Management of urban grasslands in the context of green infrastructure ecosystem services

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PhD thesis

conducted in Institute of Agroecology and Plant Production,
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Wrocław, 2023

Zarządzanie murawami miejskimi w kontekście usług ekosystemowych zielonej infrastruktury

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wykonana w Instytucie Agroekologii i Produkcji Roślinnej,
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Wrocław, 2023

Table of contents / spis treści:

SUMMARY

Urban grasslands (UGs) are among the most common types of green infrastructure (Ignatieva et al. 2020) and, due to the reference to the ecosystem services delivered, UGs are considered more broadly, encompassing meadows and lawns in domestic gardens, parks, vacant land, remnants of rural landscapes, and areas along transportation corridors (Onandia et al. 2019), including even non-grassy vegetation (Ignatieva and Hedblom 2018). To fulfil their functions, UGs need to be properly spatially arranged in a cityscape, have a high diversity of plant species, and be properly managed (Piana et al. 2019). Unfortunately, the UGs are usually managed as species-poor, short-cut lawns, and spontaneous plant migration, which can increase biodiversity, is limited (Piana et al. 2019, Klaus and Kiehl 2021). The urban environment, mostly because of high fragmentation, can lead to genetic drift within plant populations and result in biodiversity reduction. Furthermore, increasing and/or maintaining a relatively high level of plant species richness in an urban environment is limited by restricted plant dispersal.

In my PhD I examined the ecological characteristic of UG, considering Wrocław city as a model object, to improve UG management methods for increasing the ecosystem services of green infrastructure. I focused on: 1) the problem of connectivity between UG patches in the cityscape and 2) the effect of grassland type and proximity to the city center on the soil and vegetation characteristics. The practical implication of the study was to provide ideas to urban planners to enhance ecosystem services and to help improve the permeability of the city landscape to wildlife. I have tested the hypotheses: 1) the dispersal ability of grassland plant species is limited by the spatial structure of urban grasslands in the city, 2) the characteristics of urban grassland like soil properties and, plant species richness are influenced by grassland patch type and location.

First, I have examined the connectivity of urban grasslands and prioritized the impact of each patch in the entire system of Wroclaw city according to the dispersal ability of plant species and pollen flow (considering five distance thresholds of 2m, 20m, 44m, 100m, and 1000m) – article 1.

Next, to complete the ecological characteristic of urban grasslands, I have examined the chemical properties of soil and vegetation characteristics in different UG types (lawns, grasslands in parks, grasslands on river embankments, and roadsides) and their locations (city center versus peripheries) – article 2.

The results showed low connectivity of urban grassland patches, especially for plant species with low dispersal ability (2–20 m). For all dispersal distance thresholds, the patch priority for landscape connectivity was correlated with the area of the patch. The large patches, important to overall connectivity, were mostly located in urban peripheries, while in the city center, connectivity was limited, and grassland area per capita was lower. Odra River created a corridor, allowing plants to migrate along it, but it also form a barrier dividing the greenery system.

The results of soil chemical analysis showed high differentiation of measured traits unrelated to urban grassland types and location. The exception was K content, with a relatively high concentration in lawns, and some metals (Cd, Cu, Pb, Zn), with higher concentrations in the city center than in the peripheries. Also, in the case of vegetation characteristics, the variability was not structured considering the UG type, and location of the patches, except for bare soil cover, which was higher in lawns in the city center compared to embankments in the peripheries. The general correlations between vegetation traits and soil properties were mainly related to a decrease in biodiversity on UG with more fertile soils, and an increase in herb and bare soil cover on UG with higher metal content.

The practical implications of my thesis underline that, in case of the lack of possibility of extending the UG area and increasing their connectivity, especially in the city centre, the UG management should focus on improving grassland quality by seed addition and less frequent mowing, as well as developing alternative grassland forms such as green roofs and walls or green tram track lines. The results suggest a positive effect of contemporary UG management on species richness in Wrocław city, which allows establishing a herb species while increasing soil fertility increase the cover of grass species leading to a decrease in total vascular plant species richness. The observed concentration of heavy metals exceeded the allowed standards in patches located in the city centre, suggesting the necessity of continuous monitoring of heavy metals in urban soils.

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STRESZCZENIE

Murawy miejskie (UG) należą do najpowszechniej występujących typów zielonej infrastruktury (Ignatieva et al. 2020). Ze względu na spektrum świadczonych usług ekosystemowych, pojęcie UG jest rozumiane szerzej i obejmuje także łąki i trawniki w ogrodach przydomowych i parkach, nieużytki, a także pozostałości krajobrazu wiejskiego oraz pobocza dróg (Onandia et al. 2019), w tym tereny, gdzie nie dominuje roślinność trawiasta (Ignatieva i Hedblom 2018). Aby spełniać oczekiwane funkcje, UG muszą wykazywać odpowiednie rozmieszczenie przestrzenne w krajobrazie miejskim, charakteryzować się dużą różnorodnością gatunkową roślin oraz być odpowiednio zarządzane (Piana et al. 2019).

Niestety UG są zazwyczaj zagospodarowane jako ubogie gatunkowo, krótko koszone trawniki, a spontaniczna migracja roślin, która może zwiększyć bioróżnorodność, jest ograniczona (Piana i in. 2019, Klaus i Kiehl 2021). Środowisko miejskie, głównie ze względu na dużą fragmentację, może prowadzić do dryfu genetycznego w populacjach roślin i skutkować zmniejszeniem bioróżnorodności. Ponadto zwiększanie i/lub utrzymywanie stosunkowo wysokiego poziomu bogactwa gatunkowego roślin w środowisku miejskim jest utrudnione przez ograniczone rozprzestrzenianie się roślin.

W pracy doktorskiej analizowałem charakterystykę ekologiczną UG, traktując miasto Wrocław jako obiekt modelowy, aby udoskonalić metody zarządzania UG w celu zwiększenia spektrum usług ekosystemowych pełnionych przez zieloną infrastrukturę. Skoncentrowałem się na: 1) problemie łączności płatów UG w krajobrazie miejskim oraz 2) związku typu muraw miejskich i ich odległości od centrum miasta z właściwościami gleby i charakterystyką roślinności. Praktycznym aspektem badań jest dostarczenie urbanistom sposobów na poprawę spektrum usług ekosystemowych pełnionych przez łąki miejskie oraz ułatwienie migracji spontanicznie występujących gatunków roślin i zwierząt w krajobrazie miejskim. Przetestowałem hipotezy: 1) zdolność rozprzestrzeniania się gatunków roślin łąkowych jest ograniczona strukturą przestrzenną muraw miejskich w krajobrazie miasta, 2) cechy muraw miejskich, takie jak właściwości gleby i bogactwo gatunkowe roślin, są powiązane z typem muraw oraz ich lokalizacją.

Pierwszym etapem badań było określenie łączności krajobrazowej muraw miejskich i ich priorytetyzacja uwzględniająca ich znaczenie w systemie miasta Wrocławia z uwagi na zdolność rozprzestrzeniania się różnych gatunków roślin i możliwości transportu ich pyłku (analizowano pięć różnych odległości: 2m, 20m, 44m, 100m i 1000m) – artykuł 1.

Następnie, w celu dokonania charakterystyki ekologicznej muraw miejskich, zbadałem właściwości chemiczne gleb oraz cechy roślinności w (1) różnych typach UG (trawniki, murawy w parkach, murawy na wałach rzecznych i przydroża) i (2) różnej lokalizacji (centrum miasta versus peryferia) – artykuł 2.

Wyniki wykazały niską łączność płatów muraw miejskich, zwłaszcza dla gatunków roślin o małej zdolności rozprzestrzeniania się (2–20 m). Dla wszystkich analizowanych odległości znaczenie danego płatu murawy miejskiej dla całkowitej łączności krajobrazowej była związana z wielkością płatu. Duże płaty, ważne dla ogólnej łączności, znajdowały się głównie na peryferiach miasta, podczas gdy w centrum łączność była ograniczona, a powierzchnia muraw miejskich w przeliczeniu na jednego mieszkańca była niższa. Ponadto wykazano, że rzeka Odra stanowi korytarz, który umożliwia migrację roślin, ale jednocześnie tworzy barierę dzielącą system zieleni Wrocławia.

Wyniki analizy chemicznej gleb wykazały duże zróżnicowanie mierzonych cech i brak ich powiązania z typem i lokalizacją muraw miejskich. Wyjątkiem była zawartość K, oraz niektórych metali (Cd, Cu, Pb, Zn), które występowały w wyższych stężeniach w centrum miasta niż na peryferiach. Również w przypadku charakterystyki roślinności zmienność nie była skorelowana z typem UG i lokalizacją płatów, z wyjątkiem braku pokrywy roślinnej, której frakcja była wyższa na trawnikach w centrum miasta w porównaniu z terenami przyrzecznymi na peryferiach. Ogólne zależności między cechami roślinności a właściwościami gleb dotyczyły głównie spadku bioróżnorodności muraw miejskich wraz ze wzrostem żyzności gleby oraz wzrostu udziału gatunków dwuliściennych i braku pokrywy roślinnej na murawach o glebach, gdzie odnotowano wyższą zawartość metali.

Pod względem praktyki zarządzania murawami miejskimi należy podkreślić, że w przypadku braku możliwości powiększenia obszaru UG i zwiększenia ich powiązań, zwłaszcza w centrum miasta, zarządzanie UG powinno skupić się na poprawie jakości muraw miejskich poprzez wprowadzanie nasion i rzadsze koszenie, a także rozwój alternatywnych form użytków zielonych, takich jak zielone dachy i ściany lub zielone tereny wzdłuż torów tramwajowych. Uzyskane wyniki wskazują na pozytywny wpływ obecnego, ekstensywnego użytkowania muraw miejskich na bogactwo gatunkowe miasta Wrocławia. Obecny typ zarządzania murawami miejskimi pozwala na występowanie gatunków dwuliściennych na trawnikach, podczas gdy zwiększenie żyzności gleby i towarzyszący mu wzrost pokrycia traw, prowadzi do zmniejszenia ogólnego bogactwa gatunkowego roślin naczyniowych. Zaobserwowane stężenia metali ciężkich przekroczyły dopuszczalne normy w płatach zlokalizowanych w centrum miasta, co sugeruje konieczność stałego monitoringu zawartości metali ciężkich w glebach miejskich.

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3. Articles / Artykuły

3.1. Connectivity assessment and prioritization of urban grasslands as a helpful tool for effective management of urban ecosystem services

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Journal: Plos one, 15(12), e0244452.

https://doi.org/10.1371/journal.pone.0244452

PLOS ONE

RESEARCH ARTICLE

Connectivity assessment and prioritization of urban grasslands as a helpful tool for effective management of urban ecosystem services

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Abstract

Urban grasslands are usually managed as short-cut lawns and have limited biodiversity. Urban grasslands with low-intensity management are species rich and can perform numerous ecosystem services, but they are not accepted by citizens everywhere. Further, increasing and/or maintaining a relatively high level of plant species richness in an urban environment is limited by restricted plant dispersal. In this study, we examined the connectivity of urban grasslands and prioritized the grassland patches with regard to their role in connectivity in an urban landscape. We used high-resolution data from a land use system to map grassland patches in Wrocław city, Silesia, southwest Poland, Central Europe, and applied a graph theory approach to assess their connectivity and prioritization. We next constructed a model for several dispersal distance thresholds (2, 20, 44, 100, and 1000 m), reflecting plants with differing dispersal potential. Our results revealed low connectivity of urban grassland patches, especially for plants with low dispersal ability (2–20 m). The priority of patches was correlated with their area for all dispersal distance thresholds. Most of the large patches important to overall connectivity were located in urban peripheries, while in the city center, connectivity was more restricted and grassland area per capita was the lowest. The presence of a river created a corridor, allowing plants to migrate along watercourse, but it also created a barrier dividing the system. The results suggest that increasing the plant species richness in urban grasslands in the city center requires seed addition.

