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Review

Ecological restoration and biodiversity-friendly management of urban grasslands – A global review on the current state of knowledge

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ABSTRACT

In the face of the global biodiversity decline, ecological restoration measures to actively enhance urban biodiversity and options for biodiversity-friendly greenspace management are high on the agenda of many governments and city administrations. This review aims to summarize and advance the current knowledge on urban grassland restoration by synthesizing research findings on restoration approaches and biodiversity-friendly management measures globally. Indeed, we found restoration approaches to be generally effective in increasing biodiversity; yet, there were variations in the outcomes due to the difference in soil disturbance methods, management regimes, the set of species introduced to a site, and the specific local setting. Based on the reviewed studies, we formulated recommendations for maximizing restoration success of urban grasslands through: i) creating a network of heterogeneous urban greenspaces and enhancing connectivity between them; ii) maintaining the spontaneous vegetation in vacant lots and wasteland sites that can provide habitats for various invertebrate species; iii) evaluating actual soil conditions, soil seed bank, and seed rain before restoration efforts take place since these seed sources could considerably affect the restoration outcomes, iv) preserving nutrient-poor conditions in urban greenspaces instead of introducing nutrient-rich topsoil; v) shifting to less intensive, biodiversity-friendly management in urban greenspaces by reducing mowing frequency and avoiding the use of chemicals; and vi) utilizing native dry grassland species for climate adaptation without irrigation. We further identified knowledge gaps regarding i) city-scale and regional-scale effects of restoration, ii) effects of interventions on multiple taxa and multiple ecosystem services, iii) restoration in small versus mega-cities, and iv) in the global south. These gaps should be addressed in future studies for making general guidelines for urban grassland restoration broadly applicable.

1. Introduction

Urbanization considerably changes natural ecosystems and affects native biodiversity in several ways. It is one of the major causes of local species extinction and biodiversity loss due to accelerated habitat transformation (Newbold et al., 2015; Sol et al., 2014), though its impact might not always be immediate (Du Toit et al., 2020). Urbanization also strongly alters the abiotic environment, causes habitat loss, and leads to the isolation of natural habitats and populations (Kühn and Klotz, 2006). On the other hand, the number of native plant and animal species in urban areas can be relatively high. For example, in Berlin, Brussels, and Maastricht approximately 50% of the countries' native floral species exist and persist within the cities' limits (Müller, 2010). Urban areas are generally covered by pavement and buildings, while the proportion of vegetated areas ranges from 20% (Palo Alto, USA; Blair and Launer, 1997) to 40% (average total green infrastructure of European capitals; European Environmental Agency, 2023). Urban greenspaces have the potential to serve as ecologically valuable habitats, but many

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anthropogenic factors at various scales (e.g. trampling, air pollution, soil disturbance), and intensive management can strongly influence their species richness (Basta et al., 2016; Fischer et al., 2013b; McKinney, 2008). If these urban stressors are overcome or embedded in innovative management approaches, urban greenspaces might provide suitable habitats for valuable native species in novel ecosystem constellations and for conserving remnants of semi-natural habitats (Hejkal et al., 2017; Kowarik, 2011; Labadessa and Ancillotto, 2023; Planchuelo et al., 2019). Therefore, and in the face of the global biodiversity decline, measures to actively enhance urban biodiversity (i.e., urban ecological restoration) and options for biodiversity-friendly greenspace management are high on the agenda of many governments and city administrations (Klaus and Kiehl, 2021; Xie and Bulkeley, 2020) or supported by local initiatives (Sen and Nagendra, 2022). Such actions are now fostered by the current UN Decade of Restoration on a global level, which deliberately includes urban biodiversity and habitat restoration (www.decadeonrestoration.org).

Settlements are often built in geographically diverse areas, e.g. along rivers, at the meeting points of flatlands and foothills, and in other areas with diverse topography. Diverse environmental patterns, disturbance regimes, and land uses found within cities can support the coexistence of species by providing different ecological niches, which enhances overall urban biodiversity (Bretzel et al., 2016). On the other hand, it has become recently recognised, that not only remnants of natural and semi-natural habitats, but also different types of novel ecosystems contribute to the preservation of endangered biodiversity (e.g. Planchuelo et al., 2020; Soanes and Lentini, 2019). Thus, species assemblages in cities originate from very different starting points – ranging from habitat remnants to highly anthropogenic designed systems (Kowarik, 2011; Alberti and Wang, 2022). By including such variety in distributional patterns, urban biodiversity can provide many different functions and plays an important role by delivering ecosystem services such as temperature regulation, noise reduction, purification of air and water, and pollination. Moreover, urban ecosystems also contribute to the physical and mental health of the residents (Del Toro and Ribbons, 2020; Marselle et al., 2021; Miller and Hobbs, 2002; Schwarz et al., 2017). However, these benefits provided by urban green spaces can be strongly restricted if in poor ecological conditions such as low species richness (Schwarz et al., 2017). Some species may be considered benign or more socially beneficial in urban greenspaces in some contexts – for example when included as ornamentals for their aesthetic value in gardens – while eventually being rather destructive for overall ecosystem functions in other contexts (i.e., as invasive species; Guo et al., 2019; Tallamy et al., 2021).

Amongst different types of vegetation in cities, such as urban forests (Wallace and Clarkson, 2019; Johnson and Handel, 2019), aquatic vegetation (Hamer et al., 2024), wetlands (Boyer and Polasky, 2004), abandoned wastelands (Bonthoux et al., 2014), and urban grasslands (Klaus, 2013), the latter are the globally most widespread ecosystem and an important element of the greenspace network in cities (Ignatieva et al., 2020). Grasslands (i.e., habitats that are dominated by herbs and grasses and that are usually regularly mown or grazed; see Dixon et al., 2014) can be found in a variety of urban land uses such as parks and public gardens, playgrounds, roadsides, airfields, residential areas, private gardens, and wastelands (Deák et al., 2016; Klaus, 2013; Rudolph et al., 2017). Urban grasslands can range from extensively managed tallgrass meadows or steppe remnants to intensively maintained short lawns (Fischer et al., 2020). The biodiversity of urban grasslands is highly dependent on local management strategies, with, on average, a higher diversity of plant and animal species in less intensively managed grasslands (Fischer et al., 2016a). However, studies showed that a large proportion of urban grasslands is quite species poor due to, for example, the use of low-diversity seed mixtures and dispersal limitation (Rudolph et al., 2017). Therefore, several approaches to increase the biodiversity (especially of plants) of urban grasslands have been proposed (Klaus and Kiehl, 2021).

