics (Aronson et al. 2017). In addition, multiple owners often introduce a high number of non-native species for ornamental and horticultural uses. Nonetheless, private and public land managers can recognize the benefits of coordinating management efforts. For example, coordinated actions have been taken to convert lawns into native gardens (Ignatieva and Hedblom 2018) and enhance corridors between green spaces (Pirnat and Hladnik 2016). Not only do these activities increase native plant species richness in our cities, but they also enhance faunal species such as butterflies and bees (Goddard et al. 2010) and human well-being (Frumkin et al. 2017).

Lawns represent a central component of cultivated vegetation (Ignatieva et al. 2020), and their management can significantly affect biodiversity. For instance, lawns with low use of biocides and limited public access were found to have higher species richness and rarity than intensively managed lawns (Politi Bertoncini et al. 2012). Similarly, reduced mowing frequency could enhance biodiversity, aesthetics, and pollination services (O'Sullivan et al. 2017) but often conflict with local ordinances. Still, cities are starting to recognize the combined benefits of reduced mowing intensity for biodiversity and management costs (e.g. cities cooperating in a national network of biodiversity-oriented municipalities "Kommunen für biologische Vielfalt" in Germany). At the community and city level, with smart planning, large areas of lawns can be set aside for less frequent or no mowing while making the rest of the lawns accessible to the public for recreational use (Ignatieva and Hedblom 2018). Another approach to increase lawn biodiversity value is to create gaps in existing lawns and planting the gaps with seeds or seedlings of native meadow species as applied in Sweden (Mårtensson 2017).

Private gardens also provide considerable opportunities to support urban biodiversity. Private gardens often are planted for their aesthetic and utilitarian values (e.g. edible or medicinal plants), and many of them are exotic species (Clarke et al. 2014; Klepacki and Kujawska 2018). Planting

native species should be encouraged by providing the owners with knowledge of biodiversity and sources for buying native seeds and plants of regional provenance. Doody et al. (2010) showed that residential gardens in Christchurch, New Zealand, can support the regeneration of native woody species from the nearby forest if the owners were given the species' information and control over the planting locations. Similarly, Goddard et al. (2010) report the need for a landscape approach to enhancing biodiversity with green spaces across the metropolitan area.

Urban forestry provides a framework to unify all management activities on cultivated trees and shrubs in urban areas. Management options focusing on increasing biodiversity can be incorporated into all aspects of the urban forest (Alvey 2006). These options include but are not restricted to survey the baseline situation of biodiversity of urban forests, increase the use of native species in tree planting programs, retention of existing trees, create artificial gaps in the old-growth urban forest, and preserve the interconnections between urban and suburban forests (Alvey 2006; Kowarik and von der Lippe 2018; Massad et al. 2019). Cities worldwide are expanding their urban forests, for example, the Million Trees program in New York City had a goal of adding one million new trees in a decade (Onaindia and Fisher 2020). Incorporating a biodiversity dimension into urban forest planning and management at the very beginning is essential.

Wastelands and vacant lots exist in many cities and provide an opportunity to increase biodiversity (Kowarik 2011; Fischer et al. 2013). Both active and passive management options can be employed to maintain or enhance biodiversity objectives on these parcels. For instance, passive management practices that keep extant soils and resident vegetation and allow the sites to develop naturally often lead to novel communities composed of native and non-native species (Kowarik 2011; Zipperer 2002). Over time, the composition of such novel communities can become similar to natural remnants (Kowarik and von der Lippe 2018). Active management may include directly seeding and planting native species. For instance, Kövendi-Jakó et al. (2019) introduced propagules of native grassland into degraded sites in Nyírség, Hungary, to grow communities similar to those of reference grasslands. They observed that within three years, the restored sites were similar to reference sites. Equally important are the social considerations of restoring wastelands and vacant lots. Managers must balance the need for biodiversity and people's perceptions. A vacant lot with a mixture of spontaneous vegetation may be viewed as unmaintained and distracting by residents of one neighborhood, but valued for its educational and ecological benefits by residents in another neighborhood (Ignatieva and Hedblom 2018). An acceptable compromise is not to leave spontaneous vegetation in wastelands and vacant lots unattended but to actively manage it for biodiversity and ecological benefits.