OPEN ACCESS

Citation: Mollashahi H, Szymura M, Szymura TH (2020) Connectivity assessment and prioritization of urban grasslands as a helpful tool for effective management of urban ecosystem services. PLoS ONE 15(12): e0244452. https://doi.org/10.1371/journal.pone.0244452

Editor: Jun Yang, Northeastern University (Shenyang China), CHINA

Received: June 13, 2020

Accepted: December 10, 2020

Published: December 28, 2020

Peer Review History: PLOS recognizes the benefits of transparency in the peer review process; therefore, we enable the publication of all of the content of peer review and author responses alongside final, published articles. The editorial history of this article is available here: https://doi.org/10.1371/journal.pone.0244452

Data Availability Statement: All relevant data are within the manuscript and its Supporting Informationw files.

Introduction

Urban green space provides a variety of important ecosystem services [1, 2] ranging from conservation of biodiversity [3], maintenance of landscape connectivity [4], aesthetics [5], leisure and recreation [6], and human health benefits [7, 8]. It also shapes microclimates by mitigating urban heat islands [9, 10]; improving soil, water, and air quality [11, 12]; and reducing stormwater runoff [13]. Grasslands, primarily represented by urban lawns, constitute an important component of urban green space [14].

Funding: Publication financed by the project "UPWR 2.0: international and interdisciplinary programme of development of Wrocław University of Environmental and Life Sciences", co-financed by the European Social Fund under the Operational Program Knowledge Education Development, under contract No. POWR.03.05.00-00-Z062 / 18 of June 4, 2019.

Competing interests: The authors have declared that no competing interests exist.

Frequently cut urban lawns are a worldwide phenomenon of the urban landscape and represent a significant part of urban greenery. The lawns, which serve as functional and accessible areas in parks, playgrounds, and private gardens, have a generally positive public reception. However, the intensive grass-cutting regime has a negative impact on the urban environment [15], and scientists and greenery managers are increasingly considering species-rich, low-intensity urban grasslands and grass-free urban lawns. Low-intensity management benefits the richness of plant species in urban grasslands [16–19]. This richness, paired with the vegetation height of urban grasslands, positively influences soil microbial communities [20] and the diversity of arthropods, including pollinators, and provides advantages for other animals such as birds [21–24]. For example, the abundance of parasitic *Hymenoptera* is associated with herb diversity, and these insects are one the most important biocontrol agents providing natural pest management services in urban landscapes [25]. Species-rich urban grasslands with low-intensity management boost the resilience of the ecosystem, which enhances its ability to accumulate carbon and nitrogen [26, 27], and reduces the public cost for maintenance [23, 28–30]. Moreover, the high plant diversity directly increases human well-being and offers psychological benefits [31–35].

Urban grasslands are usually species poor because of intense management and the use of standard, species-poor seed mixtures in the original plantings [15, 17, 18]. In urban areas, ecologically desirable species are often completely absent because natural disperser vectors and source populations are largely missing [28, 36–40]. Additionally, the soil seed bank does not significantly contribute to the desired floristic development, especially on young, heavily altered urban soils. Therefore, the ability of urban sites to function as novel habitats for grassland species may be limited by spatial isolation and missing diaspore pools [41]. Because of these limitations, the restoration of urban grasslands mostly relies on the establishment of entirely new grasslands or by seed addition to existing grasslands [17, 19, 41, 42]. However, maintaining and/or increasing biodiversity can be restricted by limited dispersal caused by the high isolation and low connectivity of grassland patches within the urban landscape [39].

The connectivity between patches is important for maintaining a vital population, as well as allowing interaction between species. Greater connectivity between habitat patches contributes to genetic diversity, especially among insect-pollinated and outcrossing plant species [43]. In contrast, habitat fragmentation can lead to the extinction of species due to inbreeding [44, 45]. Consequently, establishing a properly managed biotope network is important in nature conservation strategies, as well as provision of ecosystem services related to landscape connectivity [46–49]. The concept of landscape connectivity, defined as the degree to which the landscape facilitates or impedes the movement of species between patches, allows us to understand how organisms disperse and to predict where they go [50, 51]. Connectivity encompasses two elements: functional and structural. Plant functional connectivity pertains to the effective dispersal of propagules or pollen between habitat patches in a landscape, while structural connectivity describes the physical aspects of the landscape (e.g., size and proximity of patches) and the configuration of habitat patches [51, 52]. Structural connectivity is not a simple concept [53], but it provides useful information for policy makers and managers to plan management strategies [39, 54–56]. To date, several projects [57, 58] and management actions have been introduced, boosting the provision of ecosystem services that have cost-effective outcomes [59, 60]. A good example of practical solutions for managing urban greenery is Detroit, Michigan, in the United States, where the concept of structural connectivity, a cost-effective plan for reconnecting isolated habitat patches, has been expanded on to maximize social and ecological functions [4, 61].

Species-poor conventional lawns are a widely accepted anthropogenic construct that is traditionally maintained as an aesthetic standard by intensive management [62, 63]. A common view among the majority of the population and even among decision-makers is that low-intensity grasslands are a sign of neglect and laziness, perhaps because they appear “messy” [16, 64]. In Poland, short-cut lawns are considered a symbol of financial status [65]. Moreover, low-intensity management can reduce the recreational value of urban grasslands [28], and therefore, it cannot be introduced everywhere. Consequently, grasslands need to be prioritized to obtain the most effective network of environment-friendly, species-rich urban grasslands.

In this study, we analyzed the spatial structure of urban grassland patches in the city of Wrocław, Poland, with a focus on the connectivity between the patches. We took into account the functional connectivity by considering various dispersal distance thresholds for both seeds and pollen, irrespective of the particular plant species. The detailed aims of the study were (a) to examine how the connectivity between grassland patches can change based on different dispersal distances, (b) to determine the prioritization among the different patches based on landscape-scale connectivity, and (c) to determine how the spatial patterns of grassland distribution and connectivity are related to human population density in the city.

Materials and methods

Study area

Wrocław is located in Silesia, southwest Poland, Central Europe (51˚ 6″ 28.3788″ N, 17˚ 2″ 18.7368″ E). The total area is about 300 km^2, and the city’s population is approximately 650,000. The city is located on the Odra River and lies mostly in the river valley at an altitude ranging from 105 to 156 m a.s.l. The average annual temperature is 9.7˚ C, and the annual precipitation is 548 mm, with most occurring as rainfall in the summer. July is the warmest month, with an average temperature of 19.9˚ C, and January is the coldest month with an average temperature of about −0.5˚ C. A typical urban heat island is observed in the city. The city is surrounded by a relatively uniform landscape of intensively used agricultural areas and narrow strips of riparian forest and seminatural vegetation along watercourses, which represent the main ecological corridors.

The system of urban green areas consists of urban forests, parks, allotment gardens, and grasslands. The total acreage of urban greenery is 15,648 ha, and it accounts for 53% of the Wrocław city land. The grasslands include public and private lawns, road verges, and grasslands on river embankments. There are also three special areas that are dominated by grasslands: so-called irrigation fields, the airport, and the aquifer area (Fig 1). The irrigation fields, which were used up to the 1990s for wastewater cleaning (septic drain fields), include approximately 10 km^2 of semi-natural vegetation, mostly grasslands and reed-beds. The fields are owned by the city and are kept for nature protection. The grasslands related to the Wrocław Airport infrastructure covers about 3.5 km^2. The aquifer area, as a protected part of the river catchment area used to supply drinking water for the city, covers an area of 2 km^2.

A considerable area of grasslands related to river banks and flood areas is owned by the state and is managed by the Regional Water Management Board. The urban grasslands in Wrocław are usually managed intensively with cutting several times per year, and, in the case of Wrocław Airport, by spraying herbicides. The exceptions are irrigation fields and aquifer areas, which are maintained with low-intensity management, with cutting once or twice per year. Low-intensity management of urban grasslands has been recently introduced by the city authorities, but it has not been widely accepted by the citizens.

Data sources

We used the Polish Database of Topographic Objects (BDOT10k), which collects data on different kinds of topographic objects, including the land-cover class “grassland” [66]. The

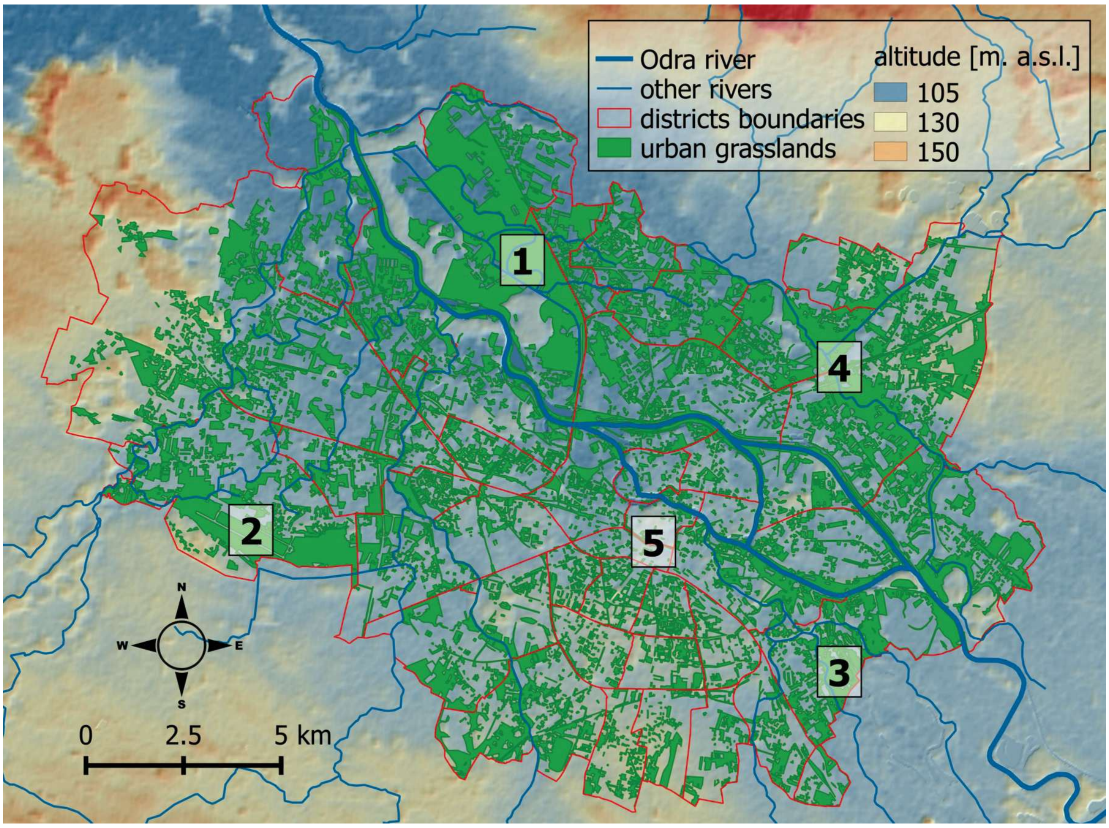

Fig 1. The urban grasslands of Wrocław city with altitude shown in the background. The numbers denote the following areas: (1) irrigation fields, (2) airport, (3) aquifer areas, (4) areas managed by the Regional Water Management Board, and (5) the city center. The shapefiles are provided by Polish Database of Topographic Objects [66] and Wrocław Spatial Information System [69]. The land relief layers were produced using data from EU-DEM [71].

https://doi.org/10.1371/journal.pone.0244452.g001

BDOT10k database roughly corresponds to a map at 1:10,000 scale and is regularly updated. The minimum size of a mapped patch is 1000 m^2, and in the case of linear features (e.g., road verges), the width must exceed 5 m. This map is considered the most comprehensive database regarding the distribution of urban green space [67] and grasslands in Poland [68]. The original map in "shp" format was cropped to the administrative boundaries of Wrocław city and checked for invalid polygon geometries. The invalid geometries were fixed, and the map was used for further analysis (Fig 1).

The map of Wrocław district boundaries was provided by Wrocław Spatial Information System [69]. For calculation of grassland area per capita, we used data on population density in Wrocław city districts obtained from the Public Information Bulletin of the Municipal Office of Wrocław [70].

Methods

Dispersal distance threshold. Estimating the dispersal ability of a plant species is difficult because dispersal traits such as pollen vector (wind, insect, self-pollination), reproduction (seed, vegetative growth, and mixed seed and vegetative), and dispersal mode (anemochory, barochory, endo- and/or epi-zoochory) may affect it [61, 72, 73]. Thomson [74] showed that the mean dispersal capacity of plant species was 203 ± 23 m based on biotic vectors, while it was 44 ± 34 m for species dispersed abiotically. Donath [75] found median dispersal distances of 13–50 m for most grassland species.

