

Original research

Alien woody plants on the retaining walls of the Vistula boulevards in Kraków, southern Poland

Artur Pliszko*

Jagiellonian University, Faculty of Biology, Institute of Botany, Gronostajowa Str. 3, 30–387 Kraków, Poland

*Corresponding author. E-mail: artur.pliszko@uj.edu.pl

Abstract

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Introducing alien plants for urban horticulture and forestry may lead to their naturalisation and invasion, bringing new challenges to protecting native biodiversity and cultural heritage in urban areas. Many old buildings and monuments are threatened by invasive trees and shrubs, which can damage their structure by physical and physiological root processes and by increasing biomass of above-ground parts. The study aimed to determine the floristic composition and abundance of alien woody plants occurring on the historic retaining walls of the Vistula boulevards in Kraków, southern Poland. A total of 11 alien woody plant species were recorded in 2022, including some invasive species in Poland, such as *Acer negundo*, *Ailanthus altissima*, *Fraxinus pennsylvanica*, *Juglans regia*, *Parthenocissus quinquefolia*, *Robinia pseudoacacia* and *Rosa rugosa*. Most of the species showed low abundance (less than 50 individuals) in each of the distinguished age classes (seedling, juvenile and mature individuals), except vines, which in some places occupied relatively large surfaces of the walls (more than 25 m²). Regular control and monitoring of trees and shrubs are recommended to properly protect the retaining walls of the Vistula boulevards in Kraków.

Keywords: anthropogenic habitats, cultural heritage sites, hydrotechnical monuments, invasive alien species.

INTRODUCTION

Trees and shrubs are essential components of green spaces in cities due to their significant and multiple environmental, economic and social functions (Nilsson et al., 2012; Cavender & Donnelly, 2019; Ghafari et al., 2020; Pataki et al., 2021). As it is well known, they regulate the microclimate, reducing the urban heat island effect, as well as purify the air, produce oxygen, protect the soil from erosion and support native biodiversity (Nilsson et al., 2012; Cavender & Donnelly, 2019; Ghafari et al., 2020). They also have great decorative value, provide food, wood and fuel, and have a positive impact on the health and well-being of city residents (Nilsson et

al., 2012; World Health Organization, 2017; Cavender & Donnelly, 2019; Ghafari et al., 2020; Pataki et al., 2021). Nevertheless, the conditions prevailing in many cities, such as air and soil pollution, water deficit, and increased temperature, may adversely affect the growth and development of many native trees and shrubs (Kowarik et al., 2013; Sjöman et al., 2016; Lüttge & Buckeridge, 2020). Moreover, in highly transformed or polluted areas, the maintenance of native woody plants is usually costly or sometimes even impossible (Sjöman et al., 2016; Lüttge & Buckeridge, 2020). Therefore, alien trees and shrubs, which show high tolerance to pollution, drought and elevated temperature, are particularly desirable in urban green spaces (Zisenis, 2015; Sjö-

man et al., 2016). However, the introduction of alien trees and shrubs for urban horticulture and forestry may lead to their invasion with many undesirable effects on native biodiversity, economy and human health (Binggeli, 2001; Pyšek & Richardson, 2010; Richardson & Rejmánek, 2011; Zisenis, 2015; Gaertner et al., 2016).

Urban areas are rich in anthropogenic habitats that can be inhabited by native and non-native plant species, depending on their ecological tolerance (Kowarik et al., 2013; Salinitro et al., 2018). The walls of buildings and other artificial structures made from stones, bricks or concrete are considered specific, polyhemerobic habitats (Boratyński et al., 2003). They are usually colonised by small organisms such as lichens and mosses, which highly tolerate unfavourable water and thermal conditions (Boratyński et al., 2003; Cathersides & Parker, 2014). Vascular plants are also found on walls, especially in cracks and losses of the mortar between the stones and bricks, where soil can form, and more water can enter. For example, *Cymbalaria muralis* G. Gaertn., B. Mey. & Scherb. is one of the most common flowering herbs occurring on walls in European cities (Tokarska-Guzik, 2005; Nedelcheva & Vasileva, 2009; Cathersides & Parker, 2014; Dahmani et al., 2020). However, the growth of trees and shrubs on walls is usually restricted due to difficulties in rooting, lack of or limited amount of water and nutrients, and elevated temperature (Boratyński et al., 2003; Cathersides & Parker, 2014). It is also relevant to mention that many woody vines are intentionally planted near walls, buildings and monuments so they can climb on them, giving mainly decorative value (Jackiewicz & Borowski, 1998). Similarly, some trees that produce aerial roots are deliberately grown on walls for ornamental and ecological purposes (Jim, 2013). Nevertheless, woody plants can cause damage to buildings and infrastructure by mechanical contact and root physiological processes, significantly when growing on old walls or at the foot of the walls (Overbeke, 2008; Satriani et al., 2010; Cathersides & Parker, 2014; Dahmani et al., 2020).

