Received: 21 August 2023 | Revised: 6 December 2023 | Accepted: 10 December 2023

DOI: 10.1002/ldr.5017

RESEARCH ARTICLE

WILEY

Fragmentation and biodiversity change in urban vegetation: A case study of tram lines

Jan Winkler[1] | Eugeniusz Koda[2] | Jana Červenová[1] | Krzysztof Napieraj[3] | Mariusz Żółtowski[2] | Aleksandra Jakimiuk[2] | Anna Podlasek[2] | Magdalena Daria Vaverková[2,4]

[1]Department of Plant Biology, Faculty of AgriSciences, Mendel University in Brno, Brno, Czech Republic

[2]Institute of Civil Engineering, Warsaw University of Life Sciences, Warsaw, Poland

[3]Bydgoszcz University of Technology, Construction, Architecture and Environmental Engineering, Bydgoszcz, Poland

[4]Department of Applied and Landscape Ecology, Faculty of AgriSciences, Mendel University in Brno, Brno, Czech Republic

Correspondence
Magdalena Daria Vaverková, Institute of Civil Engineering, Warsaw University of Life Sciences, Nowoursynowska 159, 02 776 Warsaw, Poland.
Email: magdalena.vaverkova@mendelu.cz; magdalena_vaverkova@sggw.edu.pl

Abstract

This study explores the vegetation composition along various tram line sections in Bydgoszcz, Poland, with a focus on understanding the impact of usage, maintenance, and historical development on urban vegetation dynamics. This study addresses this knowledge gap by investigating how these factors influence plant species composition, leading to variations in the prevalence of native and non-native species. The aim of this study is to contribute to urban ecological knowledge and inform vegetation management strategies. The investigation centers on five tram line sites representing different usage and maintenance scenarios: Unused line, New line, Loop rec, Loop old, and Old line. Through phytocoenological relevés conducted in 2020 and 2021, we measured the plant taxa coverage. Detrended Correspondence Analysis (DCA) and Canonical Correspondence Analysis (CCA) revealed relationships between plant species and tram line sites. The results indicated the presence of 107 plant taxa, with graphical representations highlighting the prevalent species on each tram line section. Older sections showed a higher representation of non-native plant species, whereas new sections exhibited native species dominance. Moisture-indicative values suggest an affinity for soils with average moisture content. CCA provides insights into the relationships between plant taxa and site variants and offers valuable implications for urban vegetation management and conservation strategies. The novelty of this study lies in its holistic approach for understanding how multiple factors interact to shape urban vegetation. By illuminating urban ecological dynamics and informing decision-making processes, this study contributes to urban planning, ecology, and biodiversity conservation. Additionally, this study fills a knowledge gap by providing insights into the unique ecological dynamics and species composition of tram lines in urban environments. Unlike previous research in Central European countries focusing on planted vegetation, this study explored the spontaneous spread of plants and successional patterns along tram lines, enhancing our understanding of the environmental conditions created by tram lines that influence vegetation composition and development.

KEYWORDS
biodiversity, native and non-native species, transportation, urban ecology, urban vegetation dynamics, vegetation management

1 | INTRODUCTION

The world is experiencing rapid growth in towns (Mansur et al., 2022). The urban landscape is a backdrop for 55% of the world's population and this number is expected to grow (Guyot et al., 2021). The contemporary stage of human history is often referred to as the "urban century" (Vega et al., 2021). Towns are considered to be the greatest invention of mankind, a way of living that has many advantages, including higher economic productivity and innovation, better opportunities for education and individual development, and more efficient exploitation of natural resources and energy (McDonald & Beatley, 2020). The urban century also represents a challenge to the global environment, both directly by sprawling urban development, and indirectly by the consumption of energy and resources in towns (McDonald et al., 2018). Human civilization is forced to look for new ways to maintain the biological diversity of ecosystems in towns and cities (Elmqvist et al., 2019; Kueffer, 2020; McDonald et al., 2018). The Convention on Biological Diversity currently prepares a global framework for biodiversity after 2020, that aims to determine new global goals in the field of biological diversity in the coming decades. The goals are in line with the common vision of "mankind living in harmony with nature," which is to be achieved by 50 (Mansur et al., 2022).

Growing fear of the global loss of biological diversity and understanding of ecosystem functions and services creates space for the promotion and extension of urban green infrastructure (Andersson et al., 2014; Aronson et al., 2017; Fischer et al., 2018; Lepczyk et al., 2017; Winkler, Vaverková, & Havel, 2023). Contemporary towns represent a mosaic of different habitats, including urban greenery, in multiple forms: forests, parks, wastelands, ruderal sites, grasslands, ornamental plantations, and meadows (Knapp et al., 2012; Malkinson et al., 2018). Small green areas in towns are often neglected, and greater attention has been paid to large parks and nature reserves (Gallo et al., 2017). Small green areas such as tree alleys on streets and roadsides form the majority of urban green areas, particularly in densely inhabited town cores. Because of their linear character, they make it possible to interconnect urban green areas in individual towns. Small green areas have a much higher alpha and beta diversity than large green areas, such as parks or suburban greens, which suffer from the homogenization of biodiversity and isolation from other green areas (Muvengwi et al., 2022; Vega & Küffer, 2021).

Habitat fragmentation, as explained by many ecologists (Li et al., 2022; Nisi et al., 2023; Tan et al., 2023; Zaręba et al., 2022), typically leads to the isolation of species populations within smaller patches, resulting in restricted movement and gene flow. This can be detrimental to biodiversity by increasing the vulnerability of species to extinction and by disrupting ecological processes. Land fragmentation in agriculture often involves the division of large fields into smaller plots, which can affect the efficiency of agricultural operations. However, as shown by research, such as the study of farmland fragmentation in the Qilu Lake watershed (Yu et al., 2022; Zhang et al., 2023), it can have a positive impact on agricultural production efficiency, especially when managed at an appropriate scale. Smaller fragmented plots are sometimes more manageable and allow for more diversified crop rotations, which can increase productivity.

Fragmentation can also create habitats with different living conditions, which changes the structure of the vegetation and thus the entire ecosystem. The heterogeneity of living conditions allows new plant species to grow and enrich biodiversity. Sites with strong human influence are more often characterized by homogeneous living conditions. Fragmentation of anthropogenic landscape conditions can be a way to promote biodiversity.

In the Anthropocene, the extent of ecosystems in which human civilization had become a dominant ecological power expanded (Ellis, 2011; Vega et al., 2021). Human activity generates many specific habitats that are suitable for plant development. Tram and railway lines are synanthropic habitats that host specific plant species (Heneidy et al., 2021; Májeková et al., 2021; Rendeková et al., 2020). Urban vegetation of the tram lines was intentionally seeded, but some plant species occurred spontaneously. Tram lines represent specific ecological migration corridors for plants (Rendeková et al., 2020; Woźnica et al., 2016) under specific living conditions. Plants had to adapt to this special environment, which led to the development of unique properties in them (Woźnica et al., 2016).

Tram lines are more than just transportation infrastructure; they are essential components of urban infrastructure that serve important functional roles and possess unique properties (Gössling & McRae, 2022; Qiao et al., 2022). As a form of public transportation, tram lines provide efficient and sustainable mobility options within cities, contributing to improved accessibility and reduced reliance on private vehicles (Balaban & de Puppim, 2022; Coppola & Lobo, 2022). Tram lines are artificial biotopes (Dziuba et al., 2022) that create specific habitats for plants (Rendeková et al., 2020; Woźnica et al., 2016). The construction and maintenance of tram lines create unique environmental conditions that can foster the establishment and growth of plant communities (Saggau et al., 2023). These specific conditions provide an opportunity for plant species to adapt to external stress. Tram lines often form linear features that create edge effects between the track and the adjacent habitats. Edge effects refer to ecological changes and unique conditions that occur at the boundaries between different ecosystems (Papp et al., 2022). The transition zone between the tram line and the surrounding vegetation can provide niche opportunities for plant species adapted to intermediate light conditions and edge habitats (Dziuba et al., 2022; Rendeková et al., 2020). They must also deal with traffic trampling and mechanical disturbances (Liu et al., 2009; Sudnik-Wójcikowska & Galera, 2005). The specific conditions of tram lines provide an opportunity for non-native plant species (Rendeková et al., 2020) to spread to adjacent ecosystems. Species composition shows that tram lines also change moisture conditions (Dziuba et al., 2022). Many plant species growing at these sites are tolerant of heavy mechanical disturbances and toxic substances. Although tram lines occur in many towns and cities, their flora has not been thoroughly investigated. Therefore, the aims of this study were to: (i) assess the taxonomic composition of vegetation growing on tram line sections under different conditions; (ii) determine the relationship between some plant species and functional plant groups under different tram line conditions; (iii) evaluate the ecosystem functions of tram line vegetation; and (iv) characterize trends in the fragmentation of tram line vegetation with different management strategies. Owing to their unique characteristics, the biotopes of tram lines should be included in urban botanical research to contribute to the understanding of the functions and changes in the vegetation of urban ecosystems.

This study contributes new global knowledge by shedding light on the unique ecological dynamics and species composition of tram lines in urban environments. While existing research on the flora of tram lines in Central European countries has predominantly focused on planted vegetation, this study delves into the spontaneous spread of plants and successional patterns observed. Tram lines create distinctive environmental conditions that influence the composition and development of vegetation.

2 | MATERIALS AND METHODS

2.1 | Description of the study area

The study was conducted in Bydgoszcz, Poland (53°07′27.6″N 18°00′31.1″E). Bydgoszcz is situated in the north of Poland on the Brda and Vistula Rivers. With 339,053 inhabitants (December 2021) and an urban agglomeration of more than 470,000 inhabitants, Bydgoszcz is the eighth-largest town in Poland (Taylor & Józefowicz, 2012). It is recognized for its green spaces and parks, historic mills, lush gardens, and walking paths (Sztubecka et al., 2019, 2020).