Because our study focused on the connectivity between grassland patches with different plant species, we considered a range of dispersal distances. Following the approach of Hejkal et al. [39], we set four dispersal distances as follows: 2, 20, 44, and 100 m. We assumed that the distance thresholds were adequate for our study site, because central European cities have very similar flora and urban environments [76, 77], especially in the case of urban grasslands [17–19]. In addition, we also included the threshold distance of 1000 m because gene flow by pollen is part of the plant functional connectivity [51], and this distance has been suggested for pollen movement for many plant species [53, 78].

Connectivity analysis and patches prioritization. Various methods are used to model the connectivity in an urban landscape [54, 79]. Euclidean distance and different connectivity indices are based on the geographic distance [80], gravity theory [81], a least-cost path approach [82], and graph theory [83, 84], with specific forms of the latter including network and circuit theories [85, 86]. Among the methods, graph theory offers powerful and effective tools for representing landscape patterns in a quantitative way as well as performing complex analyses regarding landscape connectivity [86]. In this approach, connectivity is represented by groups of habitat patches (i.e., *nodes*) and the links that connect paired nodes, including the movement between them. Connectivity is assumed to exist and to be unrestricted within each node (so-called intrapatch connectivity). The links encode information about the physical distances among patches and can represent structural, potential, or functional connection. Additional information regarding the dispersal abilities of focal species (e.g., maximum dispersal distance threshold) can be used to eliminate links (e.g., those exceeding the threshold distance) and finalize a representation of the potential connectivity for the focal species [86]. The term *component* considers a set of nodes (i.e., habitat patches) connected by links and thus defines a group of patches with possible migration within the system. An isolated patch is itself a component [87]. Within this general framework, many different connectivity indices have been used, including the simplest and most intuitive, such as the number of existing links between patches (NL) and the number of components (NC) representing the number of groups of patches which are connected. Both indices can be calculated by considering the maximal dispersal threshold for focal species. A higher NL and a lower NC denote better connectivity. One of the more sophisticated indices is the integral index of connectivity (IIC), which was proposed by Pascual-Hortal and Saura [87] and is considered to be very effective. This index offers a quantitative basis for adequately prioritizing the conservation of landscape elements (patches and links) that are particularly critical for maintaining the overall habitat connectivity. Therefore, the IIC allows not only estimating the current “degree of connectivity” within a landscape, but it also offers a relative ranking of patches by their contribution to overall landscape connectivity [87]. This relative ranking is considered to be the most useful tool in the decision process for planners [84, 88, 89]. The importance of each patch in overall connectivity (IIC) was assessed based on the difference (delta, d) in the IIC value when that patch was excluded from the entire system. The rank of dIIC values for each patch ranged from 0 to 1, with a higher value indicating greater importance of the patch for connectivity of the analyzed landscape [87]. Moreover, the dIIC index enables distinguishing three fractions, which additively yield the overall value. The first fraction includes the intrapatch connectivity component (*intra*), which is based on the assumption that connectivity exists within the patch. Two fractions compose the interpatch connectivity component: *flux*, which indicates whether the node is directly connected to other nodes, and *connector*, which indicates whether a node serves as a stepping stone and contributes to the connection between other nodes [90].

For the connectivity analysis, we used Conefor Sensinode 2.6 software. The input data set was created using Conefor Inputs plugin in QGIS software. Three connectivity parameters were calculated: the number of links between patches (NL), the number of components (NC), and the integral index of connectivity (IIC), which reflects the overall connectivity [91]. All metrics represent the system for specific and assumed dispersal distances [91]. For NC, we also calculated the number of components for which the sum of the area exceeded 50% of the total area of urban grasslands, for each distance threshold. We used this approach because some components consisted of only a few small patches, while others encompassed several large patches. Therefore, we considered the number of components that covered 50% of the area as better reflecting the landscape structure from a biological perspective. The prioritization of patches was assessed based on dIIC calculations. For comparing the relative role of a particular fraction in the dIIC index, we recalculated the values of $dIIC_{intra}$, $dIIC_{flux}$, and $dIIC_{connector}$ as percentages, and the average value of a particular fraction for each distance threshold was computed.

Results

The Wrocław urban grasslands, with an area of 9,523 ha, constituted 60% of the urban green areas and 32% of entire city area. The grassland patches were distributed across the city, but they were more abundant in the northern part of the city and in the peripheries. The largest grassland patches were mostly in the northern part, with a few in the southern and southwestern parts of the city (Fig 1). A total of 2442 grassland patches were analyzed. The size of the smallest grassland patches was 0.003 ha and the largest was 1179 ha. The smallest patches were the most numerous, with a size up to 0.5 ha, but the sum of their areas was low. Almost half of the total grassland area in the city belonged to a few patches that were larger than 100 ha (Fig 2). The median grassland area was 0.4 ha.

The results of the connectivity analyses revealed considerable changes of connectivity indices with assumed dispersal distance thresholds (Table 1). For the smallest dispersal threshold (2 m), the number of links between patches was only 11, causing the urban grasslands to form 2431 isolated components. The number of links increased as the distance threshold was changed from 2 to 1000 m, which indicates better connectedness of species with a greater dispersal ability. Even with larger dispersal distances, however, there were still numerous separated groups of patches (components): 1640 components for a distance threshold of 20 m, 666 for a threshold of 44 m, and 126 components for 100 m. Only with a dispersal threshold 1000

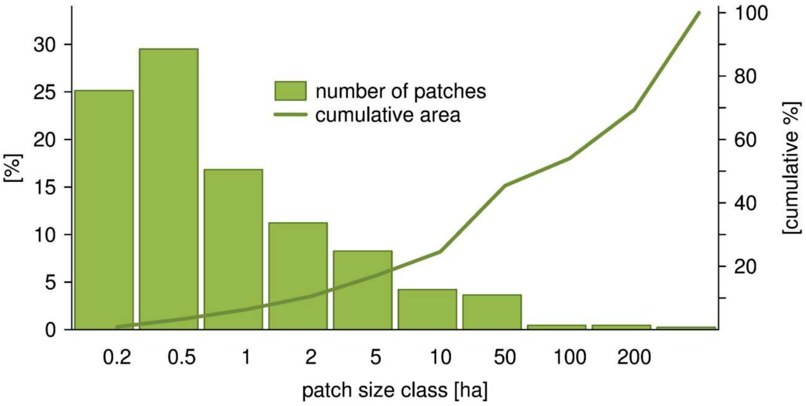

Fig 2. The distribution of grassland patches in Wrocław in terms of the number and cumulative area in patch area classes. Note the semi-logarithmic scale in patch area classes.

https://doi.org/10.1371/journal.pone.0244452.g002

Table 1. Results of connectivity indices for different dispersal distance thresholds for urban grasslands in Wrocław city.

Indices[a]	Dispersal distance thresholds [m]				
	2	20	44	100	1000
NL	11	867	2259	4480	61,762
NC [b]	2 431 (43)	1 640 (4)	666 (2)	126 (1)	2 (1)
IIC	2,468,023	4,780,829	7,485,704	14,984,170	22,666,110

[a] NL, number of links; NC, number of components; IIC, integral index of connectivity.

[b] The number of the largest components for which the sum of the area exceeded 50% of total urban grassland area is shown in parentheses.

https://doi.org/10.1371/journal.pone.0244452.t001

m was the connectivity very extensive, with only two components. Taking into account not only the number of components but also their area, we found that a considerable fraction (>50%) of all urban grassland area consisted of a smaller number of components: 43 in the case of the 2-m distance threshold; four and two for 20 and 44 m, respectively; and up to one for distances of 100 and 1000 m (Table 1 and Fig 3). For smaller distance thresholds (up to 44 m), the Odra river quite often separated the urban grasslands into disconnected components (Fig 3A and 3B).

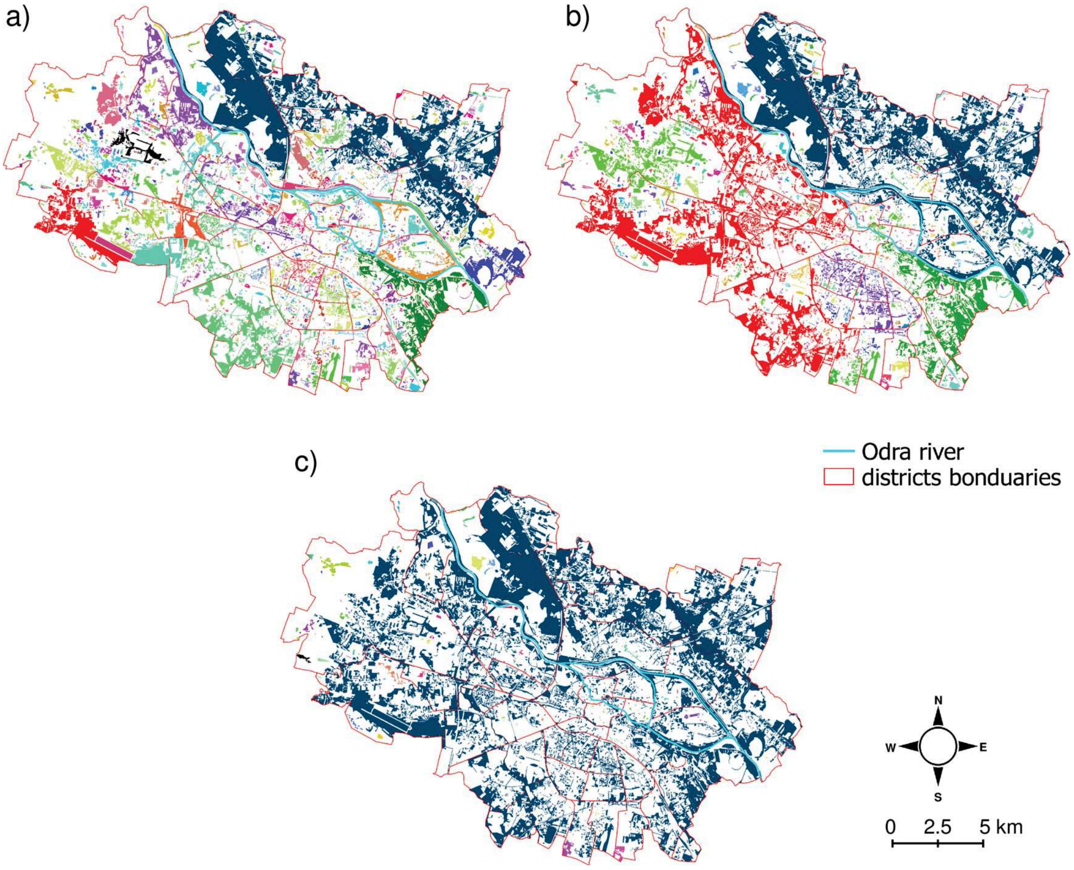

Fig 3. Spatial distribution of components in Wrocław urban grasslands. Different colors indicate particular components (groups of patches that are connected) calculated for distance threshold: (a) 20 m, (b) 44 m, and (c) 100 m. For simplicity, the smallest and largest distance thresholds (2 and 1000 m, respectively) are not shown. The shapefiles are provided by Polish Database of Topographic Objects [66] and Wrocław Spatial Information System [69].

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Examination of the relative importance of particular components for overall values of dIIC showed correlations with dispersal distance thresholds (Fig 4). For the 2-m distance, the dIIC value was almost entirely influenced by patch size (intra component). With regard to the intra component, the importance of patch size decreased as dispersal distance increased, while the influence of connection between a patch and other patches (flux component) exhibited a significant increase when the dispersal distance became greater. In the system of urban grasslands of Wrocław, the role of patches creating stepping stones for connections between other patches (connector) was rather small and had the highest influence for a dispersal distance of 44 m (Fig 4).

Nonetheless, all components of dIIC, the dIIC values themselves, and the area of patches were correlated for all dispersal distance thresholds. As a result, the large grassland patches usually had the highest dIIC values, regardless of the distance threshold (for detailed results, see S1 Table). As an example, Fig 5 shows the location of 20% of the most important patches for connectivity (i.e., those with the highest dIIC values) in Wrocław city for the 44-m distance threshold (maps for all distance thresholds are shown in map A-E in S1 File. Such spatial configuration of urban grasslands meant that the grassland patches in the Wrocław city center were isolated from other grasslands and had very low dIIC values.