Several restoration approaches have been developed to increase biodiversity in urban grasslands (e.g. Fischer et al., 2013a, 2013b; Norton et al., 2019). In this work, we refer to restoration in a broader sense, as a restorative continuum (see Chazdon et al., 2021), i.e., any measure aiming at restoring biodiversity such as species introduction but also a change in management. This often involves the reintroduction of native species to urban habitats, which would not have been able to establish otherwise due to dispersal limitation or due to habitat degradation caused by urbanization (Planchuelo et al., 2020). Besides large urban grassland areas in parks, also small habitat patches can act as stepping stones (Vega and Küffer, 2021), and the introduction of native wildflowers and a specific biodiversity-oriented management can considerably increase biodiversity even at larger spatial scales (Bretzel et al., 2016). Beside challenging conditions of the abiotic setting in cities and dispersal barriers, grassland restoration in urban contexts also faces several societal challenges that put restoration success at risk. For example, aesthetic and practical viewpoints often prevail to maintain recreational functions of parks and playgrounds to maximize human's benefit from these greenspaces (Fuller et al., 2007). Moreover, restricted financial means of cities and health concerns of the population can challenge urban grassland restoration (Klaus and Kiehl, 2021). These risks of failure make it difficult to secure financial investments for urban grassland restoration, highlighting the need to synthesize and expand our knowledge on interactions between local settings and restoration success to help ameliorate these challenges.

The purpose of this review is therefore to advance the knowledge on urban grassland restoration by synthesizing research findings on restoration approaches and related biodiversity-friendly management measures globally. Using a structured literature search, we focus on the effectiveness and success of different restoration and management practices applied to enhance urban grassland biodiversity. We further summarize the advantages and disadvantages of the different methods depending on the local setting. Based on the reviewed studies, we also identify knowledge gaps to be tackled by future research and practical implications to support future urban grassland restoration projects and biodiversity-friendly grassland management in cities.

2. Methods

We conducted a comprehensive structured literature search in the Web of Science (WoS) that included different combinations of terms referring to urban grassland restoration and management. The search string was divided into three parts, the first included terms referring to the location of the interventions (urban areas), the second part contained keywords that referred to the habitat types (grasslands) and the third part included keywords of the intervention types. Literature search was conducted on April 04, 2023 with the following search string, which we used to search in the abstracts of the articles:

AB = ((*"Urban"* *OR* *"city"* *OR* *"settlement"* *OR* *"town"*) *AND* (*"greenspace"* *OR* *"habitat"* *OR* *"grassland"* *OR* *"lawn"* *OR* *"turf"* *OR* *"meadow"*) *AND* (*restor* OR manag* OR mow* OR graz* OR cut**)).

This search resulted in 3996 unique references. During the selection procedure, we followed the PICO criteria (Higgins and Green, 2011). As the focus of the study was on restoration and biodiversity-friendly management in urban grassland habitats, we set the following criteria for the inclusion of studies.

- **Population**: Studies conducted in urban terrestrial non-woody habitats (grasslands, meadows, lawns) that assessed the abundance, diversity, or occurrence of at least one plant or animal taxon or evaluating the state of the ecosystem (e.g. ecosystem functions or services).

- **Intervention:** Studies assessing the result of active restoration or restorative management or the spontaneous recovery of the studied habitats (passive restoration).
- **Control**: Control was necessary and could be 1) a target state (e.g. a reference area nearby), 2) the starting state (in the case of the continuation of the actual management), 3) one of the applied management combinations, which is different from the starting state, or 4) a conventional management that served as a baseline.
- **Outcome**: Various outcomes were considered, e.g. the abundance or diversity of various taxa, or other characteristics of the restored ecosystem, such as ecosystem functions or services.
- **Study type:** Reviews were excluded to avoid double counting.

When applying these criteria, the body of literature was reduced using a title-based selection of all the 3996 hits and an abstract-level selection of remaining 524 hits (please see the PRISMA chart in Appendix S1).

From the articles that met the inclusion criteria, we extracted the following information: geographical characteristics (country, city, climate, city population), site characteristics (type of studied site, number of studied sites, vegetation condition at start), interventions (site preparation treatments; main intervention; additional treatments), study period, and studied taxa. Interventions included site preparation treatments (e.g. tilling, herbicide application), main interventions (mowing, seeding, planting, and other interventions) and additional treatments (e.g. mulching, irrigation, weed removal, use of fertilizers). In the case of mowing, we extracted the frequency of this treatment. In the case of seeding and planting, we extracted the characteristics of the seed mixtures (species number, origin of species (native vs. non-native), grass:forb ratio, and sowing density. All relevant key findings regarding the interventions were extracted and assembled into an overview table (Appendix 2). Furthermore, papers were screened for enablers and obstacles to urban grassland restoration if these were reported in the publications, as well as specific recommendations related to the studied systems.

Please note that even though we aimed to perform a comprehensive literature review, our search method might have some limitations. It is possible that our search string did not include all synonym terms, and that other relevant papers could have been retrieved from other publication databases. We could not representatively include grey literature in our search due to, for example, the wide diversity in languages given for this type of literature. Although, grey literature can provide important additions to this review, this type of knowledge base is so different from the peer-reviewed publications that it should be evaluated in a separate work in the future. We therefore decided to focus on peer-reviewed literature, also to ensure certain scientific standards regarding the literature-based evidence included in this review.

3. Results and discussion

In this section, we present the results of the literature review starting with (i) the general characteristics of the studies (geographical characteristics, site characteristics, studied taxa) followed by (ii) the detailed assessment of the studied intervention types (site preparation, mowing, seeding, and planting) and their outcomes. Finally, we formulate recommendations based on the findings of the studies reviewed and highlight the most important enablers, obstacles, and knowledge gaps that need to be tackled in the future.