In terms of physical geography, the estate lies within the macroregion Pradolina Toruńsko-Eberswaldzka, in the mesoregion of the Toruń Valley and the microregion of the Urban Brda Valley (terraces I-III about 30–40 m above sea level). The southern outskirts of the estate are occupied by the Bydgoszcz Slope, with a relative height of approximately 27 m, carved by a system of small ravines and erosion indentations. Similarly, the western and eastern outskirts of the unit are natural boundaries formed by ravines, that lead to communication arteries (Kujawska Street, Jana Pawła II Avenue). The northern border is the Brda River.

Bydgoszcz was chosen as the study area because its urban characteristics and well-developed tram network make it a relevant context for studying the ecological dynamics of tram lines. This choice of location allowed us to study the impact of tram lines on urban vegetation in a diverse and ecologically relevant setting.

The communication system in Bydgoszcz mirrors the area-development system and has a linear character. It has a distinct section along the E-W axis and a relatively short N-S axis. Babia Wieś is an urban unit (housing estate) of Bydgoszcz, between the Brda River and downtown Bydgoszcz. The first trams in Babia Wieś were built in 1898, when the "green" line was extended from Zbożowy Rynek along Toruńska Street to Strzelnica (Żupy Street). In 1914, the tram line extended in the direction of Małe Bartodziejów to the Bełzka Street (Toruńskie roundabout). The work was interrupted due to the outbreak of World War I. After World War II, in the years 1952–1953, a new tram line "Brda" was put into use, connecting Old Town with Kapuściska and gnow. A tram loop was built in Babia Wieś, and the tracks were laid along Babia Wieś and Toruńska streets. The complex of tram lines called "Brda" from Babia Wieś to Łęgnowo, Kapuściska and Glinki was constructed in 1953 together with other five tram lines. In 1956–1959, a new tram depot was built. The Pomorski Bridge with tram lines was put into operation in 1970. In 1974, the comprehensive modernization of rails was carried out on the upper-town terrace, and a tram line was built into the Magnuszewska tram terminal, which was extended to Karpacka St. in 1984. The tram loop of Babia Wieś with the connected tram lines was operated until 2001. Subsequently, part of the tram loop and line was reconstructed and is currently not used for tram transport.

Five tram line sites were chosen in the studied section, which differs in the way they are used: (i) Unused line: the tram line section is not used for transport and is not maintained; continuous vegetation succession is on (Figure 1a); (ii) New line: the tram line section that was reconstructed but not used for transport; vegetation succession was disrupted by gravel boxing exchange (Figure 1b); (iii) Loop rec: the tram loop section that was reconstructed; the vegetation is maintained by mowing, and its succession is disturbed by vegetation management (Figure 1c); (iv) Loop old: the tram loop section that was not reconstructed; the vegetation is maintained by mowing and its succession is disturbed by vegetation management (Figure 1d); (v) Old line: the tram line section that is not used for transport; the vegetation is maintained by mowing and its succession is disturbed by vegetation management (Figure 1e).

In terms of water-related considerations, Bydgoszcz is situated in proximity to both the Vistula and Brda Rivers, with the Brda River running near the study area. According to the "Flood risk management plan" map from the Hydroportal-IT System for the Protection of the Country (Figure 2), our study area is close to areas susceptible to river flooding. This information highlights the proximity to potential flood-prone zones. Conversely, as indicated by the "Drought Effects Counteracting Plan" map from the same system, the entire study area falls within a zone characterized by a moderate risk of drought.

2.2 | Vegetation inventory

Vegetation was assessed using phytocoenological relevés measuring 5 m^2. The shape of the phytocoenological relevés areas was a rectangle of 1 × 5 m; the shorter side was directed to the tram line, and the longer side along the tram line. Phytocoenological relevés were conducted on three plots for each variant, and vegetation was assessed in August 2020 and 2021. First, all plant taxa that occurred in the phytocoenological relevé were identified, and then, the coverage was estimated for the aboveground biomass of individual taxa. The scientific names of the plant species were obtained from the Pladias database of flora and vegetation (Chytrý et al., 2021).

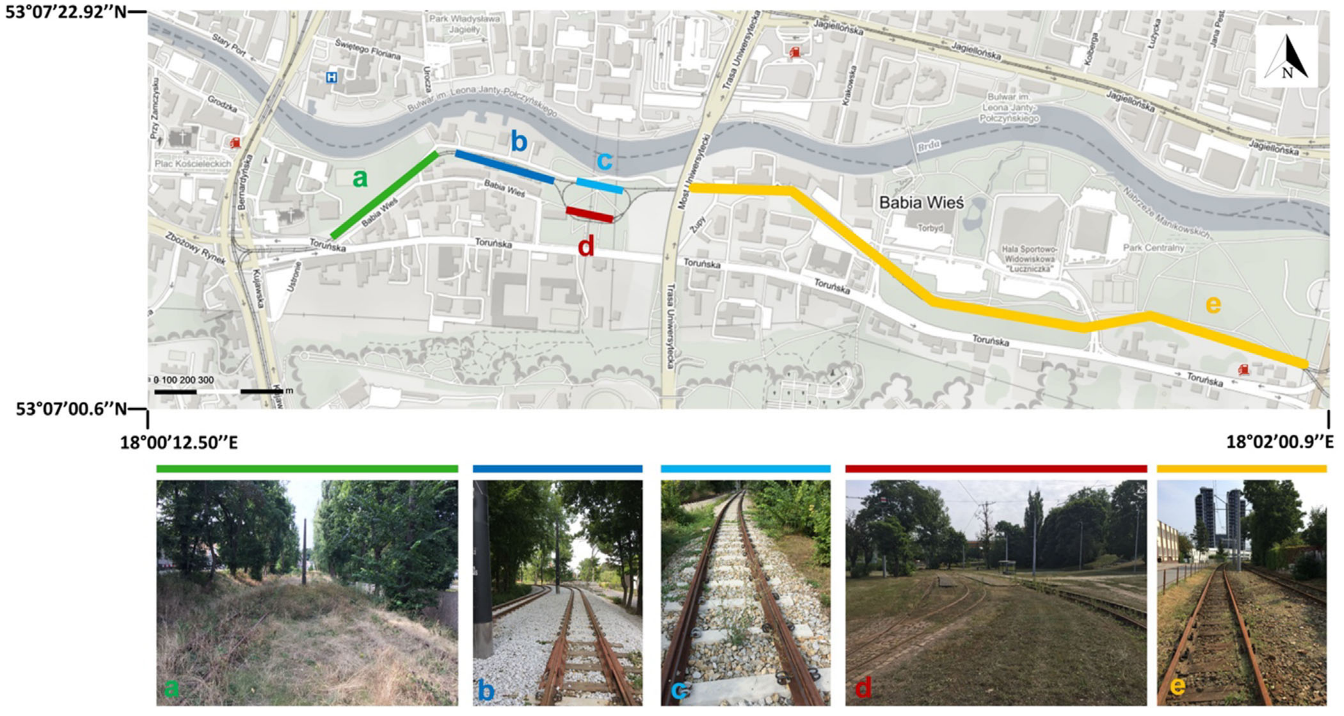

FIGURE 1 Demarcation of tram line and loop (a) unused and unused tram line section (Unused line); (b) newly reconstructed tram line section (New line); (c) newly reconstructed tram loop section (Loop rec); (d) old, maintained part of tram loop (Loop old); (e) unused and maintained tram line section (Old line). [Colour figure can be viewed at wileyonlinelibrary.com]

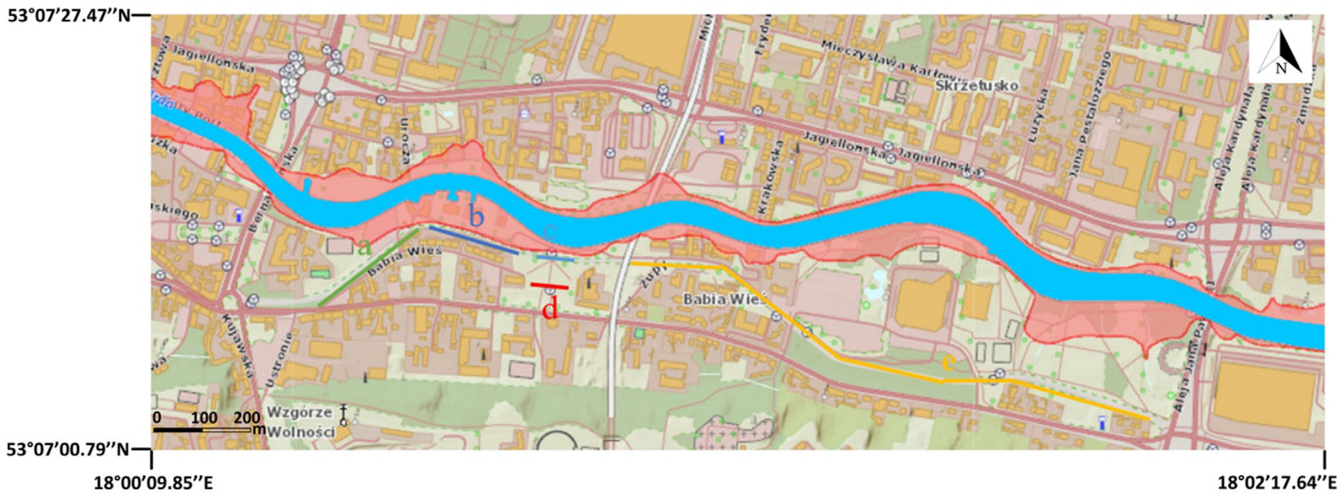

FIGURE 2 Map "Flood Risk Management Plan" in the study area (blue riverbed, red floodplain). [Colour figure can be viewed at wileyonlinelibrary.com]

Based on information from the Pladias database (Chytrý et al., 2021), plant species were classified into several groups according to the following characteristics: (i) Invasion status is the classification of non-native taxa into three groups depending on the degree of their engagement in local flora. Temporarily introduced taxa are those whose survival depends on the repeated supply of diaspores due to human activity. If they reproduce an outside culture, they are considered temporary. Domesticated (naturalized) taxa have multiplied regularly in the territory for a long time and are independent of human activities. Invasive taxa are domesticated taxa that spread rapidly in (usually extensive) territories, to a considerable distance from the mother population (Richardson et al., 2000, 2011). This classification was not used for the native taxa that were marked separately. The classification was obtained from the Catalogue of Non-native Flora of Czech Republic (Pyšek et al., 2012) with reference to the original sources of information. Categories: temporarily introduced, domesticated, invasive, and native. (ii) The indicator value for moisture was expressed on an ordinal scale from 1 to 12 (Table 1) as defined by Ellenberg et al. (1991). The values of individual taxa were adjusted and extended for the Czech flora by Chytrý et al. (2018).