Invasive species management

Urban landscapes are a source and sink for invasive species, and managing these species requires different approaches than used in rural areas (Gaertner et al. 2017). Urban residents may not support the management measures due to the species' utilitarian values (Novoa et al. 2017) or do not perceive invasive plant management as a high priority relative to other environmental problems (Potgieter et al. 2018). A vital element of invasive species management is educating the public on the negative impacts of invasive species on natural communities and the types of management used to control or eradicate targeted species on public and private lands (Novoa et al. 2017). Dearborn and Kark (2010) emphasize that managers must convey the importance of native species and the management of invasive species to create habitats (e.g. using wastelands and vacant lots) for local biodiversity and human well-being. Successful management plans focus not only on the ecological but also the human benefits.

These concerns suggest that invasive species management in urban areas should be based on biological factors, stakeholder views, and the social consequences of management actions (Dearborn and Kark 2010). Based on the social and ecological context, Gaertner et al. (2017) proposed three management approaches: tolerance, active engagement, and control priority. Non-native species that have a low potential for negative ecological impact but can benefit people may be tolerated. In contrast, active control measures should be applied to species with a relatively high potential for negative impact and deliver relatively low benefits. However, rapid actions need to be taken to control an invasive species if there is no adequate information on its impacts and benefits, preferably at the early invasion stage.

Invasive plant species can be removed from urban vegetation using biological control, mechanical removal, and chemical control. The effect of biological control tends to vary among regions. For example, biological control agents, including insects and fungus, have been applied to control common ragweed (*Ambrosia artemisiifolia* L.) in Australia, Russia, China, and some European countries with varying success (Igrc et al. 1995; Gerber et al. 2011; Kovalev et al. 2015). The biological control agents' effectiveness is determined by many factors such as climate, biology of the biological control agents, and interactions between the agents and the host plant species.

The effectiveness of mechanical removal and chemical treatment is more predictable than that of biological control. For instance, Bierzychudek (2020) found that treating *Hedera* spp. on the ground with biocides and cutting the plants' woody stems increased the abundance and the diversity of native herbs and woody seedlings substantially in natural areas in Portland, Oregon. However, adverse effects on biodiversity across taxa are apparent with repeated application of mixtures of biocides (Brittain et al. 2010; Schäfer et al. 2019; Sattler et al. 2020). Weeding was found to control the population of *Impatiens glandulifera* successfully and increased the native species richness in a riparian zone in London (Cockel et al. 2014). In New York, the combined use of mechanical removal, chemical treatment, and native tree planting has resulted in significantly lower invasive species abundance, more complex forest structure, and greater native tree recruitment in native forests in urban parks (Johnson and Handel 2016). Johnson and Handel (2016) found that active planting of native species after removing invasive species enhanced native species and vegetation structure. Consistent management over extended time frames is needed to shape the structure and composition of the plant communities. Adverse effects of treatments, especially the harmful effects of biocides on biodiversity and ecosystems, need to be weighed against the threats posed by invasive species. Those management approaches that have the smallest (or best no) adverse effects on biodiversity should be favored.

Managing urban vegetation for wildlife

Generally, more urban vegetation cover means more habitats for wildlife. Studies have shown a positive association between urban vegetation cover and species richness and abundance of wildlife such as arthropods and birds (Turrini and Knop 2015; Pena et al. 2017). Increasing the overall amount of urban vegetation cover is a viable management objective for biodiversity conservation. However, not all vegetation benefits urban biodiversity to the same extent. Urban vegetation's value to wildlife is affected by its size, origin, structure, species composition, and surrounding environments. These observations should form the basis for designing management actions.