In Wrocław the grassland area per capita ranged from 13 m^2 in the central districts, to 6592 m^2 in the suburbs. We observed a negative relationship between grassland area per capita and human population density (Fig 6). The highest population density was found in central districts (14,025 people/km^2), where sparse, small grassland patches occurred, while the area and number of grassland patches were higher in the suburbs, where the population density was lower, reaching the minimum value 83.1 people/km^2 (for details, see Map in S2 File).

Discussion

Urban grassland amount and distribution

The percentage of urban green area in Wrocław city is relatively high compared with other European cities, where it usually ranges from 2% to 46%, providing 3 to 300 m^2 of green area per capita [92]. Similar to other cities in the world [29, 64, 93], urban grasslands in Wrocław cover a considerable area and constitute a dominant component of urban greenery. The results of our study highlighted that the spatial distribution of grassland patches caused most of the city population to be separated from grasslands. The proportional decline of green space

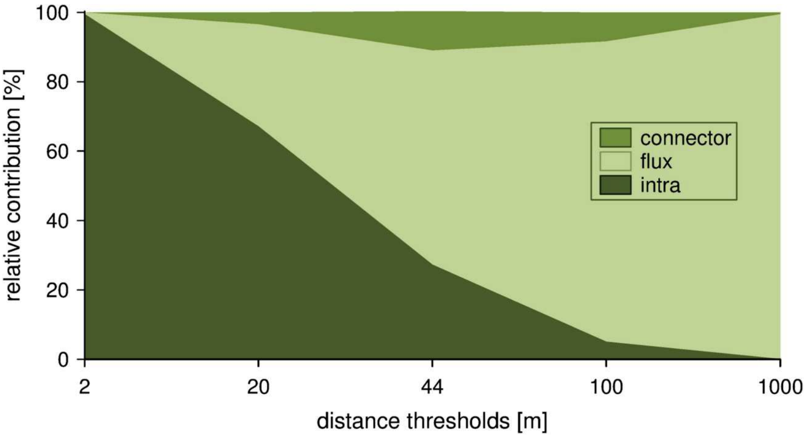

Fig 4. Relative contribution of each dIIC fraction (connector, flux, intra) on the total importance of an individual patch along with distance thresholds.

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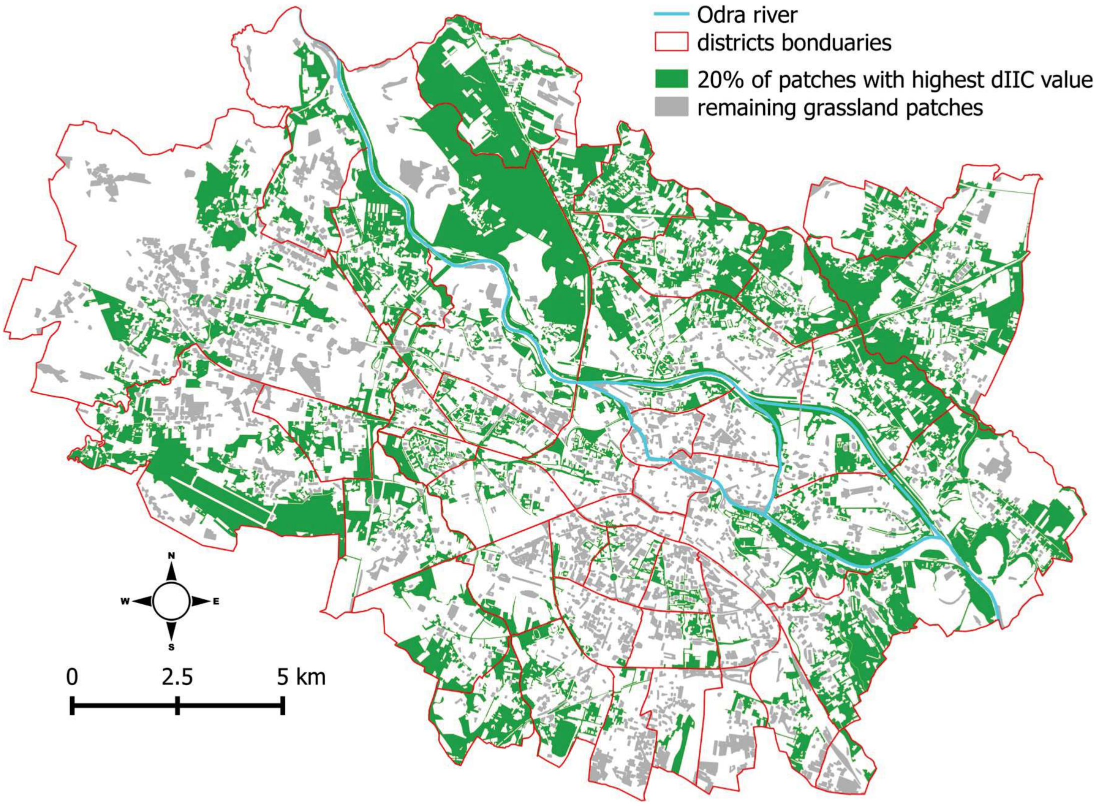

Fig 5. Location of urban grassland patches in Wrocław city. The green color shows the 20% of grasslands patches with the highest dIIC values for a dispersal distance of 44 m; the gray indicates the remaining 80% of patches. Notably, the patches with the highest dIIC values are the largest. It is also clear that patches in city center usually had a low value for overall connectivity. The shapefiles are provided by Polish Database of Topographic Objects [66] and Wrocław Spatial Information System [69].

https://doi.org/10.1371/journal.pone.0244452.g005

coverage with an increase in human population can be considered as the general pattern of greenery in European cities [92]. It is particularly true for lawns, where the cover has been found to increase from 5% in a city center to 55% in the suburbs [29].

The effect of patch size on landscape connectivity

Our results, for all dispersal distance thresholds, emphasize the positive correlation between patch size and the importance of the patch for connectivity. In practice, for small distance thresholds (2–20 m), the intracomponent fraction is the most influential for overall values of dIIC. In a situation in which interpatch connectivity is greatly limited, the intrapatch connectivity is crucial and directly related to patch size. For species with large distance dispersal (100–1000 m), direct connectivity with other patches (flux component of dIIC) is decisive. However, since the patch area and flux component are correlated, the largest patches are again more important in maintaining the connectivity within the entire system. Results suggest that the role of patches in serving as stepping stones is rather small, but it has some relevance for species with a moderate dispersal distance (44–100 m).

Individual patch size is important, and it was previously reported that patches of urban green areas need to be larger than 50 ha to prevent a rapid loss of area-sensitive species [94]. It was also previously found in Wrocław city that the area of urban greenery needed to maintain diversified bumblebee (*Apidae*, *Bombini*) communities is at least 30 ha [95]. In our study, the

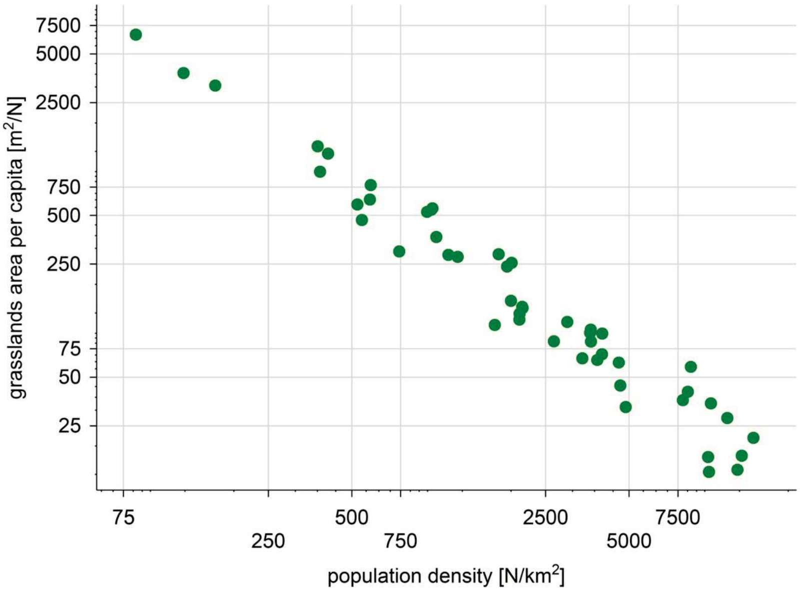

Fig 6. The relationship between population density and grassland area per capita in Wrocław city. The values on both axes are on a logarithmic scale.

https://doi.org/10.1371/journal.pone.0244452.g006

vast majority of grassland patches were smaller than 50 ha, and they constituted about 50% of all urban grassland area. Thus, it can be assumed that around half of the urban grassland areas in Wrocław city do not efficiently support biodiversity. However, Sehrt [19] showed that even on very small grassland patches (size from 0.02–0.35 ha, average 0.1 ha) with low-intensity management, 6 years after cessation of intense management, the number of vascular plant species increased up to an average of 24 species per patch as a result of spontaneous succession, while only 17 species were recorded on frequently cut lawns. The management changes also caused almost a doubling of species pool from 52 on lawns to 103 on grasslands with low-intensity management [19]. These results suggest that in the case of low-intensity management, urban grasslands with even small patches of habitats are valuable in maintaining the species richness of vascular plants. Investigations of grassland diversity in agricultural areas have yielded similar results. Small grassland remnants as midfield islets and road verges still encompass a substantial part of the grassland species pool, and they may be valuable for reconstructing grassland management at a landscape scale [96, 97]. The small habitat elements increase the total area that is available to grassland species present in the landscape, boosting the spatio-temporal dynamics of grassland communities. They may hence function as a refuge, especially in intensively utilized agricultural landscapes, and they should be regarded as a functional part of a semi-natural grassland network, analogous to a meta-population [98]. In summary, in the case of grasslands, it is important to both protect large habitat patches and maintain an ample amount of habitat in the local landscape around the patches [99].

The results also suggest that the number of components (NC) alone, without relation to their area, can be a somewhat misleading index of landscape structure. In our study, a very limited number of components can make up the majority of an entire habitat area. It is a result of specific, skewed distribution of urban grasslands patch sizes (Fig 2) and seems to be typical for cities [e.g. 39]. Consequently, the number of components that compose a certain percentage (e.g. 50%) of the entire habitat type seems to reflect the structure better than the total number of components (Table 1 and Fig 3).

Landscape corridors and barriers

The results of a meta-analysis of urban biodiversity variation across different taxonomic groups reveal that, besides patch area, the presence of continuous corridors between patches has the strongest positive effects on biodiversity [94]. This corridor influence is markedly stronger than the distance between patches [94], and it suggests that corridors can be much more effective in promoting urban species richness than stepping-stone habitats. The stepping-stone habitats are viewed as increasing the permeability of a landscape [100], but they simply decrease the distance between patches [101] and do not necessarily provide a functional corridor. In grassland conservation practice in rural landscapes, the linear grassland elements such as road verges and ditches facilitate species persistence and dispersal and the colonization of degraded sites [102]. Moreover, it was found that the connectivity of linear grassland elements is more important to plant species richness than their area for species with short or long distance dispersal [103]. Unfortunately, in spite of the relatively high cover of urban grasslands in Wrocław, their structure is strongly fragmented, with a lack of corridors (Table 1, Fig 3A and 3B). A similar situation was found by Hejkal et al. [39] in Münster, Germany.

Typically, river embankments serve as corridors for migration of plants and animals within cities [104, 105]. The results of our analysis reveal that the presence of a river can enhance dispersal along the embankments as a corridor, but the river itself seems to be a barrier to grassland species migration and divides the city into separate parts (Fig 3A and 3B). Some reports indicate that hydrochory can support seed dispersal of anemo- and zoo-choric tree species [106, 107]. However, in the case of alluvial grasslands in Europe, flooding was not found to increase the dispersal distances of characteristic for this habitat species as *Silaum silaus* and *Serratula tinctoria* [108], and poor dispersal was the main limiting factor for successful restoration of alluvial grasslands [108]. It was also found that flooding does contribute to the density and composition of the seed bank, but most of the imported seeds belong to only a few species. Therefore, flooding is unlikely to substantially enhance the potential species richness of alluvial grasslands [109, 110]. Moreover, genetic analysis has revealed that a large river can be a barrier for seed dispersal [111] and even pollen [112], although islands in rivers can serve as stepping stones for seed dispersal [111].