TABLE 1 Indicative values for moisture.

1	Indicator of severe drought, viable on drought-prone sites and bound to dry soils
2	Transition between 1 and 3
3	Taxon missing on moist soils
4	Transition between 3 and 5
5	Indicator of fresh soils, bound to soils of average moisture content, missing on moist and often drying soils
6	Transition between 5 and 7
7	Indicator of moisture, bound to soils well supplied with water but not wet
8	Transition between 7 and 9
9	Indicator of wet, water-saturated and poorly aerated soils
10	Hydrophyte surviving for a longer time on unflooded soil
11	Hydrophyte rooting under water but with leaves above water surface at least temporarily, or plant flowing on water surface
12	Hydrophyte submerged in water constantly or nearly constantly

2.3 | Statistical analyses

The values of the coverage of individual plant species at the observed sites were processed using multivariate analysis of the ecological data. The selection of the optimal analysis was based on the length of the gradient determined by segment Detrended Correspondence Analysis (DCA). After DCA, Canonical Correspondence Analysis (CCA) was applied because the dataset was relatively heterogeneous, and therefore, the length of the ordination axes in DCA was relatively long. A Monte Carlo permutation test with 999 permutations was used to reveal the effect of the obtained explanatory variables (environmental in Canoco terminology) on plant species composition. Data were processed using the Canoco 5 computer program (Ter Braak & Šmilauer, 2012).

3 | RESULTS

3.1 | Plant taxa prevalence

In total, 107 plant taxa were identified during the monitoring period. The prevalence of these plant taxa along the monitored tram line sections is shown in Figure 3. These figures provide a graphical representation of the most frequently occurring plant taxa observed during monitoring. This information contributes to our understanding of plant biodiversity and ecological dynamics in the studied urban environments.

3.2 | Taxon coverage by invasion status

The share of taxon coverage according to the invasion status is shown in Figure 4. The older tram line sections exhibit a higher representation of non-native plant species with the "naturalized" and "invasive" status as compared with the new sections. The new and reconstructed tram line sections feature the dominant representation of native plant species.

3.3 | Taxon coverage by moisture indicative values

The share of coverage of taxa according to the indicative values for moisture is shown in Figure 5. All monitored tram line sections featured the dominant representation of species with indicative values of 4 and 5. The older tram line section exhibited a higher proportion of plant species with an indicative value of 2 or 3, that is, plant species were missing in moist soils. The unused tram line section shows an increasing share of species with indicative values of 7 and 8 (indicators of moisture bound to soils well supplied with water but not wet).

3.4 | Data analysis: DCA and CCA

The values of coverage by individual plant taxa obtained from the monitoring were processed using DCA. The adjusted explained variation was calculated as 4.05. The data were processed using CCA to establish the relationship between the plant species and tram line sites. CCA delineates the spatial arrangement of individual plant taxa and site variants. The results of the analysis are graphically expressed using an ordination diagram (Figure 6).

3.5 | Classification of plant taxa

The results of the CCA analysis, which was used to evaluate the coverage of plant taxa, were significant at a level of $\alpha = 0.001$ for all canonical axes. Based on CCA analysis, the identified plant taxa were classified into seven groups. The classification of the plant species into groups is presented in Table 2.

4 | DISCUSSION

Research on the flora of tram lines in Central European countries has primarily focused on planted vegetation (Klera & Bacieczko, 2013; Sikorski et al., 2018; Sudnik-Wójcikowska & Galera, 2005; Woźnica et al., 2016; Wrzesien et al., 2016). However, only a few studies have focused on the spontaneous spread of plants (succession) (Vaverková et al., 2018). According to Rendeková et al. (2020), insufficient research on the spontaneously growing flora of tram lines can be explained by the fact that in many cities, tram lines are still covered with concrete and maintained accordingly, which inhibits plant growth. The results of our study shed light on this topic. The results showed that the tram lines are habitats for a wide range of plant species. Different uses of tram lines affect the vegetation cover (Figure 4) and significantly change the species spectrum of the vegetation (Figures 3 and 6). Based on their preferences, the plant species can be

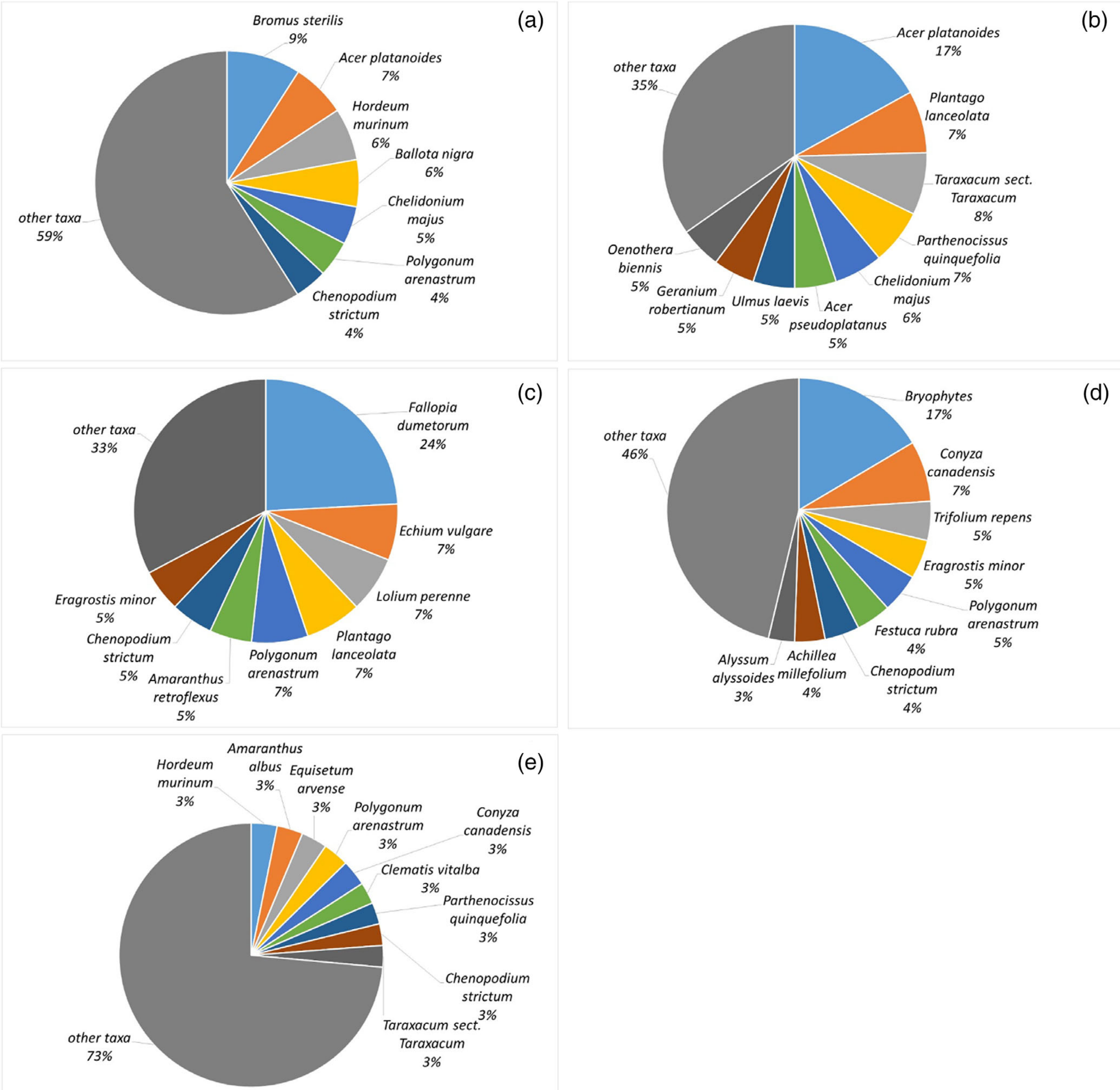

FIGURE 3 Representation of plant taxa occurring on the (a) unused and unkempt tram line section, (b) the newly reconstructed tram line section, (c) the newly reconstructed section of tram loop, (d) the old maintained section of tram loop, (e) the unused and maintained section of tram line. [Colour figure can be viewed at wileyonlinelibrary.com]

divided into groups (Table 2). Based on the species composition of vegetation, it is evident that the construction of tram lines changes the water regime, as can be seen in the different representations of plant species with different water succession requirements (Figure 5).