Maintaining natural or semi-natural vegetation should be the priority, and cultivated vegetation only used as a second option to increase urban vegetation (Chong et al. 2014). Large areas of intact connected urban vegetation need to be conserved. Intensive development should be avoided in

adjacent areas to reduce light and noise pollution, or a buffer should be created around the habitat to minimize human activities and intrusions (McDonald et al. 2014).

Creating multiple strata and adding a greater diversity of native plants will increase habitats for a broader range of flora and fauna species in cultivated vegetation (Burgin 2016). For instance, lawns can be mowed less frequently, creating vertical strata, and native meadow species can be added to enhance species richness. Studies have shown that these practices increased diversity for plants, invertebrates, and soil microbes (Norton et al. 2019; Mata et al. 2017). Similarly, in private gardens and vacant lots, non-native ornamental plants that attract pollinators and sustenance-oriented food crops can be planted to support pollinator populations (Lowenstein et al. 2019; O'Connell et al. 2020). Non-native species can serve as essential food sources for pollinators (e.g. white clover, *Trifolium repens*) in private gardens and vacant lots when native species are unavailable. As long as these species are not invasive, they can be crucial for pollinator conservation (Turo et al. 2020; Lowenstein et al. 2019).

Urban forest structure can be improved by increasing species richness through planting native tree species, preserving large-diameter trees, and increasing the complexity of understory vegetation structures (Johnson and Handel 2019). Also, adding features such as standing water and watercourses increase spatial complexity of the urban forest. These practices have been shown to positively impact birds, bats, and invertebrates (Ferenc et al. 2014; Ikin et al. 2015; Archibald et al. 2017; Pena et al. 2017; Threlfall et al. 2017).

Although threatened and endangered species may require special management attention, management, in general, should focus on the overall biodiversity of the urban landscape rather than on a small range of species. The focus on a single species may have unintended consequences, such as the decline in amenities for humans and threatened endemic species (Burgin 2016). For instance, *Grevillea* and *Callistemon* spp. have been widely planted in Australian cities to respond to Birds Australia's call for providing food plants for birds. Although the intended outcome was to enhance bird diversity by providing food, the actions led to establishing honeyeaters in Australian cities, creating an ongoing pest management problem for managers. Smaller-bodied birds were absent when the more aggressive honeyeaters were present (Burgin 2016). A solution to minimizing unintended consequences is to construct ecological species profiles, which enable land managers to manage a wide range of species according to their habitat requirements and disturbance responses simultaneously (Opdam et al. 2001; Garden et al. 2007).

Monitoring and assessment

Survey biodiversity of urban vegetation

Continuous monitoring is essential for managing urban vegetation for biodiversity. While all methods developed for monitoring biodiversity in natural environments can be adapted for use in urban areas, methods considering social and biophysical aspects of urban areas should be preferred. One of these methods is urban biotope mapping, which classifies urban areas into homogeneous habitats based on land use types and biotic and abiotic conditions (Sukopp and Weiler 1988). Urban biotope mapping is conceptually well-structured to meet the demand for maintaining biodiversity in urban areas (Qiu et al. 2010). A similar method, urban habitats biodiversity assessment (UrHBA), provides a standardized way to incorporate habitat information into a spatial data framework. The method includes three steps: interpreting drawings of the main habitat patches, recording the characteristics of those patches, and constructing maps to link with all recorded data

(Farinha-Marques et al. 2017). Detailed information on urban biodiversity can be obtained using the cited approaches. However, applications of those approaches are time-consuming and require considerable resources.

Rapid biodiversity assessment tools such as the one developed by Tzoulas and James (2010) can be deployed to get a quick overview of biodiversity in urban vegetation. These tools are simple to use, and the results are easy to interpret. They are suitable for aiding managers to develop management strategies and to reach out to the public. Nevertheless, they are not suitable for generating data that cover biodiversity in the studied area completely.