The impact of invasive alien trees and shrubs on archaeological sites, historic buildings and other cultural property items is perceived by researchers as understudied (Bravo et al., 2012; Cicinelli et al., 2018; Dahmani et al., 2020; Carrari et al., 2022).

Recently, Celesti-Grapow & Ricotta (2021) have pointed out that the invasion of alien woody plants is an emerging challenge for conserving world heritage sites. Furthermore, many historic buildings and monuments seem to be particularly exposed to damage in cities due to the spontaneous spread of alien trees and shrubs commonly grown in urban greenery (Cathersides & Parker, 2014; Dahmani et al., 2020; Celesti-Grapow & Ricotta, 2021). Therefore, floristic inventories of historic buildings and monuments should be carried out regularly as the basis for conservation activities, significantly since the invasion of alien plant species in cities increases with increasing urbanisation (Carrari et al., 2022; Ruas et al., 2022).

Retaining walls are unique structures made of stone, concrete, wood, metal or other materials that stabilise slopes and riverbanks, protecting the soil from erosion (Obi, 2017; Engineers and Geoscientists British Columbia, 2020). In cities with large rivers, retaining walls and embankments are the most critical flood protection (Cyberski et al., 2006; Obi, 2017). Moreover, retaining walls can increase cities' aesthetic and recreational values, especially if they have additional structures for ornamental plants (Jim, 2013; Fedorovskaya et al., 2021; Yuan & Liu, 2021). Like other walls in cities, retaining walls can be colonised by native and alien plant species, although the impact of invasive alien plants on retaining walls is poorly understood (Francis & Hoggart, 2009; Rotherham, 2021). As mentioned above, there is a risk that invasive alien plants reaching large sizes, such as trees and shrubs, may cause mechanical and chemical damage to retaining walls by growing their roots into the walls as well as by burdening the wall structure with their biomass.

In Poland, numerous floristic studies of archaeological sites, historic buildings, parks and cemeteries have been undertaken, but most of them refer to the problem of plant invasion to a limited extent (Celka, 1999, 2011; Kamiński, 2004; Antkowiak & Heine, 2005; Sobisz et al., 2014; Lechowicz & Wrońska-Pilarek, 2018). According to Tokarska-Guzik et al. (2021), some invasive plants in Poland have a negative impact on cultural services and infrastructure. However, the occurrence of alien woody plants on historic retaining walls of riverbanks has not been intensively studied in Poland. Therefore, the study aimed to determine the floristic composition and

abundance of alien woody species inhabiting the retaining walls of the Vistula boulevards in Kraków, southern Poland.

MATERIALS AND METHODS

Study area

The study was conducted in the Vistula boulevards in Kraków, Lesser Poland Province, southern Poland, in July and August 2022 (Fig. 1). Kraków is the second largest city in Poland, with an area of 327 km² and a population of 780 000 (Statistics Poland, 2021). The city is in the temperate climate zone. From 2001 to 2010, the average air temperature in Kraków was 8.7°C, whereas the average annual precipitation was 719 mm (Statistics Poland, 2021). The Vistula boulevards in Kraków are a hydrotechnical structure lo-

cated on both sides of the Vistula, on the route of the Kraków Technology Trail, which is the city's industrial heritage route. They were built in 1907–1961 to protect the city from flooding and as a parking and reloading area for river transport (Szelińska-Kukulak & Kukulak, 2016). They extend from the mouth of the Rudawa River to the Dąbie Barrage, including four sections on the left bank (Rodła Boulevard, Czerwieński Boulevard, Inflancki Boulevard and Kurlandzki Boulevard) and five sections on the right bank of the Vistula (Tyniecki Boulevard, Poleski Boulevard, Wołyński Boulevard, Podolski Boulevard and Lotników Alianckich Boulevard). The boulevards consist of earth embankments, retaining walls and additional infrastructure, which has been modernised many times, especially after great floods (Porębska et al., 2019). The retaining walls are concrete, with the external cladding of hewn stone made of Chrzanów