Commonly occurring in linear sections are taxa that are missing in moist soils, up to taxa that are considered indicators of moisture, bound to soils that are well supplied with water, but not wet. Owing to its linear character, it can be assumed that water is available from the surrounding area, which makes the survival of hygrophilous species possible. The tram line was more favorable for xerophytic plants. According to Májeková et al. (2016), stony and drained tram line sites provide suitable conditions for the growth of xerothermophilous synanthropic species that form an abundant part of the floristic spectrum of these habitats. As shown in Figure 2, the entire study site is in the vicinity of the river and the flood zone. This provides a prerequisite for the significant occurrence of wetland plant species. The vegetation composition of the evaluated tram lines did not correspond to this. The representation of wetland species was not significant and drought-adapted species were predominant. The conditions of the tram lines reduce the availability of water, thus

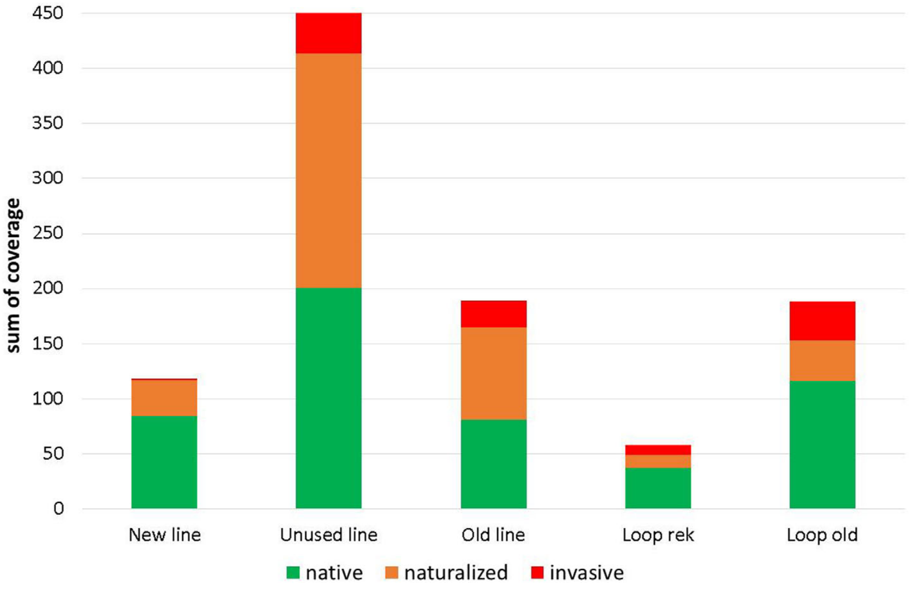

FIGURE 4 Sum of the coverage by individual taxa according to invasion status. [Colour figure can be viewed at wileyonlinelibrary.com]

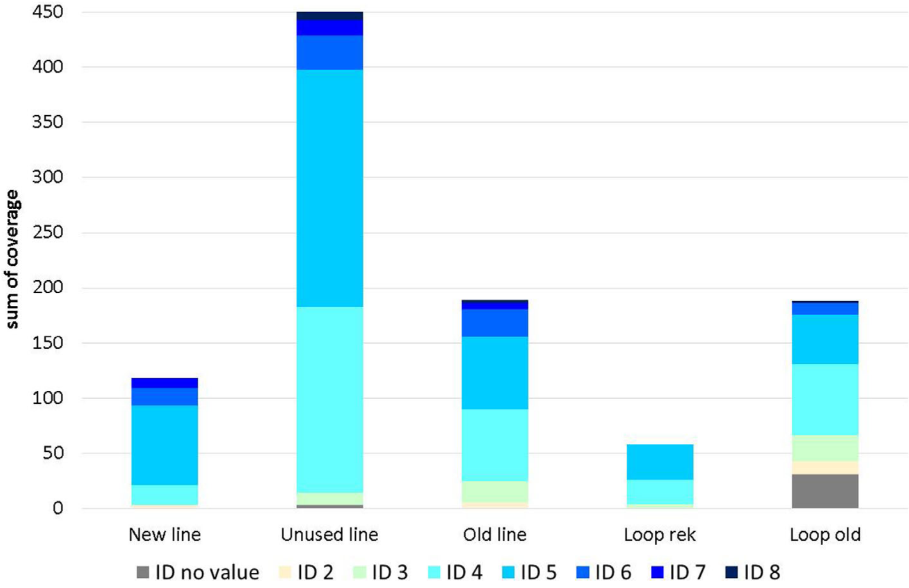

FIGURE 5 Sum of the coverage by individual taxa according to indicative values for moisture. [Colour figure can be viewed at wileyonlinelibrary.com]

creating habitats with different vegetation types. The construction of tram lines involves the placement of specific substrate materials such as ballast, gravel, or concrete (Connolly et al., 2016; Steckler et al., 2012). These engineered substrates may have distinct physical and chemical properties compared to the natural soils in the surrounding area. Variations in soil and substrate characteristics can influence the types of plants that establish and thrive along the tram lines (Heneidy et al., 2021; Łukaszkiewicz et al., 2018; Rendeková et al., 2020).

According to Dziuba et al. (2022), the species diversity of plants on tram lines depends on the succession processes in the surrounding areas. This should be considered when preparing recommendations for the authorities in urban areas. Regarding the significant differentiation of tram line biotopes, their role is irreplaceable in the preservation of urban biodiversity and in the fulfillment of the ecological functions of green areas with parks, gardens, and squares (Capotorti et al., 2020; Zaręba et al., 2022).

It follows from the results that the species composition of vegetation is subject to a certain level of development, which can be referred to as the succession of urban vegetation. This development is strongly affected by human civilization interventions (Dziuba et al., 2022). The initial stage of the succession of tram line vegetation can be seen in the new section (New line) or in the section of the reconstructed tram loop (Loop rec) (Figure 3). Typical signs include low vegetation cover and the predominance of native species whose diaspores are brought to the tram line from the surrounding area. The subsequent succession of vegetation follows a different course depending on the disturbance caused by human activity (Krzysztofik et al., 2022). The unused tram lines suggest that succession would occur without human interference. Compared with the initial stage of succession on the new

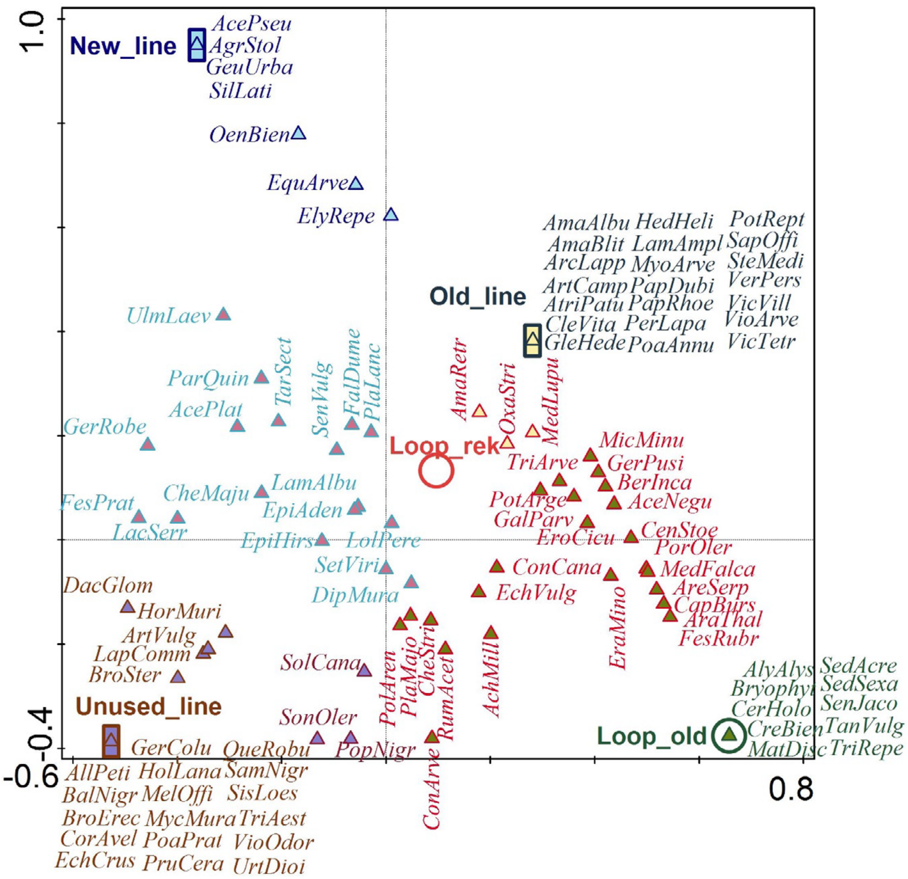

FIGURE 6 Relation of different sites on the selected tram line section and occurrence of plant taxa (total explained variability = 16.4%; the first canonical axis explains 14.59 variability, the second canonical axis explains 25.14 variability; *F*-ratio = 1.7; *p*-value = 0.001). [Colour figure can be viewed at wileyonlinelibrary.com]

line, the representation of non-native naturalized, and invasive plant species increases (Figure 4 and Table 2). The significant non-native species included *Ballota nigra*, *Bromus sterilis*, *Hordeum murinum*, *Chelidonium majus* and so forth. Plant species that are considered invasive include the following: *Epilobium adenocaulon*, *Parthenocissus quinquefolia*, *Sisymbrium loeselii*, and *Solidago canadensis*.