Some emerging methods can be adopted to supplement monitoring works based on conventional field surveys. The use of unmanned aerial vehicles (UAV) in urban vegetation monitoring is especially promising. UAV can capture high-resolution optical images of urban vegetation using cameras. The images can be used alone or together with point data captured using airborne LIDAR boarding UAV to extract information on the size, shape, distribution, species composition, and structure of urban vegetation in urban areas (Feng et al. 2015; Egerer et al. 2020; Schiefer et al. 2020). Besides the images captured using UAV, freely available satellite images can also be used in urban vegetation monitoring to increase data availability and efficiency. For example, the Weed Aerial Surveillance Program framework developed in Australia takes a structured approach to integrate multiple remote sensing technologies into urban and peri-urban weed management efforts (Sheffield and Dugdale 2020).

Using apps based on smartphones and tablets to enlist citizen scientists to assist in biodiversity monitoring work is another promising method. Citizen science projects based on apps have been successfully implemented in many cities to monitoring invasive plant species, urban tree populations, and wildlife living in urban vegetation patches (Hawthorne et al. 2015; Roman et al. 2017; Prudic et al. 2018). These projects are a cost-effective way to supplement the monitoring works and an excellent way to engage residents in biodiversity conservation works.

Assess the effectiveness of management measures

Continuous monitoring of an urban management plan provides the data needed for assessing the effectiveness of managing urban vegetation for biodiversity. An assessment program typically contains four major steps: (1) determine the purpose and scale of the assessment, (2) develop an indicator system, (3) conduct the assessment, (4) communicate the result to policymakers and the public. Defining the setting and scales at which urban vegetation is being assessed is the first step. Due to a wide range of social and ecological factors that affect urban vegetation, it is crucial to assess urban management at multiple scales and include the urban residents' perception of biodiversity associated with urban vegetation (Nilon 2011).

A set of suitable indicators are the core of an assessment. Biophysical indicators and indicators of the social-economic systems, such as measures of attitudes and ecosystem benefit indicators, should be included in that indicator system (Bastian et al. 2020). Frameworks are available to guide the cities to select indicators suitable to local conditions. An example is the City biodiversity index (CBI), which was released by the Convention on Biological Diversity in 2010. The 23 indicators of the CBI measure three aspects of urban biodiversity: (1) native biodiversity in the city (e.g. % of natural areas in the city), (2) ecosystem services provided by biodiversity in the city (e.g. regulation of the quantity of water), and (3) governance and management of biodiversity in the city (e.g. budget allocated to biodiversity). CBI serves as a basis for local governments to build their indicator systems and has been successfully applied in cities worldwide (Kohsaka et al. 2013; Uchiyama and Kohsaka this volume). Two indicators worth being included in every set of

indicators are connectivity among vegetation patches (Pirnat and Hladnik 2016) and naturalness (Bastian et al. 2020). They offer critical information on habitat network integrity and the difference between actual vegetation and potential natural vegetation.

After completing the assessment, reporting findings to policymakers and the public is essential. Five principles of reporting should be followed. First, to tailor the results to the target audience. Second, the result must be presented in a clear, transparent, and easy-to-understand manner. Third, confidence in indicator assessments must be clearly communicated. Fourth, to state the progress towards predetermined targets and goals. Finally, co-develop indicators with policymakers can ensure the usefulness of the assessment products (McQuatters-Gollop et al. 2019). Through the assessment and feedback from both the public and decision-makers, managers can adapt their management objectives to address concerns and improve strategies to meet those concerns and potentially new objectives.

Key companion papers

Aronson, M.F.J., et al. 2017. Biodiversity in the city: Key challenges for urban green space management. *Frontiers in Ecology and the Environment* 15:189–196.

Beninde, J., M. Veith, A. Hochkirch. 2015. Biodiversity in cities needs space: A meta-analysis of factors determining intra-urban biodiversity variation. *Ecology Letters* 18(6):581–592.

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