Our study confirmed the possibility to successfully restore biodiversity in urban grasslands (see examples in Fig. 1). We found restoration approaches to be generally effective in increasing plant and animal richness. Yet, there were differences in the outcomes due to soil disturbance, management regimes, the introduced set of target species, and the specific local settings.

Fig. 1. Examples of urban grasslands with native plant species in different greenspaces: A) garden meadow (Zürich, Switzerland), B) vacant lot (Detmold, Germany), C) right-off-way infrastructure (Zürich, Switzerland), D) tallgrass meadow in an urban park (Gödöllő, Hungary), E) mini-meadows in containers (Weesen, Switzerland), and F) roadside verge (Zürich, Switzerland). Photo credits: Valentin H. Klaus (A, B, C, E, F) and Balázs Deák (D).

3.1. General characteristics of the studies

3.1.1. Geographical characteristics

A total of 57 articles were retained using the search criteria. The studies derived originate from the period between 2000 and 2023 (even though the search was not restricted to any temporal period) and an increasing trend can be seen regarding the number of published studies in recent years. Most of the studies were from Europe (33), followed by North America (19), Asia (3), and Australia and Oceania (2) (Fig. 2A).

Most of the identified studies focused on a single city, but in the case of five studies, two or three cities were involved within the same country. Because some studies were carried out in the same city, the 57 included studies involved a total of 47 different cities (Fig. 2A). Climate of these cities was mostly temperate, except for two cities in tropical (Singapore) and subtropical (Miami, U.S.) climate. Studies from temperate climates were mostly from continental (27) and oceanic (26) areas, while one study involved sites with both continental and oceanic climates, and two were from a Mediterranean climate.

More than half of the studies (30) originated from cities with a population between 100,000 and 1,000,000 inhabitants (Fig. 2B). This might be partly because research publications tend to come from larger cities that have a university. However, the number of studies from large metropolitan areas with >1,000,000 inhabitants was also quite low (13).

3.1.2. Types, characteristics, and numbers of restored sites

We categorized the study sites into four categories based on their ownership, management measures and related appearance (short-vs. tall-growing), and the context in which they were established (Fig. 2C). The most frequently studied habitat type was public urban meadow (27 studies, 47.3%), including short-growing lawns that were converted to species-rich meadows by restoration and tall-growing meadows that were subjected to changes in management regimes (Aguilera et al., 2019; Buchholz et al., 2018, 2020; Fischer et al., 2016b; Sattler et al., 2010; Wastian et al., 2016). The studied urban grasslands were in (semi-)public spaces in front of apartment buildings or industrial

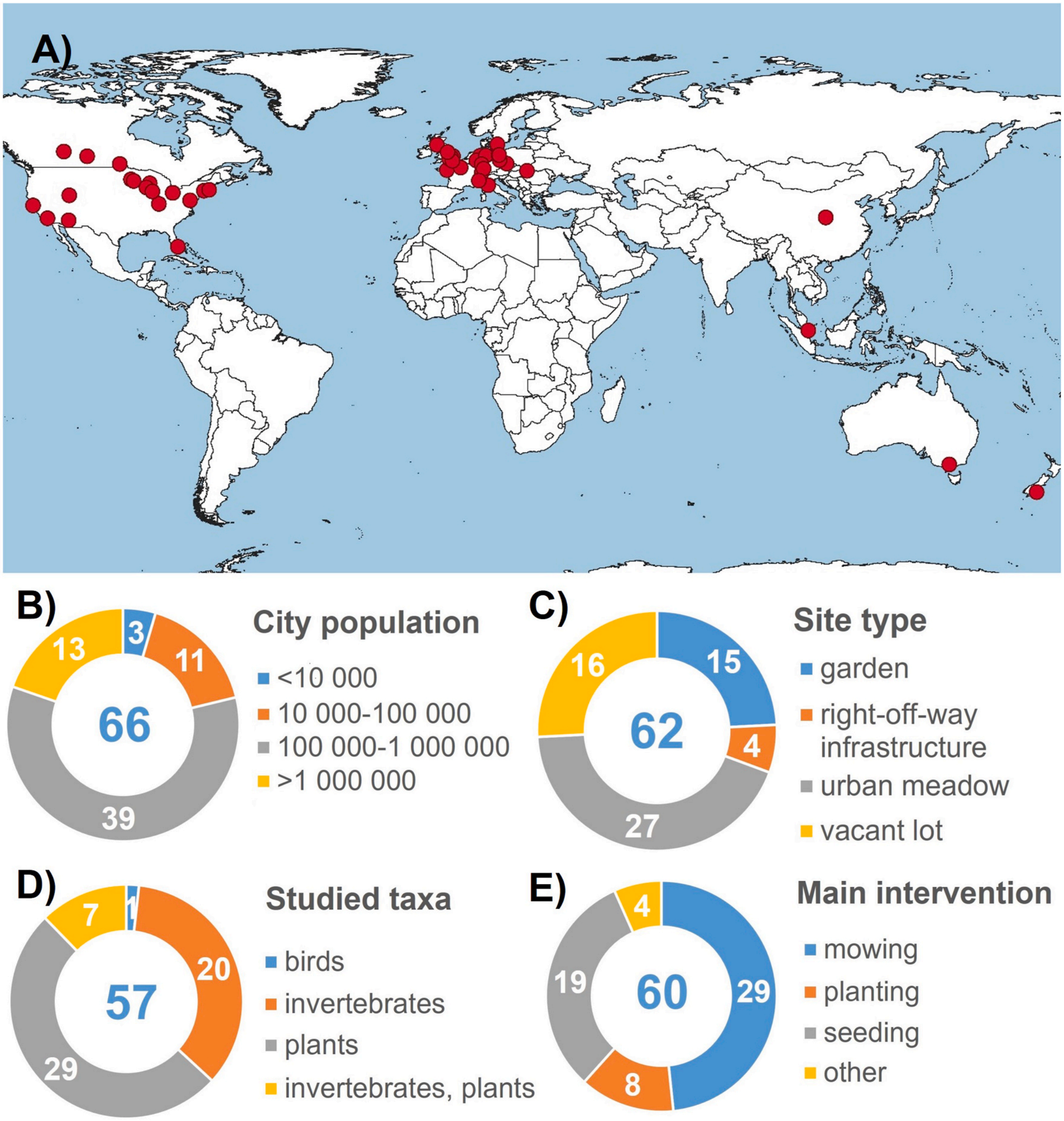

Fig. 2. Distribution and details of the reviewed studies with (A) Locations, (B) Population size, (C) Type of site, (D) Studied taxa, and (E) Intervention type. Note that also in case intervention types were applied together, such as mowing plus seeding, these were counted separately, so the total may exceed 100% or 57 studies included.