Tram line construction has changed environmental conditions for a long time, fragmenting the vegetation species composition and changing development during secondary vegetation succession. This is in accordance with numerous scientific studies that highlight the importance of railway habitats for the occurrence and distribution of non-native plant species (archaeophytes and neophytes) (Červenková et al., 2016; Dziuba et al., 2022; Hansen & Clevenerg, 2005; Jehlík et al., 2017; Májeková et al., 2016), including invasive species (Denisow et al., 2017; Wrzesien et al., 2016; Wrzesień & Denisow, 2017). However, the role of tram lines in the invasion of non-native plants remains unclear. If we change living conditions, we can change the vegetation, but which species can be considered non-native to the site? The construction of tram lines also changes the composition of vegetation, and a significant change must be expected.

The unused but maintained tram section suggests a different course of vegetation succession. Disturbances caused by tram line maintenance reduce the amount of vegetation biomass (coverage) and change species composition. The share of non-native naturalized, and invasive plant species is also increasing (Table 2). The most significant naturalized and invasive species were *Arctium lappa*, *Papaver dubium*, and *Amaranthus albus*. Specific changes in vegetation can be called cyclic succession. Repeated reconstruction of the tram line returned the vegetation to its initial stage.

A different succession course is expected in the tram loop. The beginning of succession, which is evident in the Loop rec habitat, showed low vegetation cover and a predominance of native plant species. In the old loop habitat, vegetation cover increased, and the proportion of native species was still dominant. The tram loop no longer exhibits a linear character, which is why the changes in conditions are more conspicuous, which also reflects the representation of specific plant species, such as *Alyssum alyssoides*, *Cerastium holosteoides*, *Sedum acre*, and *Sedum sexangulare*. These species would succeed in places where it is difficult for natural vegetation to grow. Distinct permanent changes in tram lines create specific conditions that are atypical for a given site. The specific development of vegetation can be referred to as a blocked succession.

Vegetation reacts to the conditions of tram lines by the fragmentation of species composition, which raises the question of its utility. On the one hand, tram lines provide space for the use and spread of invasive plant species, which can quickly spread and outcompete native species for resources such as water, nutrients, and light (Denisow et al., 2017; Hansen & Clevenerg, 2005; Jehlík et al., 2017; Májeková et al., 2016; Rendeková et al., 2020; Weidlich et al., 2020; Wrzesien et al., 2016; Wrzesień & Denisow, 2017). They create

TABLE 2 Groups of plant species according to CCA analysis.

Groups of plant species	Native	Naturalized	Invasive
Group 1 (New line)	*Acer platanoides* *Agrostis stolonifera* *Elymus repens* *Equisetum arvense* *Geum urbanum*	*Silene latifolia*	*Oenothera biennis*
Group 2 (New line; Unused line)	*Acer pseudoplatanus* *Epilobium hirsutum* *Fallopia dumetorum* *Festuca pratensis* *Geranium robertianum* *Lolium perenne* *Plantago lanceolate* *Taraxacum sect. Taraxacum* *Ulmus laevis*	*Diplotaxis muralis* *Chelidonium majus* *Lactuca serriola* *Lamium album* *Senecio vulgaris* *Setaria viridis*	*Epilobium adenocaulon* *Parthenocissus quinquefolia*
Group 3 (Unused line)	*Alliaria petiolate* *Artemisia vulgaris* *Bromus erectus* *Corylus avellana* *Dactylis glomerata* *Holcus lanatus* *Mycelis muralis* *Poa pratensis* *Populus nigra* *Quercus robur* *Sambucus nigra* *Urtica dioica*	*Ballota nigra* *Bromus sterilis* *Echinochloa crus-galli* *Geranium columbinum* *Hordeum murinum* *Lapsana communis* *Melilotus officinalis* *Prunus cerasifera* *Sonchus oleraceus* *Triticum aestivum* *Viola odorata*	*Sisymbrium loeselii* *Solidago canadensis*
Group 4 (Old line)	*Artemisia campestris* *Clematis vitalba* *Glechoma hederacea* *Hedera helix* *Persicaria lapathifolia* *Poa annua* *Potentilla reptans* *Stellaria media* *Vicia tetrasperma* *Viola arvensis*	*Arctium lappa* *Atriplex patula* *Lamium amplexicaule* *Myosotis arvensis* *Papaver dubium* *Papaver rhoeas* *Saponaria officinalis* *Vicia villosa*	*Amaranthus albus* *Amaranthus blitoides* *Veronica persica*
Group 5 (Loop rec)	*Medicago lupulina*		*Amaranthus retroflexus* *Oxalis stricta*
Group 6 (Loop rec; Loop old)	*Achillea millefolium* *Arabidopsis thaliana* *Arenaria serpyllifolia* *Centaurea stoebe* *Echium vulgare* *Festuca rubra* *Medicago falcate* *Plantago major* *Polygonum arenastrum* *Potentilla argentea* *Rumex acetosella* *Trifolium arvense*	*Berteroa incana* *Capsella bursa-pastoris* *Convolvulus arvensis* *Eragrostis minor* *Erodium cicutarium* *Geranium pusillum* *Microrrhinum minus* *Portulaca oleracea*	*Acer negundo* *Conyza Canadensis* *Galinsoga parviflora* *Chenopodium strictum*
Group 7 (Loop old)	*Alyssum alyssoides* *Cerastium holosteoides* *Crepis biennis* *Sedum acre* *Sedum sexangulare* *Senecio jacobaea* *Trifolium repens* *Bryophytes*	*Tanacetum vulgare*	*Matricaria discoidea*

entirely new environments and enable the survival of native plant species, thus enriching the species diversity in towns. However, some invasive plant species may have allelopathic effects, that is, they release chemicals into the soil, which can inhibit the growth of other plants (Kato-Noguchi & Kurniadie, 2021; Thiébaut et al., 2019). This can further reduce the diversity and productivity of vegetation on tram lines. The unique conditions of tram lines provide an opportunity for plant species to utilize elements of anthropogenic life strategies (Winkler, Koda, et al., 2023). Additionally, the presence of tram lines fosters the development of anthropogenic ecosystems (Winkler et al., 2021).

Nature conservation must move beyond the traditional notions of wild and cultivated nature (Kueffer & Kaiser-Bunbury, 2014) and embrace new hybrid approaches to protect biotopes that exhibit biological diversity, many of which have been shaped by human civilization (Burney & Burney, 2007; Higgs, 2003; Winkler et al., 2021). Respect for spontaneous vegetation can support biodiversity in urban environments (Reif & Kreß, 2014). Unfortunately, these new perspectives have little influence on the protection of biological diversity in urban areas (Vega & Küffer, 2021). However, towns and cities are hotspots for both endemic and endangered species (Goddard et al., 2010; Ives et al., 2016; Lewis et al., 2019). Rendeková et al. (2020) pointed out that, under local conditions, the habitats of trams and railway lines can serve as valuable refuges for some rare and endangered species. Understanding the role of vegetation on tram lines is crucial for effective urban and spatial planning, as it can have a significant benefit on: (i) Aesthetic value: Vegetation along tram lines can enhance the visual appeal of the urban landscape (Pochodyła et al., 2022; Sanchez et al., 2017; Sikorski et al., 2018; Vega & Küffer, 2021). Plants can create a natural and welcoming environment that softens the harshness of the urban infrastructure (Farrell et al., 2022; Teixeira et al., 2022). (ii) Environmental benefits: Vegetation on tram lines can provide a range of environmental benefits, including improved air quality (Bajçinovci & Bajçinovci, 2020; Jakubcová & Horváthová, 2020), reduced noise pollution (Akay & Önder, 2022), and mitigation of the urban heat island effect (Dian et al., 2019; Jakubcová & Horváthová, 2020; Leal Filho et al., 2021). Urban plants absorb CO_2 and other pollutants and provide shade and cooling effects that can help reduce the temperature in urban areas (Maksymenko et al., 2021; Piracha & Chaudhary, 2022). (iii) Ecological value: Vegetation on tram lines can provide habitats for a range of wildlife, from birds and insects to small mammals (Heneidy et al., 2021; Jakubcová & Horváthová, 2020; Łukaszkiewicz et al., 2021; Nilsson et al., 2014; Vega & Küffer, 2021). This can help support biodiversity in urban areas and contribute to the overall health of urban ecosystems.

The results evaluated have limitations due to the biological nature of the vegetation, and because of the case study in which the conditions of a specific city are evaluated. Despite these limitations, some general trends that can be observed in other areas can be identified. The urbanization activities of human civilization, including transportation structures, fulfill their primary functions. They also create new habitats and fragmented living conditions. Urbanized and fragmented conditions provide habitats for different plant species. The species structure of vegetation that is not intentionally planted provides feedback on the conditions created by human civilization. The use of vegetation to identify environmental conditions in biomonitoring has been well-established (Fusaro et al., 2021; Karmakar et al., 2021; Vaverková et al., 2023). However, it is not currently used in tram lines, even though vegetation provides information about environmental conditions.

Tram lines create conditions for the fragmentation of the urban environment and allow the survival of plant species that can better tolerate arid habitats and require low competition from vegetation. Human civilization is creating an ecosystem composed of specific plant species that provide specific ecosystem functions for other organisms, thus changing the composition of the urban ecosystem.

Further research investigating the impact of human activities and the microclimate on tram line ecosystems, as well as assessing the role of tram lines in urban development and the creation of green corridors, will contribute to a holistic understanding of these urban linear green spaces.

5 | CONCLUSIONS

The development of tram lines brings a number of transportation benefits to the urban landscape but also creates a new environment for plants. The linear nature of tram lines facilitates the entry of certain plant species into cities. This can increase biodiversity but can also lead to the spread of undesirable species. The linear nature of tram lines allows the introduction and spread of both native and non-native plant species. This study highlights the presence of hygrophilous species and xerophytic plants that thrive in response to specific conditions along tram lines, including the use of engineered substrates, such as ballast, gravel, and concrete. It is emphasized that the succession of urban vegetation is strongly influenced by human interventions, such as construction and maintenance, leading to different stages of development.