Practical implications

The most important strategy for maintaining high levels of urban biodiversity, including grasslands, is to increase the area of habitat patches and create a network of corridors between them [94, 113]. However, the creation of uninterrupted corridors for migration and increase of green areas in practice are only possible in shrinking cities [4, 39], while Wrocław belongs to the group of cities with stable populations [114]. One option for enhancing informal urban green space is to have low-maintenance green tram tracks [115] which can contribute to urban grasslands connectivity. Moreover, other dimensions beyond green areas on the ground need consideration, such as green roofs and walls (vertical gardens), to increase the connectivity [64].

The increase of connectivity of urban grasslands can also rely on increasing their quality, in lieu of their quantity. In a situation of moderate public acceptation of low-intensity grassland management [16], prioritization of patches with the highest importance for connectivity will optimize the selection of patches for improvement. Enhancement of biodiversity through spontaneous succession on lawns released from an intensive management regime seems to be rather restricted because of the extensive fragmentation of urban grasslands. The connection system limits spontaneous migration of species, especially in the city center. Consequently, increasing the species richness of urban grasslands in a city center will require seed addition. To increase the role of spontaneous succession, the use of seed mixtures based on species with relatively long-range propagule dispersal will be more effective. Unfortunately, most grassland species have a low potential for long-distance dispersal, not exceeding a few meters [108, 116–118]. Dispersal by insects (e.g., ants) and mice is also restricted to several meters [119]. The graph theory provides the tools for selecting the patches that will yield better results for the improvement of connectivity [39]. The dIIC values should be considered, but not as an absolute measure. The spatial context should also be considered to ensure connectivity within the entire city system. Thus, the preferred approach should be patches that have relatively high dIIC value locally (e.g., for central city districts) to ensure provision of ecosystem services for a large number of citizens in city center. The improvement should consist of reducing cutting frequency and applying seed addition, with the seed addition being concentrated on the edges of the patches to increase the probability of species migration to other patches.

It should be stressed that prioritization based on dIIC should be used as a guide to select patches for enhancing their biodiversity, not as tool for determining grassland patches that can be sacrificed. As previously discussed, the value of dIIC is positively corelated with patch size, but small grassland patches can still support a high level of biodiversity [99] and help in connectivity [39].

Conclusion

Our study reveals that despite a relatively large area of Wrocław being covered by urban grasslands, the connectivity of these grasslands is strongly limited, especially in the city center. The results suggest that when the distribution of habitat patch sizes is skewed, with the smallest patches being dominant, the component number (NC) as a connectivity measure does not reflect the entire landscape structure well. In such a landscape type, only a few components could consist prevailing area of a given habitat. With regard to connectivity, the results on patch prioritization emphasize the importance of the largest patches. However, we argue that even the smallest patches still have value for biodiversity maintenance. Moreover, the prioritization should also consider local demand for urban grasslands, which is much stronger in a highly populated city center than on the peripheries. Study results also highlight the dual role of rivers: the vegetation on embankments can serve as a migration corridor, while the water body itself can be a barrier to migration. Given the impossibility of extending the urban grassland area and creating continuous and structural corridors, increasing connectivity, especially in the city center, should focus on improving grassland quality by seed addition and proper management, as well as developing alternative grassland forms such as green roofs and walls or green tram track lines.

Supporting information

S1 Table. Spearman rank correlations between patch area (area), dIIC (dIIC) values, and dIIC components (intra, flux, connector) for distance thresholds (2, 20, 44, 100, and 1000 m). Values above the diagonal of the matrix are shown. Only significant correlations are presented.
(PDF)

S1 File. The high-resolution maps of location of urban grassland patches in Wrocław city. The green color shows the 20% of grasslands patches with the highest dIIC values for a particular dispersal distance; the gray indicates the remaining 80% of patches. The maps are ordered according to increased assumed dispersal distances thresholds: 2m, 20 m, 44 m, 100 m and 1000 m.
(PDF)

S2 File. Distribution of urban grassland patches against a background of human population density in districts of Wrocław city. The shapefiles are provided by [66, 69].
(PDF)

S3 File.
(DOCX)

Acknowledgments

The authors would like to thank Oxford Editing (https://oxfordediting.com) for the English language review.

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3.2. The effect of grassland type and proximity to the city center on urban soil and vegetation coverage

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Journal: Environmental Monitoring and Assessment 195:599

https:// doi.org/ 10. 1007/ s10661- 023- 11210-z.

Environ Monit Assess (2023) 195:599
https://doi.org/10.1007/s10661-023-11210-z

RESEARCH

The effect of grassland type and proximity to the city center on urban soil and vegetation coverage

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Received: 5 October 2022 / Accepted: 3 April 2023

Abstract Urban soils with associated vegetation are important components of urban ecosystems, providing multiple regulating and supporting ecosystem services. This study aimed to analyze the differences in the soil chemistry and vegetation of urban grasslands considering urbanization gradient and urban grassland type (UGT). We hypothesized that the chemical properties of soil, such as metal content, as well as vegetation traits, differ according to grassland type (lawns, grasslands in parks, grasslands on river embankments, and roadsides) and the location of grassland patches (city center versus peripheries). Our samples included 94 UGT patches which each patch represented by four square sampling plots sized 1 m^2. The results showed high differentiation of measured traits unrelated to UGT and location. The exception was K content, with a relatively high concentration in lawns, and some metals (Cd, Cu, Pb, Zn), with higher concentrations in the city center than in the peripheries. We found two grassland patches located in the city center where the concentrations of Pb, Zn, and Cu exceeded the level authorized by Polish standards. In the case of vegetation traits, the variability was not structured considering the UGT and location of the patches, except for bare soil cover, which was higher in lawns in the city center compared to embankments in the peripheries. We observed correlations between vegetation traits and soil chemical properties. The vascular plant species richness decreased when N, P, and C content, along with an increase in grass cover and a decrease in herbs.

Keywords Ecotoxicity · Soil chemical properties · Urban grasslands · Ecosystem services

Introduction

The urban ecosystem services provided by soil are associated with supporting roles (e.g., habitat for soil organisms) and a set of regulation services, such as nutrient and pollutant retention and release, carbon sequestration, and water storage (Calzolari et al., 2020), and regulation of the hydrologic cycle and infiltration of precipitation, where a lack of infiltration causes rapid formation of urban streams (Yeakley, 2014). Soil-based ecosystem services are associated with properties such as soil texture and

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Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10661-023-11210-z.

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nutrients (Adhikari & Hartemink, 2016). Additionally, the soil can filter pollutants from runoff waters, which carry chemical contaminants such as heavy metals, hydrocarbons, excess nutrients, pharmaceuticals, and personal-care products (Wessolek et al., 2011). Together with plants, soil contributes to the reduction of noise pollution (Derkzen et al., 2015). Urban soil and vegetation contribute to climate regulation by reducing the concentration of CO_2 and other greenhouse gases in the atmosphere. Therefore, owing to ongoing climate change, more attention is being paid to sustainable soil management in urban areas. However, there is a lack of awareness of soil function from citizens and city planners (Lal & Stewart, 2017).

Many properties of urban soil fundamentally vary from their non-urban counterparts (Mónok et al., 2021). Urban soils are mostly technosols, while soils in urban gardens can be considered anthrosols because of long and intensive cultivation. In urban areas, building activities lower the soil quality, as they contaminate soils due to the debris from demolition. Building materials such as concrete and mortar contain calcium carbonate can make urban soils more alkaline than expected (Kida & Kawahigashi, 2015). Urban soils are usually compacted, which prevents carbon accumulation and is a cause of organic-matter depletion (Lal & Stewart, 2017). Compared with non-urban soils, the soil in urban areas is polluted and contains less organic matter. Soil organic pollutants weaken the mineralization process of plant litter (Vodyanitskii, 2015) and also the biochemical processes mediated by microorganisms (Falkowski et al, 2008). The concentrations of major nutritive elements such as N, P, and K are low in urban soils (Guilland et al., 2018). Deficiencies in soil organic carbon and nutrients (N, P, and K) can reduce soil microbial activity, contributing to poorer soil quality in urban areas. Due to its thin topsoil and less plant litter, urban soil has lower levels of organic matter, which reduces the amount of soil organic acids and elevates soil pH level (Day et al., 2010; Yeakley, 2020; Mónok et al., 2021).

The atmospheric wet-depositions of inorganic nitrogen (N), calcium (Ca^{2+}), and magnesium (Mg^{2+}) may have beneficial effects on plants and microorganisms (Lovett et al., 2000), while the long-term fertilization of urban lawns increases the soil nutrient content and humus amount (Ignatieva et al., 2020).

Urbanization and vehicle emissions increase the toxic compounds in soils (e.g., heavy metals), which pose a significant risk to human health (De Miguel et al., 2006; Vrščaj et al., 2008). Despite the widespread use of lead-free gasoline, lead (Pb) can still be emitted from engines and catalysts (Guan et al., 2017), industrial emission, and atmospheric deposition of coal combustion products (Nawrot et al., 2020), which reaches high levels near roads (Day et al., 2010). High metal concentrations (especially Pb, Cu, and Cd) adversely affect soil-living organisms especially the microbial parameters of soils (Papa et al., 2010; Ren et al., 2021). As a result, heavy metal concentrations are also used as an urban soil quality index (Mamehpour et al., 2021). Human activities, such as industrial activities, as well as factors such as atmospheric deposition and urban heat island effects (Lehmann & Stahr, 2007), increase nitrogen deposition, air pollution, water runoff, and soil pollution, and they reduce vegetation cover, which impacts soil-living organisms and biodiversity (Guilland et al., 2018).

Numerous ecosystem services provided by urban soils are tied to urban vegetation (Ignatieva et al., 2015; Derkzen et al., 2015; Lal & Stewart, 2017; Onandia et al., 2019; O'Riordan, 2021). In contemporary cities, the so-called urban grasslands are an important type of urban vegetation (Ignatieva et al., 2015). Traditional urban lawns are defined as patches of turf-type grasses that coalesce spatially into a distinct vegetation type (Thompson & Kao-Kniffin, 2017). Recently, due to the appreciation of the ecosystem services delivered by different forms of vegetation, urban grasslands are considered more broadly, encompassing meadows and lawns in domestic gardens, parks, vacant land, remnants of rural landscapes, and areas along transportation corridors (Onandia et al., 2019), including even non-grassy vegetation (Ignatieva & Hedblom, 2018; Smith et al., 2015). Many ecosystem services delivered by urban grassland are related to their biodiversity (Onandia et al., 2019; Thompson & Kao-Kniffin, 2017), and the structure of the vegetation is strongly shaped by human activities, such as fertilization level, mowing frequency, irrigation, trampling, and disturbance (Ignatieva et al., 2015; Ignatieva & Hedblom, 2018). As a result, the vegetation in a city center can differ from that in the peripheries (Deák et al., 2016; Vega & Küffer, 2021).

The worldwide trend of urbanization is increasing the urban land area; thus, it is imperative to understand the characteristics, changes over time, and management options of urban soil. For this purpose, soil characteristics, especially chemical properties (e.g. pH, nutrient/elemental imbalance, and soil C pools), must be duly considered for different types of plant-occupied soil (Fung et al., 2021; Lehmann & Stahr, 2007).

This study aimed to analyze the differences in the soil chemistry and vegetation traits of urban grasslands while considering urbanization gradient and grassland type. It could be assumed that the soil chemical properties, as well as the vegetation traits, differ among the UGT (lawns, parks, embankments, and roadsides) and the location of the patches (city center versus periphery, as reflecting urbanization gradient). Therefore, we hypothesized: (1) the patches in the city center are nutrient-poor but with a higher pH and are more contaminated by heavy metals compared to patches located in city peripheries, (2) the soil in lawns is more nutrient-rich due to fertilization compared to other urban grassland types, such as parks, road verges, and river embankments, and (3) road verges have a higher amount of heavy metals compared to other urban grassland types due to high traffic. We will also determine whether there is a correlation between vegetation traits and soil properties. To test our hypotheses, we analyzed the chemical properties of the samples, including the semi-total metal content of urban soils collected from different types of urban grasslands, and we also assessed vegetation characteristics, including the total vegetation cover, the coverage of different plant groups (grasses, herbs, mosses), bare soil cover, litter cover, and the number of vascular plant species in the studied plots.