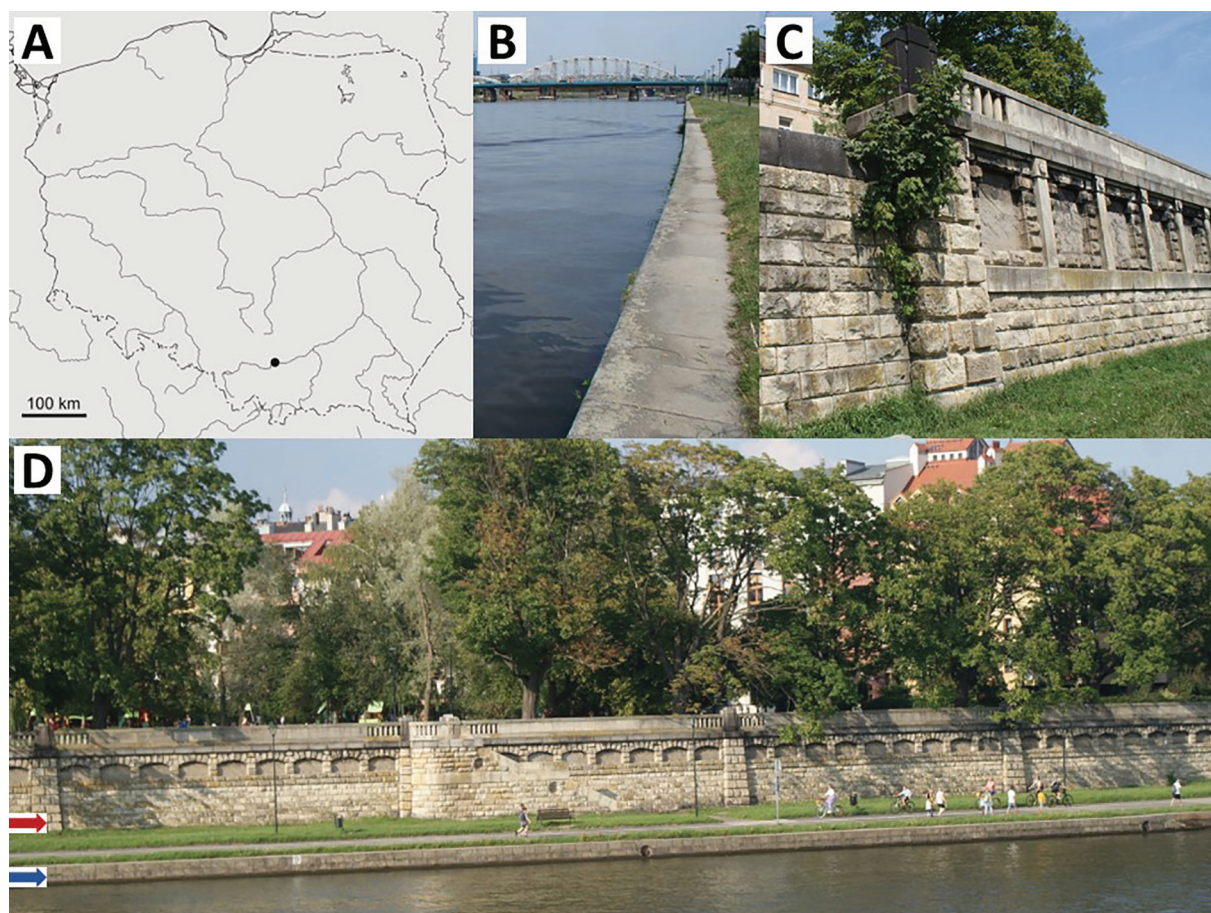


Fig. 1. Study area: A – location of Kraków in Poland, B – the lower retaining wall of Podolski Boulevard, C – the upper retaining wall of Kurlandzki Boulevard, D – lower (blue arrow) and upper (red arrow) walls of Czerwieński Boulevard (map and photos by A. Pliszko)