Tram lines in towns and cities allow for the species fragmentation of vegetation. Diverse species composition is beneficial for invasive species but also creates new environments and enables the survival of native species, thus enriching species diversity in towns. Tram loops exhibit a lack of water, indicating the occurrence of plant species with a transition value between indicators of severe drought and taxa that are missing in moist soils. The studied tram loop does not have a linear character and is therefore more suitable for the occurrence of drought-loving vegetation. The unused tram line section featured an increasing proportion of species considered indicators of moisture. Nevertheless, species with indicative values for soils with average moisture content had a dominant share in all the studied tram line sections. Distinct permanent changes caused by the construction of a tram loop create conditions atypical for a given locality.

This research also highlights the need for careful management and monitoring of tramway vegetation to balance its benefits and potential negative impacts. It provides valuable insights for urban and spatial planning by addressing the aesthetic, environmental, and ecological significance of vegetation along tram lines. It also encourages a shift towards hybrid approaches to conservation that consider the unique habitats shaped by human civilization. This underscores the significance of tramways in bolstering biodiversity, and advocates for a more profound comprehension of their ecological functions in urban landscapes.

Tram lines change the environmental conditions for a long time, which affects the course of vegetation succession. The specific development of vegetation can be characterized as either blocked or cyclic succession. As a result of human civilization, tram transport affects not only the species composition of vegetation but also vegetation succession. Our research can be used for efficient management of biological diversity in urban habitats, monitoring, and developing measures to control the spread of non-native species. It can also be useful for the sustainable planning and management of urban landscapes. It should be stressed that to balance the benefits and potential negative impacts of vegetation on tram lines, it is important to implement careful management practices. This may include regular monitoring and removal of invasive species as well as the use of native plant species adapted to the local environment.

CONFLICT OF INTEREST STATEMENT

The manuscript was approved by all authors for publication, and they declare that they have no conflicts of interest.

ACKNOWLEDGMENT

Open access publishing facilitated by Mendelova univerzita v Brne, as part of the Wiley - CzechELib agreement.

DATA AVAILABILITY STATEMENT

The data supporting the findings of this study are available within the article.

ORCID

Anna Podlasek https://orcid.org/0000-0003-0326-5672

REFERENCES

Akay, A., & Önder, S. (2022). An acoustical landscaping study: The impact of distance between the sound source and the landscape plants on traffic noise reduction. *Environment, Development and Sustainability*, *1–23*, 12036–12058. https://doi.org/10.1007/s10668-021-01930-y

Andersson, E., Barthel, S., Borgstrom, S., Colding, J., Elmqvist, T., Folke, C., & Gren, Å. (2014). Reconnecting cities to the biosphere: Stewardship of green infrastructure and urban ecosystem services. *Ambio*, *43*(4), 445–453. https://doi.org/10.1007/s13280-014-0506-y

Aronson, M. F., Lepczyk, C. A., Evans, K. L., Goddard, M. A., Lerman, S. B., MacIvor, J. S., Nilon, C. H., & Vargo, T. (2017). Biodiversity in the city: Key challenges for urban green space management. *Frontiers in Ecology and the Environment*, *15*(4), 189–196. https://doi.org/10.1002/fee.1480

Bajçinovci, B., & Bajçinovci, M. (2020). Prishtina: Urban health related to air quality. *Environmental and Climate Technologies*, *24*(1), 294–309. https://doi.org/10.2478/rtuect-2020-0017

Balaban, O., & Puppim de Oliveira, J. A. (2022). Finding sustainable mobility solutions for shrinking cities: The case of Toyama and Kanazawa. *Journal of Place Management and Development*, *15*(1), 20–39. https://doi.org/10.1108/JPMD-04-2021-0047

Burney, D. A., & Burney, L. P. (2007). Paleoecology and "inter-situ" restoration on Kaua'i, Hawai'i. *Frontiers in Ecology and the Environment*, *5*(9), 483–490. https://doi.org/10.1080/01426397.2011.559311

Capotorti, G., Bonacquisti, S., Abis, L., Aloisi, I., Attorre, F., Bacaro, G., Balletto, G., Banfi, E., Barni, E., Bartoli, F., Bazzato, E., Beccaccioli, M., Braglia, R., Bretzel, F., Brighetti, M. A., Brundu, G., Burnelli, M., Calfapietra, C., Cambria, V. E., … Blasi, C. (2020). More nature in the city. *Plant Biosystems: An International Journal Dealing with all Aspects of Plant Biology*, *154*(6), 1003–1006. https://doi.org/10.1080/11263504.2020.1837285

Červenková, J., Chovancová, S., & Winkler, J. (2016). Comparison of the species composition of vegetation on selected sections of railway. In MendelNet 2016: Proceedings of international PhD students conference. 716–721. https://mnet.mendelu.cz/mendelnet2016/mnet_2016_full.pdf

Chytrý, M., Danihelka, J., Kaplan, Z., Wild, J., Holubová, D., Novotný, P., Řezníčková, M., Rohn, M., Dřevojan, P., Grulich, V., Klimešová, J., Lepš, J., Lososová, Z., Pergl, J., Sádlo, J., Šmarda, P., Štěpánková, P., Tichý, L., Axmanová, I., Bartušková, A., Blažek, P., Chrtek, J. Jr., Fischer, F.M., Guo, W.-Y., Herben, T., Janovský, Z., Konečná, M., Kühn, I., Moravcová, L., Petřík, P., Pierce, S., Prach, K., Prokešová, H., Štech, M., Těšitel, J., Těšitelová, T., Večeřa, M., Zelený, D., & Pyšek, P. (2021). Pladias database of the czech flora and vegetation. *Preslia*, *93*, 1–87.

Chytrý, M., Tichý, L., Dřevojan, P., Sádlo, J., & Zelený, D. (2018). Ellenberg-type indicator values for the Czech flora. *Preslia*, *90*(2), 83–103.

Connolly, D. P., Marecki, G. P., Kouroussis, G., Thalassinakis, I., & Woodward, P. K. (2016). The growth of railway ground vibration problems—A review. *Science of the Total Environment*, *568*, 1276–1282. https://doi.org/10.1016/j.scitotenv.2015.09.101

Coppola, P., & Lobo, A. (2022). Inclusive and collaborative advanced transport: Are we really heading to sustainable mobility? *European Transport Research Review*, *14*(1), 46. https://doi.org/10.1186/s12544-022-00570-1

Denisow, B., Wrzesień, M., Mamchur, Z., & Chuba, M. (2017). Invasive flora within urban railway areas: A case study from Lublin (Poland) and Lviv (Ukraine). *Acta Agrobotanica*, *70*(4), 1–14. https://doi.org/10.5586/aa.1727

Dian, C., Pongrácz, R., Incze, D., Bartholy, J., & Talamon, A. (2019). Analysis of the urban heat Island intensity based on air temperature measurements in a renovated part of Budapest (Hungary). *Geographica Pannonica*, *23*(4), 277–288. https://doi.org/10.5937/gp23-23839

Dziuba, T. P., Dubyna, D. V., Iemelianova, S. M., & Tymoshenko, P. A. (2022). Vegetation of the railways of the Kyiv urban area (Ukraine). *Biologia*, *77*(4), 931–952. https://doi.org/10.1007/s11756-021-00961-0

Ellenberg, H., Weber, H. E., Düll, R., Wirth, V., Werner, W., & Paulißen, D. (1991). *Zeigerwerte von Pflanzen in Mitteleuropa*. Scripta Geobotanica 18 (pp. 1–248). Verlag Erich Goltze GmbH & Co KG.

Ellis, E. (2011). The planet of no return: Human resilience on an artificial earth. *Breakthrough Journal*, *2*(Fall), 37–44.

Elmqvist, T., Andersson, E., Frantzeskaki, N., McPhearson, T., Olsson, P., Gaffney, O., Takeuchi, K., & Folke, C. (2019). Sustainability and resilience for transformation in the urban century. *Nature Sustainability*, *2*(4), 267–273. https://doi.org/10.1038/s41893-019-0250-1

Farrell, C., Livesley, S. J., Arndt, S. K., Beaumont, L., Burley, H., Ellsworth, D., Esperon-Rodriguez, M., Fletcher, T. D., Gallagher, R., Ossola, A., & Power, S. A. (2022). Can we integrate ecological approaches to improve plant selection for green infrastructure? *Urban Forestry & Urban Greening*, *127732*, 127732. https://doi.org/10.1016/j.ufug.2022.127732

Fischer, L. K., Honold, J., Cvejić, R., Delshammar, T., Hilbert, S., Lafortezza, R., Nastran, M., Nielsen, A. B., Pintar, M., van der Jagt, A. P., & Kowarik, I. (2018). Beyond green: Broad support for biodiversity in multicultural European cities. *Global Environmental Change*, *49*, 35–45. https://doi.org/10.1016/j.gloenvcha.2018.02.001

Fusaro, L., Salvatori, E., Winkler, A., Frezzini, M. A., de Santis, E., Sagnotti, L., Canepari, S., & Manes, F. (2021). Urban trees for biomonitoring atmospheric particulate matter: An integrated approach combining plant functional traits, magnetic and chemical properties. *Ecological Indicators*, *126*, 107707. https://doi.org/10.1016/j.ecolind.2021.107707

Gallo, T., Fidino, M., Lehrer, E. W., & Magle, S. B. (2017). Mammal diversity and metacommunity dynamics in urban green spaces: Implications for urban wildlife conservation. *Ecological Applications*, *27*(8), 2330–2341. https://doi.org/10.1002/eap.1611