buildings, or they were typical amenity grasslands in traditional parks, which are public and maintained generally by the city, mainly for aesthetic reasons, or used for sport and leisure activities (e.g., Aguilera et al., 2019; Garbuzov et al., 2015; Helden et al., 2018; Hoyle et al., 2018; Hwang et al., 2017; Lonati et al., 2017; Norton et al., 2019; Rudolph et al., 2017). The high proportion of meadows managed by the cities underline the key role of city administrations in restoration and biodiversity-friendly management of urban grasslands, while also smaller, private patches need to be included in urban habitat networks for grassland species (Hejkal et al., 2017).

Fewer studies (15 studies, 27.3%) examined gardens and yards, such as private gardens or backyards (van Heezik et al., 2016; Lerman et al., 2018), and university experimental gardens (Hall and Zedler, 2010; Hitchmough, 2000; Lane et al., 2019; Smith and Fellowes, 2015). King's College in the UK drew considerable public attention when they converted their iconic lawn into a biodiverse meadow (see Marshall et al., 2023), helping to increase public awareness of biodiversity-friendly grassland management in urban contexts. Private gardens were previously shown to be highly suitable to support urban biodiversity and are appropriate greenspace types for ecological research since they cover large areas in cities (Thompson et al., 2004). Furthermore, it is possible to follow their altered management through involving the public into research and shaping the lawn mowing habits of garden owners (Del Toro and Ribbons, 2020; Lerman et al., 2018).

Vacant lots were investigated in sixteen studies. These are basically abandoned residential or industrial areas or wastelands, and widespread mainly in post-industrial cities that have gone through a depopulation process in the past (Newman et al., 2016). Ruderal grasslands in vacant lots developed mainly due to the abandonment or demolishment of built structures in shrinking cities (Fischer et al., 2013b, 2016b; Köppler et al., 2014; Schröder and Kiehl, 2020). They provide new open spaces and represent a novel ecosystem type characterized by heavily altered site conditions and the presence of alien species (Kowarik, 2011). Such sites have become common targets for urban greening and restoration to make use of the sometimes vast spatial potential or urban planning approaches that aim to re-vitalize areas by greening (Heckert and Mennis, 2012). Yet, even without restoration interventions wasteland sites might already serve as valuable habitats for several organisms and provide many ecosystem services (Anderson and Minor, 2020; Mathy et al., 2015; Washbourne et al., 2020), but usually need some regular management to avoid being overgrown by woody species. Grasslands around factories and in other industrial areas (Kövendi-Jakó et al., 2019; Sattler et al., 2010) were also characterized by a heavily disturbed environment including altered soils that may impact the success of species that are usually used for restoration.

Four studies surveyed grasslands along right-off-way infrastructure, such as roadsides (Mody et al., 2020), roundabouts (Helden and Leather, 2004), and power transmission lines (Leston and Koper, 2016, 2017). These types of linear infrastructures can provide essential habitat for threatened species. In their analysis, Soanes and Lentini (2019) found that there are 39 threatened species in Australia restricted to urban areas, and the largest number of them occur on roadsides.

In regard to study design, altogether 27 studies (47.3%) examined 1–10 sites, but the majority of these involved only 1–3 sites (19 studies) and fewer involved 4–10 sites (8 studies). When only one site was studied, it was mostly a large area containing several sampling blocks or plots (Bretzel et al., 2009; Hoyle et al., 2018; Kövendi-Jakó et al., 2019). There were 19 studies (33.3%) investigating 11–50 sites and 11 studies (19.3 %) with more than 50 sites each. One of these even involved 174 private gardens from seven cities in the United States (Wheeler et al., 2017). The second highest number of sampling sites was from a study conducted in Paris, where 100 urban lawns were surveyed (Bertoncini et al., 2012).

3.1.3. Studied taxa

Most of the studies (36 studies, 63.2%) surveyed plants, followed by different invertebrate taxa (27 studies, 47.4%), and only one study investigated grassland specialist birds (Fig. 2D). In these numbers there are seven studies included that investigated both plants and invertebrates (e.g. Del Toro and Ribbons, 2020; Sexton et al., 2023; Yang et al., 2019).

Most of the studies where the targeted group was plants surveyed the whole vegetation via vegetation records, and three studies surveyed populations of one focal plant species in differently managed urban grasslands (Esparrago and Kricsfalusy, 2015; Niederer et al., 2014; Sexton et al., 2023).

Studies that surveyed the broadest spectrum of animals investigated multiple arthropod taxa and/or snails (Helden et al., 2018; Hoyle et al., 2018; Mody et al., 2020; Norton et al., 2019; Perry et al., 2021), or various insect groups (Garbuzov et al., 2015; Smith et al., 2015; Wintergerst et al., 2021). Some studies surveyed only one group of arthropods such as bees (Buchholz et al., 2020; Fischer et al., 2016b; Lerman et al., 2018; Turo et al., 2021), butterflies (Lange-Kabitz et al., 2021; Leston and Koper, 2016), spiders (Burkman and Gardiner, 2015; Delgado de la Flor et al., 2020), or lady beetles (Parker et al., 2020), suggesting that more multi-taxa studies are needed to comprehensively assess the effects of urban grassland restoration on faunal biodiversity.

3.2. Interventions: types and key findings

Most of the studies tested the effects of different mowing regimes (29), seeding (19), planting (8), and various combinations of these interventions (Fig. 2E). Other treatments investigated were the use of pesticides (Wheeler et al., 2017), invasive plant removal with harvesting and herbicide use (Hall and Zedler, 2010), and burning (Esparrago and Kricsfalusy, 2015; Farrar et al., 2020).