dolomites and the cordon slab of grey Silesian granite (Zachariasz, 2009). They are differentiated into lower and upper walls. The lower retaining walls embrace the riverbed and create a trans-shipment wharf. In contrast, the upper walls protect against high water levels and flooding (Fig. 1). In the line of the upper walls, there are also brick terrain stairs for pedestrians and paved ramps for vehicle communication. In 2011, the Vistula boulevards in Kraków were registered as monuments of the Lesser Poland Province (Szelińska-Kukulak & Kukulak, 2016). It is also relevant to mention that most of the Vistula boulevards are situated within the buffer zone of the Historic Centre of Kraków, one of the Polish sites included in the World Heritage List (Porębska et al., 2019; World Heritage Convention, UNESCO, 2022). Moreover, the Vistula boulevards are an attractive and popular place for recreation and sports, appreciated by residents and tourists (Nowacka-Rejzner, 2019).

Field observations and data sources

Field observations were conducted along the section from the mouth of the Rudawa River (50.051846° N, 19.916231° E) to the Kotlarski Bridge (50.053114° N, 19.960402° E) on the left bank of the Vistula and along the section from the Dębnicki Bridge (50.053695° N, 19.928882° E) to the Kotlarski Bridge (50.051982° N, 19.961034° E) on the right bank of the Vistula. The walls of the Retmański Bridge, located at the mouth of the Wilga River, were not included in the study. The total length of the riverbank line on both sides of the Vistula in the investigated sections was about 7.2 km. The retaining walls were divided into two categories, namely lower (L) and upper (U) walls, as they are usually distinguished in the literature (Zachariasz, 2009; Szelińska-Kukulak & Kukulak, 2016). The seedlings and older individuals of alien woody plants (trees, shrubs and vines) growing on the lower and upper retaining walls and at the foot of the upper walls (individuals extending close to the wall, with stems no more than 5 cm away from the wall) were observed and counted. The observations were made during walks along the walls, stopping every 2 meters if possible. The abundance of individuals was determined in three age categories (i.e. seedling, juvenile and mature) using the following scale: 1 – very low (1–10 individuals), 2 – low (11–50 individuals), 3 – medium

(51–100 individuals), 4 – high (101–200 individuals) and 5 – very high (> 200 individuals). It was shown as the total number of individuals for all examined sections, considering the division into wall type and age categories. The names of plant taxa were given after Plants of the World Online (2022), the terminology of alien plants after Pyšek et al. (2004), and the life forms after Rutkowski (2004). The geographical-historical status of Polish flora followed Tokarska-Guzik et al. (2012, 2021) and Mirek et al. (2020).

RESULTS AND DISCUSSION

A total of 11 alien species (seven species of trees, two species of shrubs and two species of woody vines) belonging to eight families were recorded on the retaining walls of the Vistula boulevards in Kraków (Table 1, Figs 2, 3). They are established in Polish flora, except *Parthenocissus tricuspidata*, which is only cultivated in Poland (Mirek et al., 2020). Moreover, five of the established species are nationally invasive (*Acer negundo*, *Fraxinus pennsylvanica*, *Parthenocissus quinquefolia*, *Robinia pseudoacacia* and *Rosa rugosa*), and two are regionally invasive (*Ailanthus altissima* and *Juglans regia*) (Tokarska-Guzik et al., 2012). The juvenile individuals dominated within the species; however, *Parthenocissus quinquefolia*, *Parthenocissus tricuspidata*, *Prunus cerasifera* and *Rosa rugosa* were also represented by mature individuals (Table 1). Moreover, most recorded species showed a low abundance, reaching less than 50 individuals in each distinguished age class. However, the vines covered relatively large surfaces of walls (> 25 m²) in some places (Table 1, Fig. 3, B and C). *Malus domestica* and *Rosa rugosa* were found only on lower walls, whereas *Ailanthus altissima*, *Juglans regia*, *Parthenocissus quinquefolia*, *Parthenocissus tricuspidata*, *Prunus cerasifera* and *Robinia pseudoacacia* grew only on upper walls. The remaining species inhabited the lower and upper walls, with more individuals occurring on the upper walls (Table 1). Although native woody plants were not the subject of the study, it seems relevant to mention that the retaining walls of the Vistula boulevards in Kraków were also inhabited by native woody plants such as *Acer platanoides* L. (Fig. 1, C), *Acer pseudoplatanus* L., *Alnus glutinosa* (L.) Gaertn., *Betula pendula* Roth, *Crataegus* L. sp., *Fraxinus excelsior* L., *Hedera helix* L., *Rubus caesius* L., *Salix*