Material and methods

This survey was conducted in 2020 in the city of Wrocław, Lower Silesia, Poland (51° 6′ 28.3788″ N, 17° 2′ 18.7368″ E). The city's population is approximately 650,000, and the total urban area is approximately 300 km^2. The city is located at altitudes ranging from 105 to 156 m above sea level along the Odra River Valley. Because of the city's location in the river valley, the city's shape is rather elongated. The annual sum of precipitation is 548 mm, with most occurring as rainfall in the summer, and the average annual temperature is 9.7 °C, with July being the warmest month and January being the coldest (https://bip.um.wroc.pl/artykuly/196/o-wroclawiu). Urban grasslands, mostly in form of public and private lawns, road verges, and grasslands on river embankments, altogether cover 9523 ha, which constitutes 32% of the entire city area. The grassland patches are scattered all over the city, but they are more frequent in the northern part and the peripheries. The median area of the urban grassland patches is 0.4 ha. The smallest patches, with areas as high as 0.5 ha are the most numerous, particularly in the city center (Mollashahi et al., 2020). The grasslands in parks, roadsides, and some lawns are managed by the City Greenery Board; the grasslands along the watercourses are managed by the Regional Water Management Authority in Wrocław, while the remaining urban lawns are managed by numerous owners. The grasslands managed by public institutions are not fertilized, while the private grassland's fertilization is dependent on the owner's decisions. Also, sprinkling roads with salt in winter is common.

Experimental design

The selection of patches for soil sampling was based on our previous investigation (Mollashahi et al., 2020). The different urban grassland types (UGTs), including road verges (R), embankments (E), parks (P), and lawns (L), were considered (Table 1). The patches were also classified according to their location: in the city center (C) and periphery (P). Because of the elongated city shape, classifying areas as the city center and periphery was based on both the geographical location of a particular district and information on population density. Districts with a population density above 2500 persons per ha were considered city center (see: SI Fig. 2). Generally, each of the eight groups of urban grasslands (4 UGT × 2 localities) was represented by 12 patches. However, in the case of parks in the city center (CP), only eight parks with lawns were found. Additionally, in the case of lawns in the city center (CL) and embankments in peripheries (PE), 13 patches were sampled. Altogether, 94 patches of urban grasslands were sampled. The locations of the patches tended to be spatially balanced, and the patches were uniformly distributed throughout different UGTs (Fig. 1). Each patch was

Table 1 Types of analyzed grassland patches

The combination of different patches
CE, CL, CR, PE, PL, PP, PR, CP

Typology	Description	Number of patches
Location	City center (C): the geographic core of the city and human population density larger than 2500 persons per ha	$n=45$
	Periphery (P): city peripheries and human population density smaller than 2500 persons per ha	$n=49$
Urban grassland types (UGT)	Road verges (R)	$n=24$
	Embankment (E)	$n=25$
	Parks (P)	$n=20$
	Lawns (L)	$n=25$

represented by four plots, each sized at 1 m^2, placed at regular distances. Soil samples (approximately 200 g) were taken from each plot (at a depth of 15 to 20 cm from the surface) and then mixed into one sample representing a particular patch. Artifacts such as plastic and glass were removed from the samples. Next, the samples were dried at room temperature and then crushed and sieved (Ø 0.5 mm) for subsequent analyses.

The cover of vegetation was assessed using a visual method in percentage scale (Mueller-Dombois & Ellenberg, 1974); this included the total vegetation cover, as well as the grass cover, herb cover, mosses cover, bare soil cover, and litter cover for each plot.

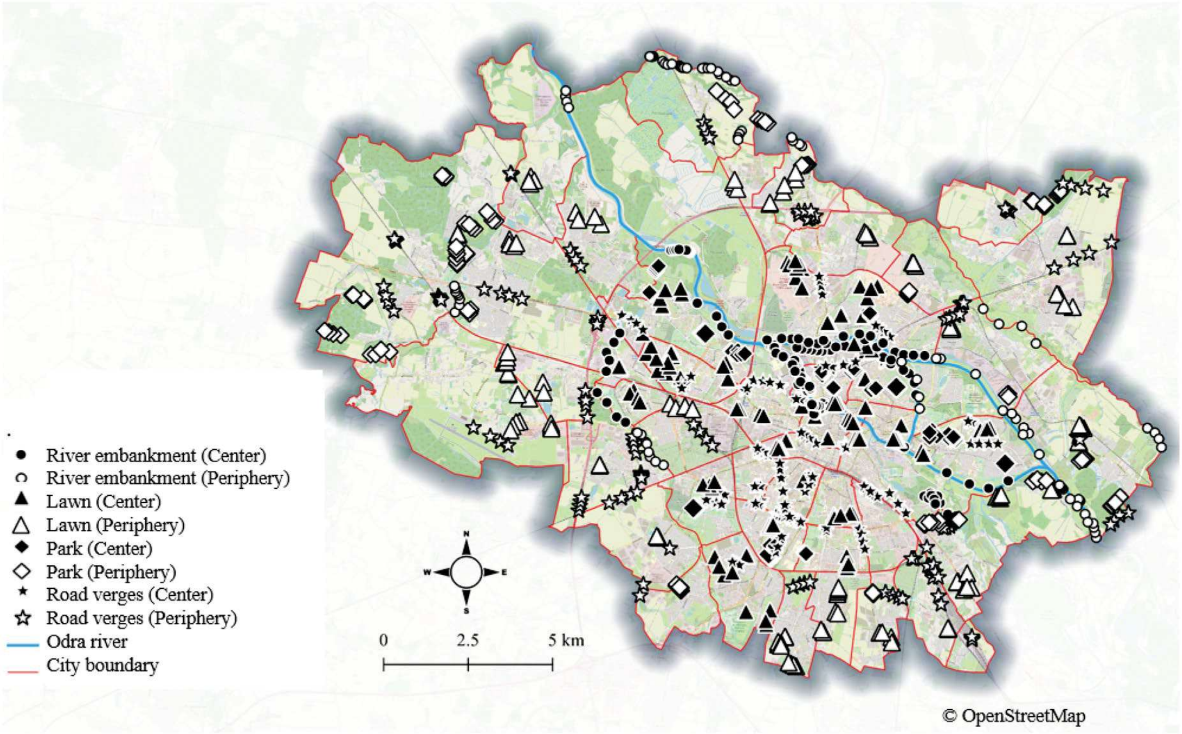

Fig. 1 Distribution of sampling plots within Wroclaw City; each point represents 1 plot, which is equal to 1 m^2. The background layer: OpenStreetMap contributors (https://www.openstreetmap.org/copyright)

The vascular plant species richness (N) that occurred in each plot was also calculated.

Soil chemical analysis

Standard methods were used for soil chemical analysis: Kiejdhal's method for total nitrogen content (N %), the Egner–Riehm spectrophotometric method for available P (mg*kg^{-1}); flame photometry for available K (mg*kg^{-1}) using ammonium acetate ($C_2H_7NO_2$), elemental analysis for C (%), and spectrophotometry with titanium yellows for available Mg (mg*kg^{-1}); The flame photometer method was used for the available form of Ca (mg*kg^{-1}), soil pH in water, and KCl by potentiometric method (Sparks et al., 2020). The C:N and N:P ratios are also considered for the statistical analysis. For N:P calculation, N % was converted to mg*kg^{-1}.

Metal analysis

The total concentration of metals including Cd, Pb, Zn, Cu, Mn, Al, and Fe was measured after microwave digestion with aqua regia (HCl:HNO3 ratio 3:1). In short, 1 g of soil sample was digested with 10 mL of aqua regia using a microwave oven, in high-pressure PTFE beakers (Medyńska & Kabała, 2010; Microwave Plasma Atomic Emission Spectroscopy (MP-AES, 2022) Agilent Technologies). Extracts were filtered with Munktell No. 2 filters, grade 0.84 g/cm^2 (Ahlstrom Munksjö, Helsinki, Finland), and diluted with distilled water to 50 mL. Metal concentrations in obtained extracts were analyzed on Microwave Plasma-Atomic Emission Spectrometer MP-AES 4200 (Agilent Technologies, Santa Clara, CA, USA). Provided results are means from triplicate measurements, with the relative standard deviation automatically calculated by MP Software. (Medyńska-Juraszek et al., 2020; Pueyo et al. 2008). Quality of determination has been monitored using soil reference materials (NIST-1515, IAEA-V-10) with a certified total content of trace elements being analyzed. This method has been internationally standardized under European regulations and Environmental Protection Agency directions (Pillay, 2020; Soodan et al., 2014). The results were compared with the Polish standard for the accumulation of hazardous elements (Dziennik Ustaw, 2016), the values are shown in (SI Table 2).

Statistical analysis

The normality of the data distribution was checked using the Shapiro–Wilk test. Because the distribution often differs from normal, and different forms of data transformation to obtain normality of the distribution not always were successful, the Kruskal–Wallis ANOVA by ranks, with multiple comparisons of the median as the post hoc tests were applied to check the significant differences between groups in median values. The correlations between the analyzed traits were checked using Spearman rank correlations. To elucidate general patterns of analyzed traits, variability of Principal Component Analysis (PCA) was performed. Prior to the PCA, the data were normalized, and the lacking data values in Cd content were subtracted by the iterative imputation approach. The number of the analyzed axis was chosen based on the "brocek stick" approach, and the first analysis reveal the ordination was strongly biased by two samples, 35 and 40; thus, they were removed from the final PCA analysis. The analysis was performed using Statistica (version 13) and Past software, with a significance level of $p < 0.05$.

Results

Soil chemical properties

The urban soil from grasslands in Wrocław had an almost neutral reaction (mean value $pH_{H2O} = 6.93$, $pH_{KCl} = 6.37$). The minimum soil pH $_{KCl}$ and pH_{H2O} was approximately 5, and the maximum soil pH was from 7 to 8. There were no significant differences in the concentration of the analyzed elements or the ratios between them within grassland patches located in the city center or periphery, or belonging to different UGTs (embankments, parks, lawns, and road verges), except for the available K concentration (Table 2), which differed significantly among different grassland types and locations. The available K concentration was the highest in soils collected from lawns and the lowest in embankments soils, whereas road verges and park soils represented intermediate values (Fig. 2A). In the case of interaction, the post hoc tests were not able to detect differences between particular groups (Fig. 2B), contrary to the results of

Table 2 Kruskal–Wallis ANOVA results (chi^2, *p* value) for differences in chemical element content for different locations, urban grassland types, and the interaction of these factors (* during N:P calculation N % was converted to mg*kg^{-1})

	Location		**Urban grassland-type**		**Interaction**	
	H (chi^2)	***p***	**H (chi^2)**	***p***	**H (chi^2)**	***p***
N [%]	2.05	0.15	4.78	0.19	8.49	0.29
P [mg*kg^{-1}]	0.04	0.85	7.35	0.06	10.77	0.15
K [mg*kg^{-1}]	0.00	0.96	15.82	0.00	16.72	0.02
pH (KCl)	0.13	0.72	0.68	0.88	1.10	0.99
pH (H_2O)	1.85	0.17	1.23	0.74	4.99	0.66
C [%]	0.43	0.51	2.26	0.52	6.82	0.45
Mg [mg*kg^{-1}]	0.03	0.86	3.90	0.27	11.99	0.10
Ca [mg*kg^{-1}]	3.33	0.07	0.63	0.89	4.88	0.67
C/N	0.00	0.99	0.15	0.98	3.24	0.86
N/P*	0.01	0.88	6.71	0.08	10.25	0.17

Table 2. Detailed data concerning the soil's chemical properties are presented in (SI Table 1).

Metal content in grassland soils

Generally, the soils from grasslands in the city center experienced higher metal deposition than those located in the urban periphery, especially grassland soil that occurred in road verges.

There were significant differences in the total concentration of metals, including Cd, Pb, Zn, and Cu (*p* value < 0.05), which depended on the patch location (center vs. periphery) and the interaction of location and UGT, whereas the total concentration of Cu and Mn varied with UGT (Table 3). The mean value of Cd, Pb, Zn, and Cu was higher in soil collected from plots located in the city center compared to that of the periphery (Fig. 3).