3.2.1. Site preparation

Various site preparation techniques were used to eliminate vegetation or to reduce weed coverage to create open surfaces for seeding and planting. These site preparation techniques involved tilling (Köppler et al., 2014; Rojas et al., 2022), rototilling (Lane et al., 2019; Schmithals and Kühn, 2017), and herbicide application (Lane et al., 2019; Leston and Koper, 2016; Parker et al., 2020; Rojas et al., 2022; Smith and Fellowes, 2015). In total, there were 12 (21.1%) studies where bare ground was the initial state of the experimental sites, mainly due to previous construction work (e.g. Hoyle et al., 2018; Schröder and Kiehl, 2020; Smith et al., 2015). In the case of 42 studies (73.7%), the starting condition was vegetated sites (e.g. Bertoncini et al., 2012; Garbuzov et al., 2015; Wintergerst et al., 2021).

3.2.2. Mowing

Studies dealing with mowing (29) mostly tested the effects of different mowing regimes without additional treatments (18) or in combination with other interventions (11), such as herbicide application (Helden and Leather, 2004; Leston and Koper, 2016), fertilizer and pesticide use (herbicides, fungicides and/or insecticides; Bertoncini et al., 2012), or hay-making (Leston and Koper, 2016, 2017). The reviewed studies tested various mowing frequencies (**Table 1**), and there was one study investigating 21 different mowing regimes (Sattler et al., 2010). In the case of two studies, mowing effects were compared in previously restored and previously not restored sites (Buchholz et al., 2020; Fischer et al., 2016b). Two studies compared the effects of mowing and grazing (Lange-Kabitz et al., 2021; Rudolph et al., 2017).

Out of the 29 studies investigating mowing, 23 found that the reduction of mowing frequency had a positive effect on the diversity and/or on the abundance of the target species (Buchholz et al., 2018; Burkman and Gardiner, 2015; Helden and Leather, 2004; Horák et al., 2022), while other studies found no effect or a taxon-dependent effect (5), or a positive effect of increased mowing frequency (1) (**Table 1**). The effect of mowing frequency was influenced by the habitat type studied: In public urban grasslands, the reduction of mowing frequency

Table 1
Details of the mowing regimes in the 18 studies evaluating the effect of mowing frequencies (without additional treatments) on the abundance or diversity of certain taxa. The “best treatment” describes the strongest increase in diversity while the “worst treatment” showed the smallest increase, the (undesirable) baseline or even a decrease in diversity.

Reference	Country	Number of mowing frequencies tested	Studied mowing frequencies	Best treatment	Worst treatment	Habitat type	Target
Sehrt et al. (2020)	Germany	2	mowing 6–12 times a year; mowing once or twice a year	mowing once or twice a year	mowing 6–12 times a year	meadow	vascular plant richness
Chollet et al. (2018)	France	2	mowing 15–20 times a year; mowing 7–9 times a year; mowing once a year	mowing once a year	mowing 15–20 times a year	meadow	vascular plant richness
Lonati et al., 2017	Italy	3	1 mowing per year; 4 mowing per year; 8 mowing per year	4 mowing per year	1 mowing per year	meadow	vascular plant richness
Hwang et al., 2017	Singapore	1	abandonment of grasslands which were previously mown 2 times a month	no mowing	mowing 2 times a month	meadow	vascular plant richness
Wintergerst et al. (2021)	Germany	2	mowing 0–3 times a year; 4–5 times a year	mowing 0–3 times a year	mowing 4–5 times a year	meadow	vascular plant and arthropod richness
Garbuzov et al. (2015)	United Kingdom	4	regular mowing every 2 weeks; regular mowing until 5 July (afterwards no mowing); regular mowing until 2 June (afterwards no mowing); no mowing since the previous year; mowing every 2 weeks	no mowing since the previous year	regular mowing every 2 weeks	meadow	vascular plants, flower-visiting insects
Del Toro and Ribbons (2020)	United States	2	no mowing; mowing every 5–7 days	no mowing	mowing every 5–7 days	garden, meadow	vascular plants, bees
Wastian et al. (2016)	Germany	2	mowing 12 times a year; mowing 2 times a year	mowing 2 times a year	mowing 12 times a year	meadow	wild bees
Buchholz et al. (2018)	Germany	2	mowing once a year; less than once a year	mowing less than once a year	mowing once a year	meadow	spiders
Horák et al. (2022)	Czech Republic	3	no mowing; mowing only once a year; mowing 2 or more times a year	mowing in mosaic, or only once a year	more than 1 mowing per season	meadow	butterflies
Aguilera et al. (2019)	Sweden	3	irregular mowing (abandoned); mowing once or twice a year; intensive mowing (not specified)	irregular mowing	intensive mowing	meadow	butterflies
Lerman et al. (2018)	United States	3	mowing every week; mowing every 2 weeks; mowing every 3 weeks	mowing every 2 weeks (bee species richness), mowing every 3 weeks (bee abundance)	mowing every week (bee species richness), mowing every 2 weeks (bee abundance)	garden	bees
Sattler et al. (2010)	Switzerland	21	mowing 0–20 times a year	1-6 cuts a year	7-20 cuts a year	garden, meadow, industrial site	arthropods
Helden et al. (2018)	United Kingdom	3	mowing every 7–14 days; once a year	mowing once a year	mowing every 7–14 days	right-off-way infrastructure	arthropods
	ConclusionI: Reduction of mowing frequency is recommended.						
Perry et al., 2021	United States	2	monthly mowing from April to September; mowing once a year	monthly mowing	mowing once a year	vacant lot	vascular plants, soil invertebrates
	ConclusionII: Increase of mowing frequency is recommended.						
Anderson and Minor (2020)	United States	2	intensive mowing; infrequent mowing (not specified)	no effect of treatment	no effect of treatment	vacant lot	vascular plant richness
Thompson et al. (2004)	United Kingdom	2	mowing twice per week; once per month	no effect of treatment	no effect of treatment	garden	vascular plant richness
van Heezik et al. (2016)	New Zealand	2	mowing; no mowing	no effect of treatment	no effect of treatment	garden	beetles
	ConclusionIII: No clear trend regarding mowing frequency.						