Table 1. Characteristics of alien trees and shrubs recorded on retaining walls of the Vistula boulevards in Kraków, southern Poland. Explanations: life form: M – megaphanerophyte, N – nanophanerophyte, WV – woody vine; status in Poland: C – cultivated alien, E – established neophyte (kenophyte), I – nationally invasive in Poland, RI – regionally invasive in Poland; abundance: 1 – very low (1–10 individuals), 2 – low (11–50 individuals), 3 – medium (51–100 individuals), 4 – high (101–200 individuals), 5 – very high (> 200 individuals), * – dense stands of individuals covering more than 25 m² of the wall surface

Species	Family	Life form	Status in Poland	Total abundance of individuals					
				Lower wall			Upper wall		
				seedling	juvenile	mature	seedling	juvenile	mature
<i>Acer negundo</i>	Sapindaceae	M	E, I	–	1	–	–	2	–
<i>Ailanthus altissima</i>	Simaroubaceae	M	E, RI	–	–	–	–	2	–
<i>Fraxinus pennsylvanica</i>	Oleaceae	M	E, I	–	2	–	–	1	–
<i>Juglans regia</i>	Juglandaceae	M	E, RI	–	–	–	–	1	–
<i>Malus domestica</i>	Rosaceae	M	E	–	1	–	–	–	–
<i>Morus alba</i>	Moraceae	M	E	–	1	–	1	1	–
<i>Parthenocissus quinquefolia</i>	Vitaceae	WV	E, I	–	–	–	1	1	*
<i>Parthenocissus tricuspidata</i>	Vitaceae	WV	C	–	–	–	–	–	*
<i>Prunus cerasifera</i>	Rosaceae	N	E	–	–	–	–	1	1
<i>Robinia pseudoacacia</i>	Fabaceae	M	E, I	–	–	–	–	1	–
<i>Rosa rugosa</i>	Rosaceae	N	E, I	–	1	1	–	–	–