Goddard, M. A., Dougill, A. J., & Benton, T. G. (2010). Scaling up from gardens: Biodiversity conservation in urban environments. *Trends in Ecology & Evolution*, *25*(2), 90–98. https://doi.org/10.1016/j.tree.2009.07.016

Gössling, S., & McRae, S. (2022). Subjectively safe cycling infrastructure: New insights for urban designs. *Journal of Transport Geography*, *101*, 103340. https://doi.org/10.1016/j.jtrangeo.2022.103340

Guyot, M., Araldi, A., Fusco, G., & Thomas, I. (2021). The urban form of Brussels from the street perspective: The role of vegetation in the definition of the urban fabric. *Landscape and Urban Planning*, *205*, 103947. https://doi.org/10.1016/j.landurbplan.2020.103947

Hansen, M. J., & Clevenerg, A. P. (2005). The influence of disturbance and habitat on the presence of non-native plant species along transport corridors. *Biological Conservation*, *125*(2), 249–259. https://doi.org/10.1016/j.biocon.2005.03.024

Heneidy, S. Z., Halmy, M. W., Toto, S. M., Hamouda, S. K., Fakhry, A. M., Bidak, L. M., Eid, E. M., & Al-Sodany, Y. M. (2021). Pattern of urban flora in intra-city railway habitats (Alexandria, Egypt): A conservation perspective. *Biology*, *10*(8), 698. https://doi.org/10.3390/biology10080698

Higgs, E. (2003). *Nature by design: People, natural process, and ecological restoration*. MIT Press.

Ives, C. D., Lentini, P. E., Threlfall, C. G., Ikin, K., Shanahan, D. F., Garrard, G. E., Bekessy, S. A., Fuller, R. A., Mumaw, L., Rayner, L., & Rowe, R. (2016). Cities are hotspots for threatened species. *Global Ecology and Biogeography*, *25*(1), 117–126. https://doi.org/10.1111/geb.12404

Jakubcová, E., & Horváthová, E. (2020). Costs and benefits of green tramway tracks. *Scientia Agriculturae Bohemica*, *51*(4), 99–106.

Jehlík, V., Zaliberová, M., & Májeková, J. (2017). The influence of the eastern migration route on the Slovak flora—A comparison after 40 years. *Tuexenia*, *37*, 313–332. https://doi.org/10.14471/2016.37.023

Karmakar, D., Deb, K., & Padhy, P. K. (2021). Ecophysiological responses of tree species due to air pollution for biomonitoring of environmental health in urban area. *Urban Climate*, *35*, 100741. https://doi.org/10.1016/j.uclim.2020.100741

Kato-Noguchi, H., & Kurniadie, D. (2021). Allelopathy of Lantana camara as an invasive plant. *Plants*, *10*(5), 1028. https://doi.org/10.3390/plants10051028

Klera, M., & Bacieczko, W. (2013). *Specyfika flory infrastruktury tramwajowej szczecina jako przejaw skrajnej synantropizacji siedliska* (p. 25). Folia Pomeranae Universitatis Technologiae Stetinensis. Agricultura, Alimentaria, Piscaria et Zootechnica.

Knapp, S., Dinsmore, L., Fissore, C., Hobbie, S. E., Jakobsdottir, I., Kattge, J., King, J. Y., Klotz, S., McFadden, J. P., & Cavender-Bares, J. (2012). Phylogenetic and functional characteristics of household yard floras and their changes along an urbanization gradient. *Ecology*, *93*(8), 83–98. https://doi.org/10.1890/11-0392.1

Krzysztofik, R., Dragan, W., & Soida, K. (2022). A unique type of industrial railway–the sand railways of southern Poland. *Environmental & Socio-Economic Studies*, *10*(4), 1–11. https://doi.org/10.2478/environ-2022-0019

Kueffer, C. (2020). Plant sciences for the Anthropocene: What can we learn from research in urban areas? *Plants, People, Planet*, *2*(4), 286–289. https://doi.org/10.1002/ppp3.10124

Kueffer, C., & Kaiser-Bunbury, C. N. (2014). Reconciling conflicting perspectives for biodiversity conservation in the Anthropocene. *Frontiers in Ecology and the Environment*, *12*(2), 131–137. https://doi.org/10.1890/120201

Leal Filho, W., Wolf, F., Castro-Díaz, R., Li, C., Ojeh, V. N., Gutiérrez, N., Nagy, G. J., Savić, S., Natenzon, C. E., Quasem Al-Amin, A., & Maruna, M. (2021). Addressing the urban heat islands effect: A cross-country assessment of the role of green infrastructure. *Sustainability*, *13*(2), 753. https://doi.org/10.3390/su13020753

Lepczyk, C. A., Aronson, M. F. J., Evans, K. L., Goddard, M. A., Lerman, S. B., & Macivor, J. S. (2017). Biodiversity in the city: Fundamental questions for understanding the ecology of urban green spaces for biodiversity conservation. *Bioscience*, *67*(9), 799–807. https://doi.org/10.1093/biosci/bix079

Lewis, A. D., Bouman, M. J., Winter, A. M., Hasle, E. A., Stotz, D. F., Johnston, M. K., Klinger, K. R., Rosenthal, A., & Czarnecki, C. A. (2019). Does nature need cities? Pollinators reveal a role for cities in wildlife conservation. *Frontiers in Ecology and Evolution*, *7*, 220. https://doi.org/10.3389/fevo.2019.00220

Li, D., Yang, Y., Xia, F., Sun, W., Li, X., & Xie, Y. (2022). Exploring the influences of different processes of habitat fragmentation on ecosystem services. *Landscape and Urban Planning*, *227*, 104544. https://doi.org/10.1016/j.landurbplan.2022.104544

Liu, H., Chen, L. P., Ai, Y. W., Yang, X., Yu, Y. H., Zuo, Y. B., & Fu, G. Y. (2009). Heavy metal contamination in soil alongside mountain railway in Sichuan, China. *Environmental Monitoring and Assessment*, *152*, 25–33. https://doi.org/10.1007/s10661-008-0293-7

Łukaszkiewicz, J., Fortuna-Antoszkiewicz, B., Botwina, J., Oleszczuk, Ł., & Wiśniewski, P. (2018). Sustainable development of the city's transport infrastructure—A project of a new tram line with a linear park along the Exhibition Channel in Warsaw. *Journal of Environmental Science and Engineering A*, *7*, 285–300. https://doi.org/10.17265/2162-5298/2018.07.004

Łukaszkiewicz, J., Fortuna-Antoszkiewicz, B., Oleszczuk, Ł., & Fialová, J. (2021). The potential of tram networks in the revitalization of the Warsaw landscape. *Land*, *10*(4), 375. https://doi.org/10.3390/land10040375

Májeková, J., Jarolímek, I., Zaliberová, M., & Medvecká, J. (2021). Alien (invasive) vascular plants in Slovakia—a story of successful plant immigrants. *Environmental & Socio-Economic Studies*, *9*(4), 23–31. https://doi.org/10.2478/environ-2021-0022

Májeková, J., Jehlík, V., & Zaliberová, M. (2016). Railway stations vs. thermophilous species (example from eastern Slovakia). *Thaiszia – Journal of Botany*, *26*(2), 173–188.

Maksymenko, N., Sonko, S., Skryhan, H., Burchenko, S., & Gladkiy, A. (2021). Green infrastructure of post-USSR cities for prevention of noise pollution. In *SHS web of conferences* (Vol. 100, p. 5004). EDP Sciences.

Malkinson, D., Kopel, D., & Wittenberg, L. (2018). From rural-urban gradients to patch–matrix frameworks: Plant diversity patterns in urban landscapes. *Landscape and Urban Planning*, *169*, 260–268. https://doi.org/10.1016/j.landurbplan.2017.09.021

Mansur, A. V., McDonald, R. I., Güneralp, B., Kim, H., de Oliveira, J. A. P., Callaghan, C. T., Hamel, P., Kuiper, J. J., Wolff, M., Liebelt, V., & Martins, I. S. (2022). Nature futures for the urban century: Integrating multiple values into urban management. *Environmental Science & Policy*, *131*, 46–56. https://doi.org/10.1016/j.envsci.2022.01.013

McDonald, R., & Beatley, T. (2020). *Biophilic cities for an urban century: Why nature is essential for the success of cities*. Springer Nature.

McDonald, R. I., Colbert, M., Hamann, M., Simkin, R., & Walsh, B. (2018). Nature in the urban century [The Nature Conservancy (2018)]. https://doi.org/10.1787/19970900

Muvengwi, J., Fritz, H., Mbiba, M., & Ndagurwa, H. G. (2022). Land use effects on phylogenetic and functional diversity of birds: Significance of urban green spaces. *Landscape and Urban Planning*, *225*, 104462. https://doi.org/10.1016/j.landurbplan.2022.104462

Nilsson, M., Bengtsson, J., & Klæboe, R. (Eds.). (2014). *Environmental methods for transport noise reduction*. CRC Press.