The mean concentration of Cu in road verges was higher than that for other UGTs; however, it differed significantly from embankments (Fig. 4A). It was also observed that Cu concentration was higher in the soils of road verges in the city center than in other UGT located in the center and periphery; except for parks of periphery which shows the same mean value like road verges of the central part (Fig. 5D). The mean concentration of Mn was higher in park soils than in embankments and lawns (Fig. 4B). The mean concentration of Cd was higher in parks located in the city center than in parks and embankments located in the periphery and lawns in the central part of the city (Fig. 5A). The mean concentration of Pb was higher in road verges and parks located in the city center than in embankments and lawns in the periphery (Fig. 5B). The mean Zn concentration was higher in road verges in the city center and differed from other UGTs except for embankments and parks in the city center, and it

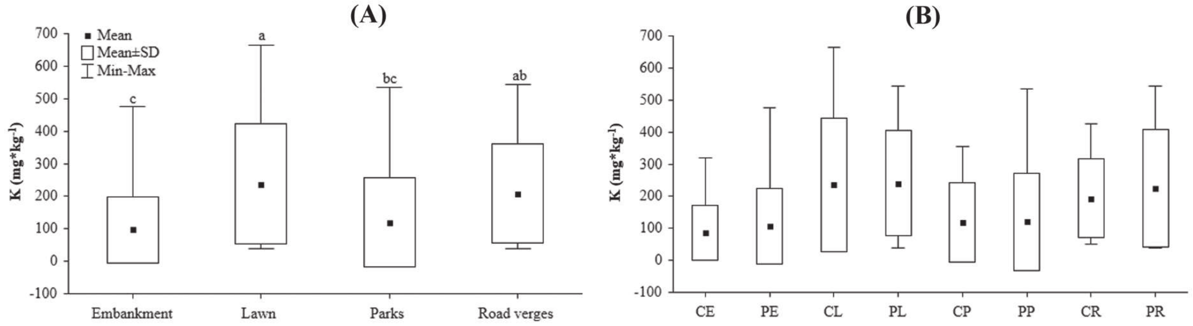

Fig. 2 Differences in potassium content among soils from different urban grassland type (UGT) types (**A**) and the combination of localization and UG types (**B**). Abbreviations: city center (C), urban periphery (P), embankments (E), lawns (L), parks (P), and road verges (R)

Table 3 Kruskal–Wallis ANOVA results (chi^2, *p* value) for differences in heavy metal content for different locations, urban grassland types, and the interaction of these factors

Variable	Location		Urban grassland-type		Interaction	
	H (chi^2)	***p***	**H (chi^2)**	***p***	**H (chi2)**	***p***
Cd [mg*kg^{-1}]	6.28	0.00	2.25	0.41	13.67	0.02
Pb [mg*kg^{-1}]	25.22	0.00	5.88	0.12	32.03	0.00
Zn [mg*kg^{-1}]	12.41	0.00	3.46	0.33	18.88	0.01
Cu [mg*kg^{-1}]	12.65	0.00	10.01	0.02	25.25	0.00
Mn [mg*kg^{-1}]	0.13	0.71	8.00	0.05	9.28	0.23
Al [mg*kg^{-1}]	0.03	0.87	4.72	0.19	6.35	0.50
Fe [mg*kg^{-1}]	0.78	0.38	3.87	0.28	5.64	0.58

was lowest in soils in parks located in the periphery (Fig. 5C). Basic descriptive statistics of metal content in the collected soils is presented in (SI Table 2).

Vegetation coverage on urban grasslands

The average total vegetation cover for urban grassland was approximately 70% of the plots, bare soil cover was approximately 10%, and plant litter was approximately 20%; for details, see (SI Table 3). Within the average vegetation cover, the grasses had the highest average cover at 42%, followed by herbs and mosses at approximately 25% and 1.6%, respectively. The analysis indicated that the vegetation parameters did not differ among UGTs and locations, except for bare soil coverage, which was significantly higher in lawns placed in the city center (Table 4 and Fig. 6).

Among the observed traits (SI Fig. 1), we found a significant negative correlation of species richness with N, P, and C content in the soils, as well as grass cover, while there was a positive correlation with herb cover. Grass cover correlated positively with N content in the soils, while herb cover negatively correlated with N and K. We also observed significant positive correlations between herb cover and the content of heavy metals such as Cd, Pb, Zn, and Cu. The content of Cd, Zn, Mn, and Fe also correlated positively with the percentage of bare soil (SI Fig. 1).

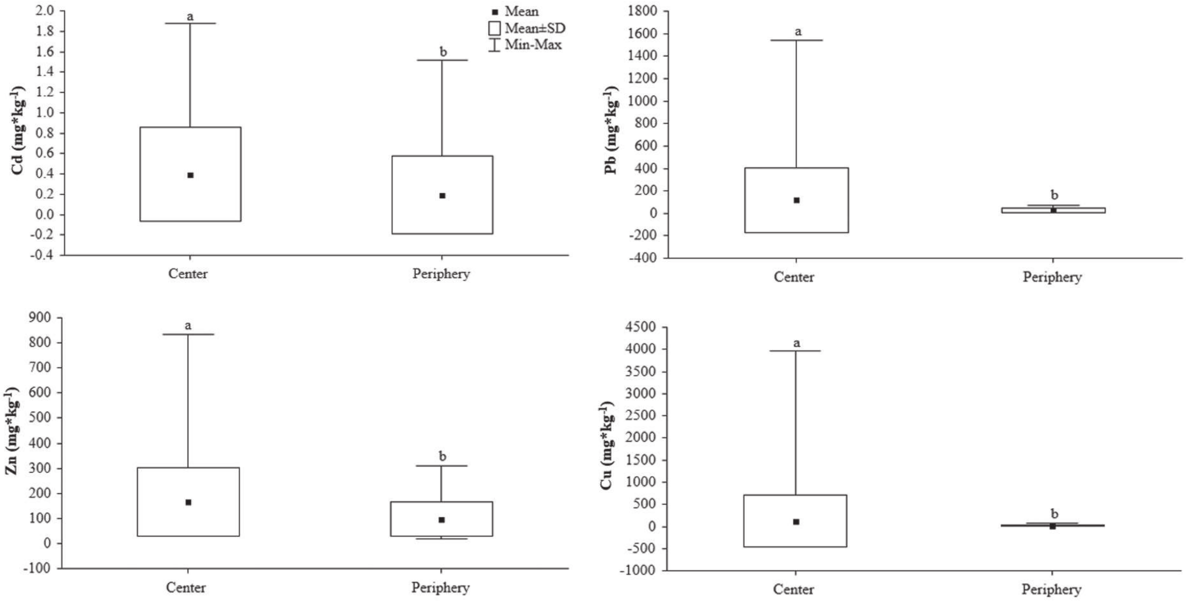

Fig. 3 Differences in heavy metal (lead, cadmium, zinc, and copper) content in different sampling locations [city center (C) and periphery (P)] in the city

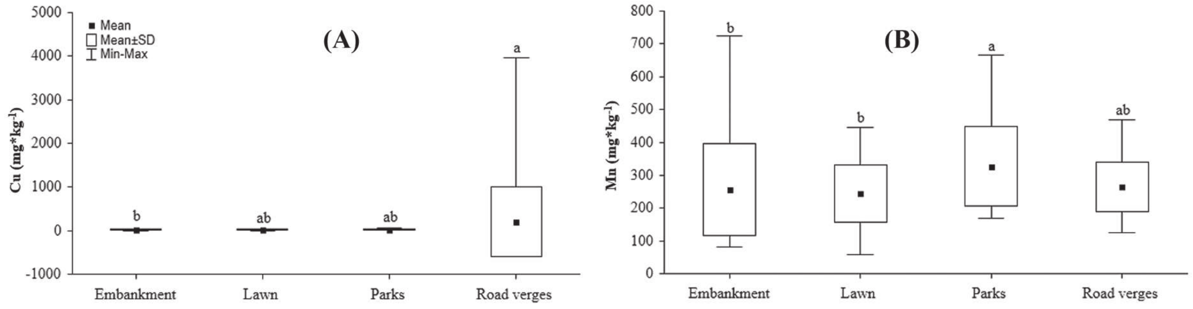

Fig. 4 Differences in heavy metal content: **A** copper and **B** magnesium in different UGT

The first four axes of PCA explain 46.87% of the entire set data variation. The first PCA was correlated positively with the metal concentrations, except Pb (Table 5, Fig. 7). The second with the vegetation traits: the bare soil and litter cover was correlated negatively with species richness and plant cover. The third axis can be interpreted as an effect of N and K over fertilization, which increases grass cover while decreasing species richness and herbs and mosses cover. The N and K concentrations correlated also negatively with pH. The fourth axis reveals the effect of P concentration in soils, which influences the N/P ratio. This axis correlate also positively with pH but negatively with Ca concentration (Table 5, Fig. 7).

Discussion

Our results did not confirm our hypothesis regarding differences in macroelements and pH between particular UGTs and patch localities: the variability within distinguished groups exceeded the differentiation between UGTs and localities. The exception was available K concentration, but its variable pattern is not easy to explain. Intuitively, the higher K content in lawns can be related to their fertilization (Cekstere & Osvalde, 2013; Ignatieva et al., 2020), but in Poland, the typically used fertilizers are NPK (Gospodarczyk & Rutkowska, 2006). However, here, the observed patterns of P and N content are not

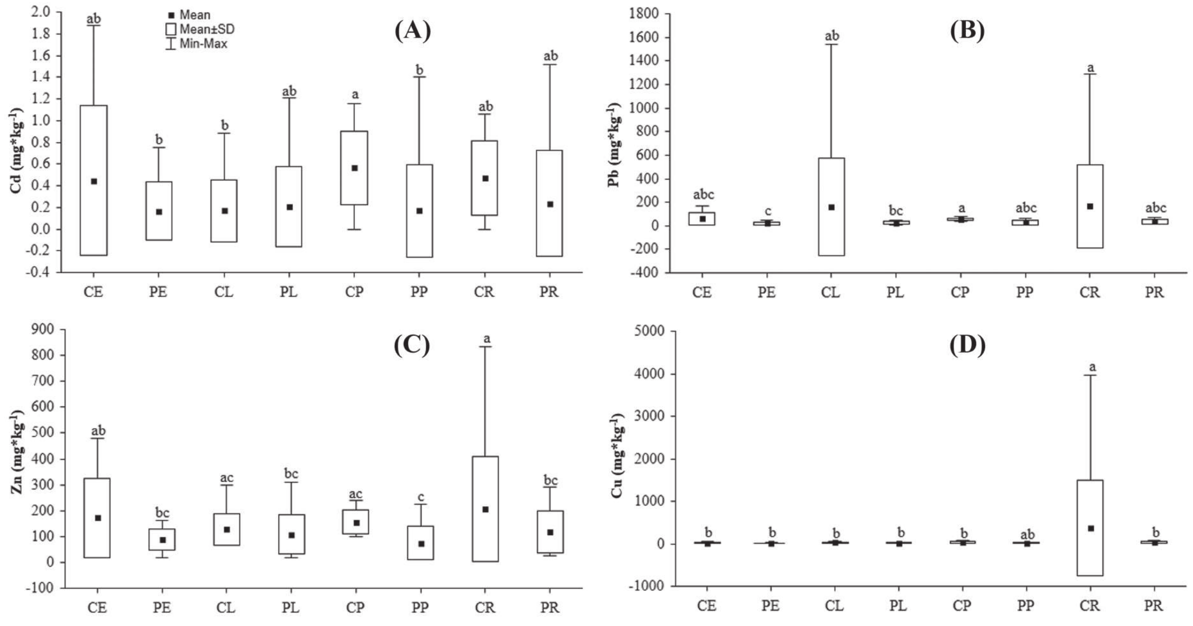

Fig. 5 Differences in heavy metal content: **A** cadmium, **B** lead, **C** zinc, and **D** copper for the interaction of UGT and location of grasslands. Abbreviations: city center (C), urban periphery (P), embankments (E), lawns (L), parks (P), road verges (R)

Table 4 Kruskal–Wallis ANOVA (chi^2, *p* value) results for the vegetation coverage for different locations, urban grassland types, and the interaction of these factors

	Location		Urban grassland-type		Interaction	
	H(chi^2)	*p*	H (chi^2)	*p*	H (chi^2)	*p*
Total vegetation cover (%)	0.71	0.40	7.25	0.06	8.61	0.28
Grass cover (%)	0.92	0.34	6.91	0.07	9.84	0.20
Herb cover (%)	0.16	0.69	4.47	0.21	9.93	0.19
Mosses cover (%)	0.42	0.44	1.95	0.40	2.90	0.74
Bare soil cover (%)	11.65	0.00	8.37	0.04	19.60	0.01
Litter cover (%)	1.49	0.22	1.40	0.71	5.01	0.66
Vascular plant species richness (N)	0.21	0.65	3.41	0.33	4.95	0.66

correlated with K (SI Fig. 1); thus, it is unlikely that the high K levels result from lawn fertilization.