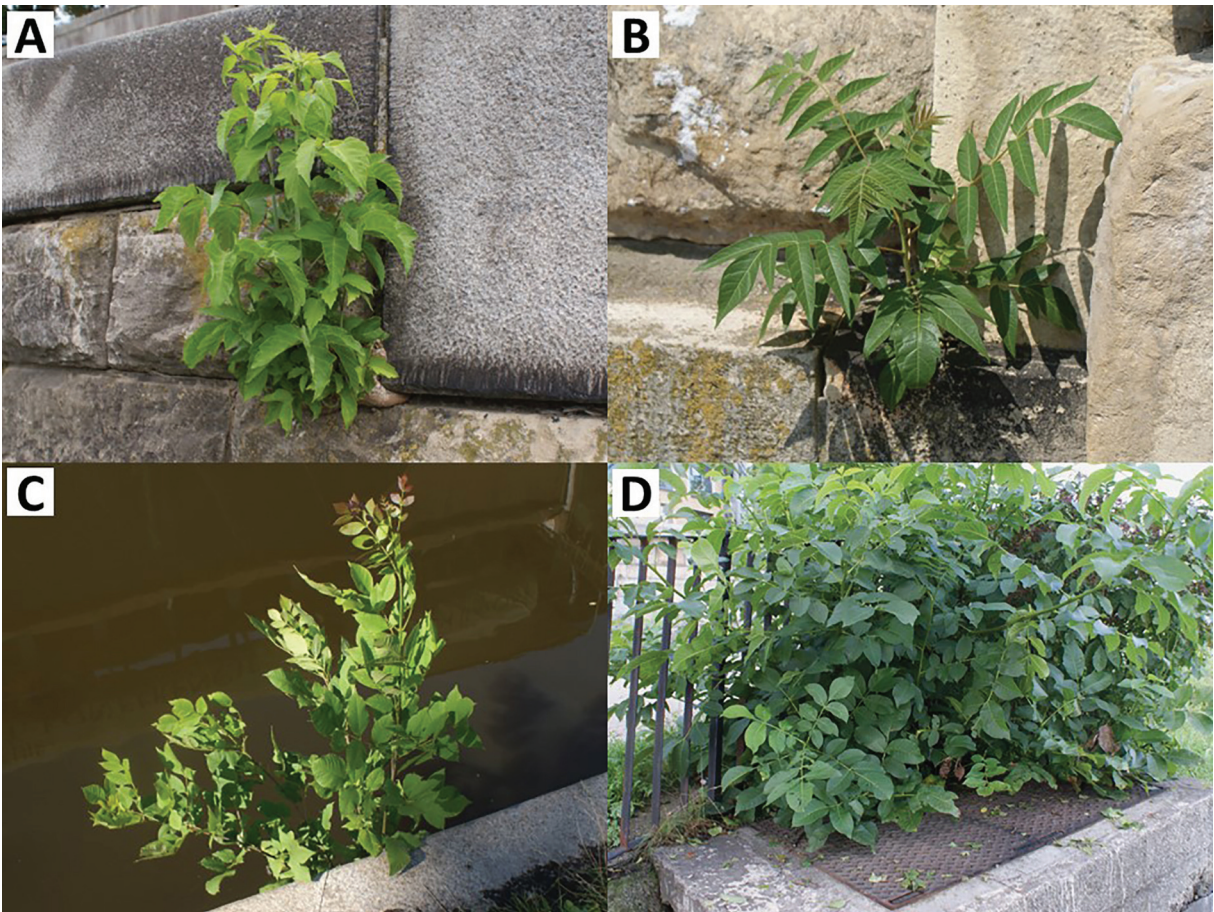


Fig. 2. Examples of alien woody plants inhabiting the retaining walls of the Vistula boulevards in Kraków, southern Poland: A – *Acer negundo* on the upper wall of Kurlandzki Boulevard, B – *Ailanthus altissima* on the upper wall of Kurlandzki Boulevard, C – *Fraxinus pennsylvanica* on the lower wall of Czerwieński Boulevard, D – *Juglans regia* on the upper wall of Poleski Boulevard (photos by A. Pliszko)

caprea L., *Salix cinerea* L., *Salix viminalis* L., *Sambucus nigra* L. and *Ulmus laevis* Pall. Moreover, there was *Ligustrum vulgare* L., a taxon of uncertain status in Polish flora (Mirek et al., 2020). The abundance of native species was low, except *Hedera helix*, which formed a few relatively large stands ($> 4 \text{ m}^2$) on some of the walls. Moreover, some individuals of *Betula pendula*, *Hedera helix*, *Rubus caesius*, *Sambucus nigra* and *Ligustrum vulgare* were mature and produced flowers and fruits.

The walls are specific anthropogenic habitats, similar to cliffs and steep rocky mountain slopes in terms of a vertical surface and rocky substrate (Cathersides & Parker, 2014). Some plants such as mosses and ferns can thrive in wall crevices or mortar cavities. However, the walls are generally extreme habitats for trees and shrubs, mainly due to a lack or limited amount of soil and nutrients and high exposure to thermal stress and drought (Boratyński et al., 2003; Cathersides & Parker, 2014; Huang et al., 2019). Therefore, the low abundance of trees and shrubs on retaining walls of the Vistula boulevards in Kraków is not surprising. According to Huang et al. (2019), seed germination and maturity are difficult for flowering plants to achieve in the conditions found on walls. Nevertheless, woody vines rooted in the soil beneath the wall can grow profusely by climbing the walls (Fig. 3, B). Also, other woody plants, if grown on the soil at the foot of the wall (Fig. 3, A), have more favourable conditions for growth and development than plants growing directly on walls.

The occurrence of alien woody plants on walls is aided by wind and birds, the most critical seed dispersal agents contributing to the spread of plants in cities (Huang et al., 2019; Celesti-Grapow & Ricotta, 2021). It is worth noting that the cracks in walls can act as traps for spores, seeds and fruits, from which they cannot be easily blown away by wind or washed away by rainwater (Huang et al., 2019). The fruits of *Acer negundo*, *Ailanthus altissima*, *Fraxinus pennsylvanica*, *Robinia pseudoacacia* are easily dispersed by wind. In contrast, the fruits or seeds of *Juglans regia*, *Malus domestica*, *Morus alba*, *Parthenocissus quinquefolia*, *Prunus cerasifera* and *Rosa rugosa* are commonly dispersed by birds (Tokarska-Guzik, 2005; Lenda & Skórka, 2009; Wojtatowicz & Pietrzykowska, 2018). However, the presence of *Acer negundo*, *Fraxinus pennsylvanica*, *Malus domestica* and *Rosa rugosa* on lower retaining

walls of the Vistula boulevards suggests that the fruits of these species can also be dispersed by water (at least for a short distance, after the fruits or seeds are carried by the wind or birds into the water).