always resulted in increased abundance or diversity of the target taxa. Usually, the reduction of mowing frequency to an intermediate level (Lonati et al., 2017) was the most suitable restorative management, especially compared to very frequently cut amenity lawns (Sehrt et al., 2020). This can be explained by the intermediate disturbance hypothesis: disturbance regimes affect biodiversity along a unimodal curve and the highest diversity is maintained under medium disturbance regimes, i.e., at an intermediate mowing frequency (Connell, 1978; Deák et al., 2016). Note that the mowing frequencies applied in urban grasslands, especially lawns, are considerably higher compared to other types of semi-natural grasslands managed for an agricultural purpose. While in European agricultural grasslands, the mowing frequency usually varies between less than once a year to four times per year (Tälle et al., 2018), in the reviewed studies, the maximum mowing frequency was up to twenty times per year. This shows that urban grasslands are often much more intensively managed than other types of semi-natural grasslands, and the most biodiversity-friendly ‘intermediate’ mowing regime can be considered an extensive management in an urban setting. Decreasing the very high mowing frequencies has been shown to be beneficial for grassland biodiversity since it allows plant species to complete their reproductive cycle and provides a more complex vegetation structure providing feeding, resting, and reproductive possibilities for various animal taxa (Del Toro and Ribbons, 2020). However, it should also be considered, that the complete cessation of mowing also leads to a decline in biodiversity since in temperate climates the existence of grasslands depends on regular management to prevent woody encroachment.

Three studies found that no mowing of grasslands, which were previously frequently mown was the best management type for increasing the species richness of plants and flower-visiting insects (Del Toro and Ribbons, 2020; Garbuzov et al., 2015; Hwang et al., 2017) in the short term (1–3 years). Hwang et al. (2017) recommended no mowing as a rewilding management for increasing plant species richness in a tropical city (Singapore). However, eliminating mowing will not maintain grassland vegetation in the long run where growth of woody species is generally possible. It is therefore important to consider the potential natural vegetation in the certain regions (Somodi et al., 2021), and in areas with high forest potentiality, biomass removal is necessary to avoid woody encroachment.

One study conducted in vacant lots found that a more frequent mowing regime could be more appropriate for maintaining a diverse community of flower-visiting insects as it resulted in greater biomass and blossoms of spontaneous forbs (Perry et al., 2021). Two studies found that the surveyed species showed multidirectional responses to the effects of different mowing regimes suggesting the importance of mosaic mowing and maintenance of more frequently and rarely mown patches (Fischer et al., 2016b; Leston and Koper, 2017); and in three cases there was no detectable effect of mowing intensity (Anderson and Minor, 2020; Thompson et al., 2004; van Heezik et al., 2016).

3.2.3. *Seeding*

We found 19 studies focusing on the effects of seeding. In most of these studies, there were several alternative treatments applied besides seeding, such as hay transfer (Fischer et al., 2013a; Kövendi-Jakó et al., 2019), various mulching methods (Jiang and Hitchmough, 2022; Kövendi-Jakó et al., 2019; Mårtensson, 2017; Wang et al., 2017), and seeding together with mycorrhizal inoculation (Fischer et al., 2013a, 2013b). Out of the 19 studies dealing with seeding, 13 used only native species for restoration, while six used non-native species as well. Characteristics of the seed mixtures are shown in Appendix 3. These studies assessed one to nine types of seed mixtures, and the mixtures were composed of 1–46 species. Regional seed mixtures originating from the production of locally sourced ecotypes were used in four studies, native seeds from commercial source in six studies, and in the remaining nine cases the origin of the seeds was not specified. Decisions on the provenance of plant material – whether seeds from distant regions can be used for restoration when local sources are not available – are important bottlenecks in many grassland restoration projects (Török et al., 2024), and can be especially challenging in urban settings. In landscapes heavily modified by anthropogenic land transformation not only the availability of regionally grown propagules of native plant species can be limiting, but the pristine reference state of the ecosystems, i.e., reference grasslands are also lacking (Reyes-Aldana, 2024). This makes it difficult to reconstruct the regional species pool and choose the most suitable species for restoration.

The studies on seeding often used complex study designs and multiple indicators of restoration success, but some general conclusions on the effectiveness of various seed mixtures can be drawn. Low-diversity native seed mixtures were similarly effective as high-diversity seed mixtures in reducing the abundance of woody and invasive species (Schröder and Kiehl, 2020). However, sowing of high-diversity mixtures was recommended for increasing plant and invertebrate species richness (Jiang and Hitchmough, 2022; Norton et al., 2019). Native seed mixes were more effective than mixes that also included non-native species in terms of higher numbers of germinated seeds and established species (Bretzel et al., 2012). The reason is likely that properly selected native species from the regional species pool of grasslands are better adapted to the local environmental conditions (e.g., climatic and soil conditions) and are thus able to become established more effectively than non-native (ornamental) species (Borowy and Swan, 2022). Seeding with native species provided more suitable habitat for native arthropods, compared to commercial non-native herbaceous (for bees and wasps, Turo and Gardiner, 2021) or woody (for multiple arthropod taxa, Mody et al., 2020) urban vegetation. However, the spontaneously established ruderal vegetation can be similarly beneficial for several arthropod groups compared to sites seeded with native species, which was observed e.g. for native lady beetles (Parker et al., 2020) or bees (Turo et al., 2021). Studies comparing hay transfer with seeding found that seeding was a more successful method in terms of target species establishment and similarity of the newly created plant communities to the reference sites (Fischer et al., 2013a; Kövendi-Jakó et al., 2019).

3.2.4. *Planting*

Among the eight studies employing planting, there were two that combined planting with different soil amendment and mulching treatments (Schmithals and Kühn, 2017; Rojas et al., 2022). These studies found that the establishment of planted species were less successful on gravel mulch than on bare topsoil since the mulch layer inhibited germination (Schmithals and Kühn, 2017). Moreover, soil amendment with compost was more successful than no compost addition in supporting the establishment of native forbs (Rojas et al., 2022).