The range of pH variability in urban areas can be related to the effect of human activities. Mostly, the soils of Wrocław exhibited a nearly neutral pH, whereas according to majorities of studies, urban soil pH is slight to very strongly alkaline, which is typical of urban soils (Yang & Zhang, 2015). A neutral or moderately alkaline pH is beneficial to ecosystems since it can avoid the movement of hazardous elements such as heavy metals, which are dangerous to humans and beneficial organisms. At the soil-particle surface, trace metals are immobilized due to the high pH (Ge et al., 2000), where metal solubility decreases by increasing soil pH (Chuan et al., 1996). This also occurs because of a high cation exchange capacity that can bind contaminants (Kargar et al., 2015). A few plots exhibited an alkaline soil reaction, which can be attributed to the presence of construction materials in the soils, such as concrete and cement, contamination by ash from coal-fired powder, or even sands that are used for gritting (Birke et al., 2011; Gaberšek & Gosar, 2018). Rather, the presence of patches with acidic soils can be attributed to possible soil transportation from other, non-urban sites. Nonetheless, recent studies revealed that in urban regions, nitrogen (N) and sulfur (S) deposition could cause soil acidification, but these observations came from regions with a warm and humid climate (En-Qing et al., 2015; Huang et al., 2015), and they are rather unlikely to occur in a temperate climate. However, building materials such as concrete and mortar contain calcium carbonate, which can make urban soils more alkaline than expected (Asabere et al., 2018). The alkaline soil pH can negatively impact the plant and soil organisms in the cities, creating a habitat more suitable for non-native species (Delgado-Baquerizo et al., 2021; McKinney, 2006).

Contrary to macroelements and pH, we observed significant differences in metal concentration among the UGTs and locations of urban grasslands. The grassland soils in the central part of the city had a higher metal content, which can be attributed to urban activities. Human activities such as vehicular traffic,

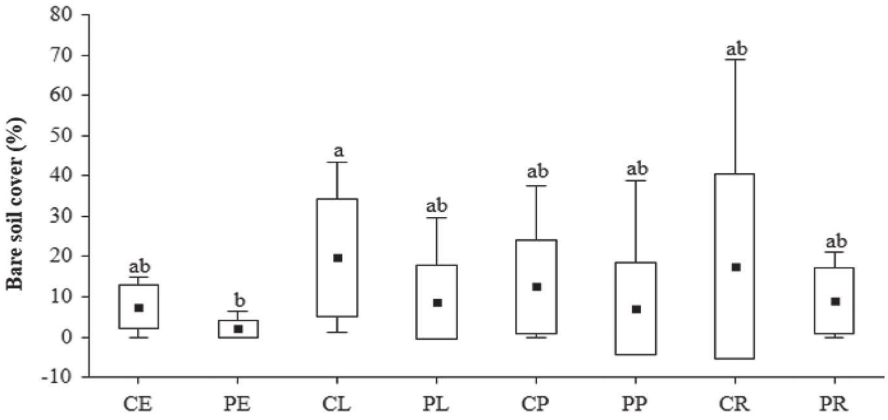

Fig. 6 Differences in bare soil cover in grasslands located in the city center/periphery (**A**), different UGT (**B**), and interactions of location and UGT (**C**). Abbreviations: city center (C), urban periphery (P), embankments (E), lawns (L), parks (P), and road verges (R)

Table 5 The loadings values of particular variables in the Principal Component Analysis axis

Variable name	PC 1	PC 2	PC 3	PC 4
pH [KCl]	0.0640	0.1323	**−0.2314**	**0.2890**
pH [H_2O]	0.0933	0.0990	**−0.2722**	**0.3878**
Cd	**0.4484**	0.1568	0.0274	−0.0065
Pb	0.0441	0.0741	0.0533	0.0383
Zn	**0.3562**	0.0505	0.1007	−0.0472
Cu	**0.3450**	−0.0222	0.0877	−0.0677
Mn	**0.3505**	0.0044	−0.0642	−0.0558
Al	**0.3346**	0.0003	0.0710	−0.1032
Fe	**0.4574**	−0.0261	0.0603	−0.0658
N	0.0004	−0.0052	**0.4724**	−0.0198
P	0.0314	−0.0357	0.1174	**0.5784**
K	0.1270	−0.1278	**0.2104**	0.1415
C	−0.1171	−0.1419	**0.2323**	−0.0558
Mg	0.0969	0.0375	0.1314	0.1944
Ca	0.0171	−0.0376	0.0857	**−0.2101**
C/N	−0.0467	−0.0762	−0.1304	0.0319
N/P	−0.0074	−0.0009	−0.0634	**−0.4739**
Total vegetation cover	−0.0816	**0.5553**	0.1516	−0.0149
Grass cover	−0.1343	**0.2710**	**0.4011**	−0.0123
Herb cover	0.0643	**0.3862**	**−0.2222**	0.0391
Mosses cover	−0.0507	0.0501	**−0.3752**	−0.1393
Bare soil cover	0.1262	**−0.3238**	−0.1166	0.0959
Plant litter cover	0.0297	**−0.4268**	−0.0996	−0.0622
Vascular plant species richness	0.0588	**0.2684**	**−0.2449**	−0.1993
Explained variation [%]	17.53	11.64	10.04	7.66

The largest values (above absolute value 0.2) in a particular axis are highlighted in bold

urbanization, and increased population density usually correlate with an increase in metal content in urban soil (Mónok et al., 2021; Argyraki & Kelepertzis, 2014). This was clear for road verges located in the city center. We linked this phenomenon to higher car traffic, which is an important source of metals (Adamiec et al., 2016; Napier et al., 2008; Silva et al., 2021). Typically, the main source of metals is brake and tire wear, motor oil, and traffic for Zn, brake wear, stop points, and traffic for Cu, tire wear for Cd, and brake, oil and additives, gasoline, and traffic for Pb, where high volumes of traffic occur (Bari & Kindzierski, 2017; Crosby et al., 2014; Ferreira et al., 2016; Hsu et al., 2017; Nawrot et al., 2020). Despite the use of unleaded gasoline,

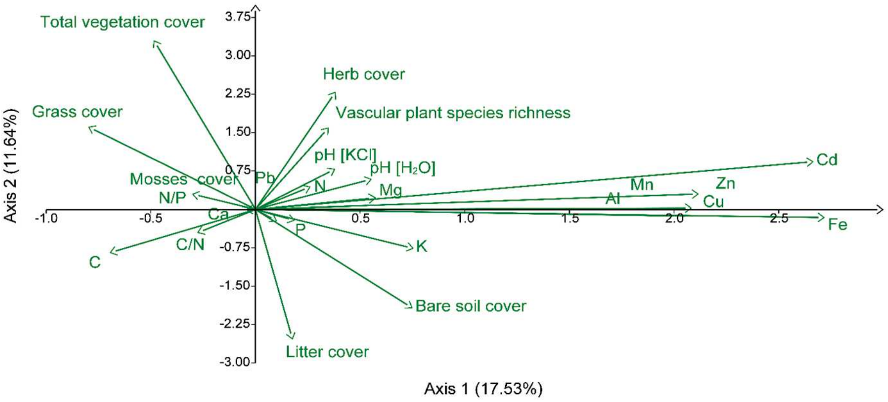

Fig. 7 The biplot of two first axis of Principal Component Analysis

gasoline emission still was the main source of Pb in a study by Hong et al. (2018). In two patches belonging to road verges and lawns located in the city center, the concentration of Pb, Zn, and Cu even exceeded the background level authorized by the Polish standard for the accumulation of hazardous elements (SI Table 2, Fig. 2). This may increase the risk of human-related diseases in the long term (Lamas et al., 2016).

In the case of the vegetation, our observations suggest that the higher soil fertility, as expressed by nitrogen, phosphorus, and carbon amount, decreased species richness by increasing the cover of grasses at the expanse of herbs—such a phenomenon was reported for semi-natural grasslands (Ceulemans et al., 2013; Harpole & Tilman, 2007). The results suggest that physical disturbances of the vegetation coincide with contamination with metals, but they were beneficial for herbs. We did not have detailed data regarding plant species composition, but it can be assumed that strongly competitive grass species dominated the vegetation on more fertile and undisturbed sites, while disturbances causing the presence of bare soil which create empty niches for ruderal herb species (Nabe-Nielsen et al., 2021), which increase species richness in urban grasslands. Nonetheless, the observed regularities were rather independent of UGT and periphery, except for bare soil cover, which showed a higher percentage of lawns placed in the city center compared to embankments in peripheries and can be directly related to anthropogenic disturbances such as trampling by pedestrians (Wang et al., 2018).

Conclusions

Obtained results show differentiation of soil and vegetation traits of urban grasslands, which is usually not structured regarding urban grassland type and patch locations (city center vs periphery). Considering the fertility of the soils, lawn soils contain only a higher concentration of K, than other UGT, but the value did not differ from road verges. A higher amount of heavy metals was detected in road verges located in the city center compared to other UGTs. The prominent, and rather easy-to-explain, patterns were exhibited by heavy metals whose concentrations were higher in the city center. The general correlations between vegetation traits and soil properties were mainly related to the decrease of biodiversity on UG with more fertile soils and the increase of herb and bare soil cover on UG with higher metal content. Moreover, the results suggest a positive effect of contemporary management on species richness, which allows establishing a herb species while increasing soil fertility to increase the cover of grass species leading to a decrease in total vascular plant species richness.

The observed concentration of heavy metals exceeded the allowed standards in patches located in the city center, suggesting the necessity of continuous monitoring of heavy metals in urban soils.

Acknowledgements The authors are thankful to Mgr inż Agnieszka Falkiewicz and Mgr inż Joanna Nowak for support during the lab work, as well as Ph.D. students Mr. Kacper Nowak during the soil sampling, and Miss Magdalena Bednik for the scientific consultation. We also appreciate Oxford Editing (https://oxfordediting.com) for the English language review. Map data is copyrighted from OpenStreetMap contributors and available from https://www.openstreetmap.org.

Author contributions Conceptualization: Hassanali Mollashahi, Magdalena Szymura, Tomasz H. Szymura. Formal analysis: Hassanali Mollashahi, Magdalena Szymura,Tomasz H. Szymura. Funding acquisition: Hassanali Mollashahi, Magdalena Szymura. Investigation: Hassanali Mollashahi, Magdalena Szymura, Tomasz H. Szymura. Methodology: Hassanali Mollashahi, Magdalena Szymura, Peliyagodage Chathura Dineth Perera, Tomasz H. Szymura. Software: Hassanali Mollashahi, Magdalena Szymura, Tomasz H. Szymura. Supervision: Magdalena Szymura. Writing – original draft: Hassanali Mollashahi, Magdalena Szymura, Tomasz H. Szymura. Writing—review & editing: Hassanali Mollashahi, Magdalena Szymura, Peliyagodage Chathura Dineth Perera, and Tomasz H. Szymura. The authors read and approved the final manuscript.

Funding The publication is financed by the project “UPWR 2.0: international and interdisciplinary programme of development of Wrocław University of Environmental and Life Sciences” and co-financed by the European Social Fund under the Operational Program Knowledge Education Development, under contract No. POWR.03.05.00–00-Z062 / 18 of June 4, 2019.

Data availability All relevant data are within the manuscript and its Supporting Information files.

Declarations

Ethical approval All authors have read, understood, and have complied as applicable with the statement on “Ethical responsibilities of authors” as found in the Instructions for Authors and are aware that with minor exceptions, no changes can be made to authorship once the paper is submitted.

Conflict of interests The authors declare no competing interests.

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