Nisi, A. C., Benson, J. F., King, R., & Wilmers, C. C. (2023). Habitat fragmentation reduces survival and drives source–sink dynamics for a large carnivore. *Ecological Applications*, *33*(4), e2822. https://doi.org/10.1002/eap.2822

Papp, C. R., Dostál, I., Hlaváč, V., Berchi, G. M., & Romportl, D. (2022). Rapid linear transport infrastructure development in the Carpathians: A major threat to the integrity of ecological connectivity for large carnivores. *Nature Conservation*, *47*, 35–63. https://doi.org/10.3897/natureconservation.47.71807

Piracha, A., & Chaudhary, M. T. (2022). Urban air pollution, urban heat Island and human health: A review of the literature. *Sustainability*, *14*(15), 9234. https://doi.org/10.3390/su14159234

Pochodyła, E., Jaszczak, A., Illes, J., Kristianova, K., & Joklova, V. (2022). Analysis of green infrastructure and nature-based solutions in Warsaw–selected aspects for planning urban space. *Acta Horticulturae et Regiotecturae*, *25*(1), 44–50. https://doi.org/10.2478/ahr-2022-0006

Pyšek, P., Danihelka, J., Sádlo, J., Chrtek, J., Jr., Chytrý, M., Jarošík, V., Kaplan, Z., Krahulec, F., Moravcová, L., Pergl, J., Štajerová, K., & Tichý, L. (2012). Catalogue of alien plants of The Czech Republic (2nd edition): Checklist update, taxonomic diversity and invasion patterns. *Preslia*, *84*, 155–255.

Qiao, S., Huang, G., & Yeh, A. G. O. (2022). Mobility as a service and urban infrastructure: From concept to practice. *Transactions in Urban Data, Science, and Technology*, *1*(1–2), 16–36. https://doi.org/10.1177/27541231221114171

Reif, J., & Kreß, C. (2014). Blackbox Gardening – Mit Versamenden Pflanzen Garten̈ Gestalten. Verlag Eugen Ulmer.

Rendeková, A., Mičieta, K., Randáková, Z., Ballová, D., Eliašová, M., & Miškovic, J. (2020). Flora of the tram tracks of Bratislava. *Urban Ecosystem*, *23*, 875–891. https://doi.org/10.1007/s11252-020-00952-0

Richardson, D. M., Pyšek, P., & Carlton, J. T. (2011). A compendium of essential concepts and terminology in biological invasions. In D. M. Richardson (Ed.), *Fifty years of invasion ecology: The legacy of Charles Elton* (pp. 409–420). Blackwell Publishing.

Richardson, D. M., Pyšek, P., Rejmánek, M., Barbour, M. G., Panetta, F. D., & West, C. J. (2000). Naturalization and invasion of alien plants: Concepts and definitions. *Diversity and Distributions*, *6*, 93–107.

Saggau, P., Kuhwald, M., & Duttmann, R. (2023). Effects of contour farming and tillage practices on soil erosion processes in a hummocky watershed. A model-based case study highlighting the role of tramline tracks. *Catena*, *228*, 107126. https://doi.org/10.1016/j.catena.2023.107126

Sanchez, G. M. E., van Renterghem, T., Sun, K., de Coensel, B., & Botteldooren, D. (2017). Using virtual reality for assessing the role of noise in the audio-visual design of an urban public space. *Landscape and Urban Planning*, *167*, 98–107. https://doi.org/10.1016/j.landurbplan.2017.05.018

Sikorski, P., Wińska-Krysiak, M., Chormański, J., Krauze, K., Kubacka, K., & Sikorska, D. (2018). Low-maintenance green tram tracks as a socially acceptable solution to greening a city. *Urban Forestry & Urban Greening*, *35*, 148–164. https://doi.org/10.1016/j.ufug.2018.08.017

Steckler, P., Klug, B., Gasser, F., & Wehr, W. (2012, May 7–9). Green track–environmental performance evaluation for "green" tramway superstructure. 2nd International Conference on Road and Rail Infrastructure, Dubrovnik, Croatia.

Sudnik-Wójcikowska, B., & Galera, H. (2005). Floristic differences in some anthropogenic habitats in Warsaw. In *Annales Botanici Fennici* (pp. 185–193). Finnish Zoological and Botanical Publishing Board.

Sztubecka, M., Skiba, M., Mrówczyńska, M., & Bazan-Krzywoszańska, A. (2019). Various presentation of noise perception in Bydgoszcz green areas. *Architecture, Civil Engineering, Environment*, *12*(3), 113–120. https://doi.org/10.21307/acee-2019-041

Sztubecka, M., Skiba, M., Mrówczyńska, M., & Mathias, M. (2020). Noise as a factor of green areas soundscape creation. *Sustainability*, *12*(3), 999. https://doi.org/10.3390/su12030999

Tan, W. C., Herrel, A., & Rödder, D. (2023). A global analysis of habitat fragmentation research in reptiles and amphibians: What have we done so far? *Biodiversity and Conservation*, *32*(2), 439–468. https://doi.org/10.1007/s10531-022-02530-6

Taylor, Z., & Józefowicz, I. (2012). Intra-urban daily mobility of disabled people for recreational and leisure purposes. *Journal of Transport Geography*, *24*, 155–172. https://doi.org/10.1016/j.jtrangeo.2011.12.008

Teixeira, C. P., Fernandes, C. O., & Ahern, J. (2022). Adaptive planting design and management framework for urban climate change adaptation and mitigation. *Urban Forestry & Urban Greening*, *70*, 127548. https://doi.org/10.1016/j.ufug.2022.127548

Ter Braak, C. J., & Šmilauer, P. (2012). Canoco reference manual and user's guide: software for ordination, version 5.0.

Thiébaut, G., Tarayre, M., & Rodríguez-Pérez, H. (2019). Allelopathic effects of native versus invasive plants on one major invader. *Frontiers in Plant Science*, *10*, 854. https://doi.org/10.3389/fpls.2019.00854

Vaverková, M. D., Paleologos, E. K., Goli, V. S. N. S., Koda, E., Mohammad, A., Podlasek, A., Winkler, J., Jakimiuk, A., Černý, M., & Singh, D. N. (2023). Environmental impacts of landfills: Perspectives on bio-monitoring. *Environmental Geotechnics*, *4*, 1–10. https://doi.org/10.1680/jenge.23.00003

Vaverková, M. D., Radziemska, M., Bartoň, S., Cerdà, A., & Koda, E. (2018). The use of vegetation as a natural strategy for landfill restoration. *Land Degradation and Development*, *29*(10), 3674–3680. https://doi.org/10.1002/ldr.3119

Vega, K. A., & Küffer, C. (2021). Promoting wildflower biodiversity in dense and green cities: The important role of small vegetation patches. *Urban Forestry & Urban Greening*, *62*, 127165. https://doi.org/10.1016/j.ufug.2021.127165

Vega, K. A., Schläpfer-Miller, J., & Kueffer, C. (2021). Discovering the wild side of urban plants through public engagement. *Plants, People, Planet*, *3*(4), 389–401. https://doi.org/10.1002/ppp3.10191

Weidlich, E. W., Flórido, F. G., Sorrini, T. B., & Brancalion, P. H. (2020). Controlling invasive plant species in ecological restoration: A global review. *Journal of Applied Ecology*, *57*(9), 1806–1817. https://doi.org/10.1111/1365-2664.13656

Winkler, J., Koda, E., Červenková, J., Děkanovský, I., Nowysz, A., Mazur, Ł., Jakimiuk, A., & Vaverková, M. D. (2023). Green space in an extremely exposed part of the city center "aorta of Warsaw"—case study of the urban lawn. *Urban Ecosystem*, *26*, 1–14. https://doi.org/10.1007/s11252-023-01380-6

Winkler, J., Koda, E., Skutnik, Z., Černý, M., Adamcová, D., Podlasek, A., & Vaverková, M. D. (2021). Trends in the succession of synanthropic vegetation on a reclaimed landfill in Poland. *Anthropocene*, *35*, 100299. https://doi.org/10.1016/j.ancene.2021.100299

Winkler, J., Vaverková, M. D., & Havel, L. (2023). Anthropogenic life strategy of plants. *Anthropocene Review*, *10*(2), 455–462. https://doi.org/10.1177/20530196221149120

Woźnica, P., Urbisz, A., Urbisz, A., & Franiel, I. (2016). Tram tracks as specific anthropogenic habitats for the growth of plants. *PeerJ Preprints*, *4*, e2606v1. https://peerj.com/preprints/2606.pdf

Wrzesień, M., & Denisow, B. (2017). Factors responsible for the distribution of invasive plant species in the surroundings of railway areas. A case study from SE Poland. *Biologia*, *72*(11), 1275–1284. https://doi.org/10.1515/biolog-2017-0146

Wrzesien, M., Denisow, B., Mamchur, Z., Chuba, M., & Resler, I. (2016). Composition and structure of the flora in intra-urban railway areas. *Acta Agrobotanica*, *69*(3), 1–14. https://doi.org/10.5586/aa.1666

Yu, P., Fennell, S., Chen, Y., Liu, H., Xu, L., Pan, J., Bai, S., & Gu, S. (2022). Positive impacts of farmland fragmentation on agricultural production efficiency in Qilu Lake watershed: Implications for appropriate scale management. *Land Use Policy*, *117*, 106108. https://doi.org/10.1016/j.landusepol.2022.106108

Zaręba, A., Krzemińska, A., Truch, E., Modelska, M., Grijalva, F. J., & Monrealf, N. R. (2022). Linear cities as an alternative for the sustainable transition of urban areas in harmony with natural environment principles. In *Urban and transit planning: Towards Liveable communities: Urban places and design spaces* (pp. 87–99). Springer International Publishing. https://doi.org/10.1007/978-3-030-97046-8_7

Zhang, X., Sun, S., & Yao, S. (2023). Spatiotemporal distribution and dynamic evolution of grain productivity efficiency in the Yellow River Basin of China. *Environment*, *Development and Sustainability*, 1–26. https://doi.org/10.1007/s10668-023-03619-w

How to cite this article: Winkler, J., Koda, E., Červenová, J., Napieraj, K., Żółtowski, M., Jakimiuk, A., Podlasek, A., & Vaverková, M. D. (2024). Fragmentation and biodiversity change in urban vegetation: A case study of tram lines. *Land Degradation & Development*, *35*(5), 1734–1747. https://doi.org/10.1002/ldr.5017