Three studies examined planting together with seeding (Anderson and Minor, 2020; Hitchmough, 2000; Mody et al., 2020). Three studies used only native species (Mody et al., 2020; Rojas et al., 2022; Smith et al., 2015), three used both native and non-native plants (Köppler et al., 2014; Smith and Fellowes, 2015), and in two studies only non-native species were planted (Hitchmough, 2000; Schmithals and Kühn, 2017). Planting of native species was more successful when comparing it with the planting of non-native species due to very low seedling survival rate of the latter (Köppler et al., 2014). Native species proved to be better suited climatically and performed better regarding floral productivity, visibility, and variety than non-natives (Smith and Fellowes, 2015). Two studies examined grass-free lawns of planted species and found that the number of adult insects was greater on native species than on classical lawn or non-native species (Smith et al., 2015). Furthermore, native species provided the greatest floral performance (Smith and Fellowes, 2015).

3.3. *Recommendations for urban grassland restoration and biodiversity-friendly management*

The reviewed studies provided information regarding other aspects linked to the successful restoration and biodiversity-positive management of urban grasslands. These cover various aspects, ranging from spatial arrangement of sites to soils, and can be helpful for planning future restoration projects in urban settings.

3.3.1. *Planning urban grasslands: habitat networks, size, and other factors*

At larger spatial scales and at a conceptual level, it is recommended to create a network of heterogeneous urban greenspaces and to establish functional connections between them by designing habitat corridors (Ancillotto et al., 2024; Buchholz et al., 2020; Kirk et al., 2023; Lynch, 2019) that can upscale the local positive effects of habitat restoration to larger spatial scales (Tarabon et al., 2020, 2021). Planning heterogeneous habitats means supporting the development of both different types of grassland ecosystems (e.g. dry vs. mesic grassland spaces) and enforcing different levels of public accessibility. Bertoncini et al. (2012) recommends designating areas for public access, taking into consideration potential losses due to trampling and compaction, while restricting access to other spaces to protect biodiverse urban nature. Maintaining and accepting the spontaneously recovering vegetation in wastelands, vacant lots, and other unused areas can also contribute to increase the area of urban greenspaces more generally, and provide potential habitats or feeding sites for various invertebrate species specifically (Buchholz et al., 2018; Parker et al., 2020; Turo et al., 2021). There is furthermore a need for developing guidelines for the management of greenspaces in vacant lots, considering both social and ecological needs and benefits (Anderson and Minor, 2020).

3.3.2. Soil preparation

When designing urban greenspaces or planning urban restoration actions, one important aspect is to consider soil quality and options to improve it (Rudolph et al., 2017). Due to long-term disturbance, urban soils often exhibit altered physical, chemical, and biological characteristics in comparison to local non-urbanized soils. Urban soils are often characterized by a compacted structure, low water availability, low activity of soil organisms and elevated heavy metal concentrations (Pavao-Zuckerman, 2008). Thus, it is useful to evaluate soil conditions, the soil seed bank, and potential incoming seed rain before planning restoration measures since these could considerably affect the outcomes of restoration. In general, nutrient-poor conditions should be preserved in urban greenspaces instead of the direct introduction of nutrient-rich topsoil that is still a common practice (Schröder and Kiehl, 2020). One costly method for lowering nutrient content (especially phosphorous) in urban soils is the removal of topsoil; however, liming of acidic soils could be a more feasible and cost-effective alternative to reduce phosphorus availability (Kiehl et al., 2010). According to Rojas et al. (2022) soil amendment with compost had a positive impact on the restoration of planted native forbs, but at the same time it increased weed cover. Thus, the authors suggested the use of compost in soils with very low nutrient and organic matter content combined with appropriate weed management. The nutrient content of soils could affect several aspects of the restoration, e.g. on less fertile soil or in sites with lower chance of weed encroachment. Here, lower sowing rates can be more cost-effective than higher sowing rates (Jiang and Hitchmough, 2022). Hence, lower sowing rates on less productive sites can be recommended when there is no urgent pressure for the rapid creation of dense species-rich meadows, considerably reducing restoration costs.

3.3.3. Suggestions for low-intensity and cost-effective urban greenspace management

Eliminating fertilizer and chemical applications in urban grasslands is critical to increase biodiversity (Wheeler et al., 2017; Yang et al., 2019). This has the added benefit of reducing management costs, which can be advantageous from a financial perspective and can therefore convince city councils to take action (Mody et al., 2020; Watson et al., 2020). For example, cost-intensive pruning of hedges of non-native species along streets can be eventually replaced by native herbaceous vegetation, an urban grassland type that is mown only once or twice a year when soil fertility is low (Mody et al., 2020). Regarding climate change, species selection for urban restorations should consider future extreme environmental conditions (Schröder and Kiehl, 2020). Thus, further low-cost maintenance schemes include the maintenance of urban vegetation with considerably less irrigation or no irrigation at all, and by using native drought-tolerant grassland species that can also have a great ornamental value (e.g. in Central Europe, Köppler et al., 2014). Using regional seed material could support the adaptation of urban habitats by introducing native species suitable for local climatic and soil conditions (Fischer et al., 2013a; Lane et al., 2019). However, only a small portion of the reviewed studies could apply this method, mainly due to the lack of regionally available native seed stocks. Building regional initiatives to bolster native seed production and availability for urban biodiversity work would be tremendously beneficial to the genetic diversity and long-term resilience of grassland habitats in cities.

According to most of the reviewed studies, one of the simplest and cheapest options to increase biodiversity in urban greenspaces is to reduce maintenance costs via the reduction of mowing frequency (Lerman et al., 2018; Sehrt et al., 2020; Turo et al., 2021), but several studies suggest the importance of diversification, i.e., the maintenance of a diverse range of habitats and mowing regimes which are beneficial for different taxa (Chollet et al., 2018; Fischer et al., 2016b; Helden and Leather, 2004; Lange-Kabitz et al., 2021; Norton et al., 2019). This could be achieved by rotational management, which means establishing areas being mown at different times and with different frequencies (Buchholz et al., 2018). Potentially, some areas could temporarily be abandoned, especially to serve reproduction and hibernation of arthropods (Horák et al., 2022). Such a diversified approach also allows maintenance of short-grass lawns in intensively used areas (e.g. sport ground, resting areas). Yet, in places not used intensively by the public, urban meadows could be created by reduced mowing frequency, preferably mowing maximum once a year in dry and/or nutrient poor conditions (Chollet et al., 2018). The number of mowing events could be chosen according to the soil nutrient content. One mowing per year is only suitable on very nutrient poor soils, while in places of elevated nutrient availability two to three cuts are required to maintain plant community composition in a temperate climate (Wintergerst et al., 2021). Also, it is recommended to leave the cut vegetation for a few days and harvest it as hay (Wintergerst et al., 2021), and to delay mowing of some areas from spring to summer (Chollet et al., 2018). From the stakeholder viewpoint, both reduced mowing and elimination of chemical/fertilizer applications can be very beneficial options to considerably reduce maintenance-related costs (Klaus and Kiehl, 2021).

3.4. Obstacles to urban grassland restoration

There were several practical obstacles influencing feasibility, target species establishment, and public attitudes towards urban grasslands reported in the reviewed studies. For example, tilling urban soils is often difficult due to the prevalence of buried rubble, requiring machinery that can handle high stone or brick content of the soil (Fischer et al., 2013a). In many urban sites, predominantly nutrient-poor and acidic soil conditions hamper the establishment of several species (Schröder and Kiehl, 2020). In contrast, in more nutrient-rich sites, competition by sown grasses or resident weeds can be another limiting factor for target plants (Norton et al., 2019; Schröder and Kiehl, 2020). Weed encroachment has also been an obstacle in some experiments, especially on bare soil or after soil treatment (Rojas et al., 2022; Turo and Gardiner, 2021).

Several widely applied restoration and management measures, such as grazing or prescribed burning are especially difficult to implement in an urban context (Niederer et al., 2014). Privately owned greenspaces constitute a large part of urban habitat networks; however, maintaining spontaneously established or restored vegetation in these areas, especially on the long term, is often difficult and negotiating and planning management actions involves various conflicts with the owners and other stakeholders (Aguilera et al., 2019). This makes large-scale, city-level planning of green habitat networks challenging.

One very important factor in the creation and maintenance of urban habitats is public attitude (Fischer et al., 2020) since it could have a major effect on the acceptance of urban restoration projects. When designing greening policies, it is important to take into consideration the perceptions of the citizens to avoid conflict and on the other hand to ensure long-term ecological benefits. Public perception mostly depends on the appearance and usability of greenspaces, which can be individual and value-dependent (Hoyle et al., 2017; Lampinen et al., 2021; Southon et al., 2017). It may be challenging to change management and transform large areas such as in traditional parks to semi-natural habitats, as urban greenspaces are often used for various human activities that require more intensive maintenance. A solution for keeping a traditional park appearance while enhancing urban biodiversity could be the creation of diverse patches with native wildflower species or urban meadows, that also support flower-visiting insects and increase the potential for citizens to observe different faunal species (Threlfall et al., 2017). Another possibility to support biodiversity and enable sport and leisure activities at the same time is to create short grasslands comprising of short-growing native herb species instead of frequently cut species-poor lawns dominated by grasses rather than herbs (Smith and Fellowes, 2015). In places where the greenspace is not primarily used for sports or other human activities, tall grasslands are biodiversity-friendly alternative to lawns but may be perceived as visually unattractive by parts of the public (Fischer et al., 2020). To enhance their aesthetic value and acceptance, native species could be used together with some ornamental non-invasive exotics (Mody et al., 2020), while the joint presence of annuals and perennials can also make the plant community more attractive throughout the year (Bretzel et al., 2012). When designing urban meadows, landscape features such as well-maintained pathways and mown borders are very important for enhancing public acceptance (Farrar et al., 2020). Moreover, intensive information campaigns and a coalition with local community members are definitively important for designing widely accepted urban greenspaces (Klaus and Kiehl, 2021). Frequent consultation and involvement of the public would therefore promote the acceptance of biodiversity-friendly management practices and facilitate positive attitudes toward urban restoration projects and may also inspire ecological improvements in private gardens (Soanes and Lentini, 2019).

3.5. Knowledge gaps in urban grassland restoration

Our review showed that there are still several knowledge gaps that challenge making general guidelines for broadly applicable urban grassland restoration. There are very few studies on large-scale (e.g. city-scale, regional-scale) effects of urban grassland restoration projects, although such studies would be especially needed to address knowledge gaps related to city-level urban greenspace design and management at a more conceptual level. Also, comparative studies using the same design in cities with different local settings, climates, neighborhoods, and landscaping practices are urgently needed to better understand the (interacting) influence of local and regional factors on the restoration interventions to establish general guidelines for urban greenspace restoration and management (Lerman et al., 2018).

Despite our robust research design, the studies retrieved for review were partially biased in terms of methods and origin. For example, almost no study assessed the effects of urban grazing management on grassland biodiversity – most likely as such projects are still rare or may lack a standard monitoring scheme. Moreover, future studies should investigate urban areas in currently understudied regions, such as Africa and Asia, from where there were no or only a few studies. The lack of studies in certain regions suggests that in those areas where only few or no analogue habitats occur outside of cities, lawns are still the type of grassland that is maintained. Similarly, we found smaller sized cities and the largest metropolitan areas to be understudied, meaning these should also be included more often in future studies.

Most of the reviewed studies utilized short-term monitoring, and there are important knowledge gaps related to the feasibility of the methods and sustainability of the results. Further studies are therefore needed to evaluate long-term effects of altered lawn management practices, such as reduced mowing frequency, the use of native species and eliminating the use of chemicals (Bertoncini et al., 2012), or the sustainability of the restoration projects on longer terms, e.g. in terms of seedling establishment (Rojas et al., 2022) or the success of planting. We found that only a few studies considered multiple taxa and interspecific interactions, which would be much needed for the complex understanding of the functioning of the restored urban ecosystems. Finally, insight in restoration and maintenance measures that simultaneously enhance biodiversity and several other ecosystem services is still not widely available.

CRediT authorship contribution statement

Réka Fekete: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Orsolya Valkó:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Leonie K. Fischer:** Writing – review & editing, Supervision, Conceptualization. **Balázs Deák:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization. **Valentin H. Klaus:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary data

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