Many authors have suggested that trees and shrubs can damage walls and that they should be removed from walls as soon as possible (Satriani et al., 2010; Nedelcheva, 2011; Cathersides & Parker, 2014; Dahmani et al., 2020; Carrari et al., 2022). On the other hand, woody vines climbing on walls of historic buildings and monuments are often seen as low-risk, and their decorative value is usually highly appreciated (Jackiewicz & Borowski, 1998; Cathersides & Parker, 2014). Moreover, in some cases, the walls can improve urban biodiversity (Jim, 2013; Chen et al., 2020). Nevertheless, the physical and chemical impact of the roots, as well as the increasing biomass of the above-ground parts of trees and shrubs, may cause severe damage to the construction of historic buildings and walls and thus reduce their cultural values, as well as economic and social functions (Cathersides & Parker, 2014; Dahmani et al., 2020). Some species of invasive trees such as *Acer negundo* and *Ailanthus altissima* have been very well recognised as posing a threat to infrastructure and buildings in European cities (Tokarska-Guzik, 2005; Nedelcheva, 2011; EPPO, 2020). In Poland, *Acer negundo* often forms dense thickets near railway tracks and on flood embankments, impeding access to railway infrastructure and hydrotechnical devices. In addition, seedlings or young trees of this species are often found on old walls and roofs (Chmura et al., 2018). *Ailanthus altissima* can undermine pavement tiles, asphalt and fence foundations with its roots or cause damage to sewage (rainwater) infrastructure by the intensive root growing through the pipes (Jackowski et al., 2018). At the same time, it should be emphasised that *Ailanthus altissima* is in the list of invasive alien species of concern in the European Union (European Commission, 2020), as well as in the Polish list of alien species that, if released into the natural environment, may threaten native species or natural habitats (Dziennik Ustaw, 2011). Interestingly, *Acer negundo* and *Ailanthus altissima*, together with *Parthenocissus quinquefolia* and *Robinia pseudoacacia*, have recently been listed among the most widespread alien woody plants on walls of heritage sites in Italy (Celesti-Grapow & Ricotta, 2021). Moreover, *Ailanthus altissima*, *Morus alba* and *Robinia pseudoacacia*

have been reported from old masonry walls in China (Huang et al., 2019). It is also worth noting that the previous studies conducted in Poland do not confirm the negative impact of *Fraxinus pennsylvanica* on infrastructure (Gazda et al., 2018). However, this study suggests that *Fraxinus pennsylvanica* can inhabit the retaining walls of riverbanks, posing a threat to their construction and function. Moreover, the increasing spread of *Morus alba* observed in recent years in the area of Kraków suggests that this species has the potential to become invasive in the future. Although the abundance of the recorded woody plant species was relatively low, it cannot be unequivocally stated that their threat to the retaining walls of the Vistula boulevards in Kraków is negligible. Sometimes even a single tree, if it reaches a considerable size (biomass) and is deeply rooted in the wall, can cause significant damage to the wall structure, especially during a vio-

lent storm (Wong et al., 2011). Moreover, reaching maturity and producing fruits by some alien woody plants growing on the retaining walls indicate that they are well-adapted to unfavourable conditions and can spread further.

Due to dissemination by wind and birds, woody plants often grow at considerable heights and in hard-to-reach places (vertical and high walls), which makes their removal difficult and expensive (Celesti-Grapow & Ricotta, 2021). To protect historic buildings and monuments against invasive trees and shrubs in cities, it is necessary to properly plan and manage green areas (Nedelcheva, 2011). Although alien trees and shrubs have many valuable features in urban environments (Sjöman et al., 2016; Lüttge & Buckeridge, 2020), their cultivation should be controlled. Many exotic woody plant species grown in cities can easily escape cultivation and threaten his-

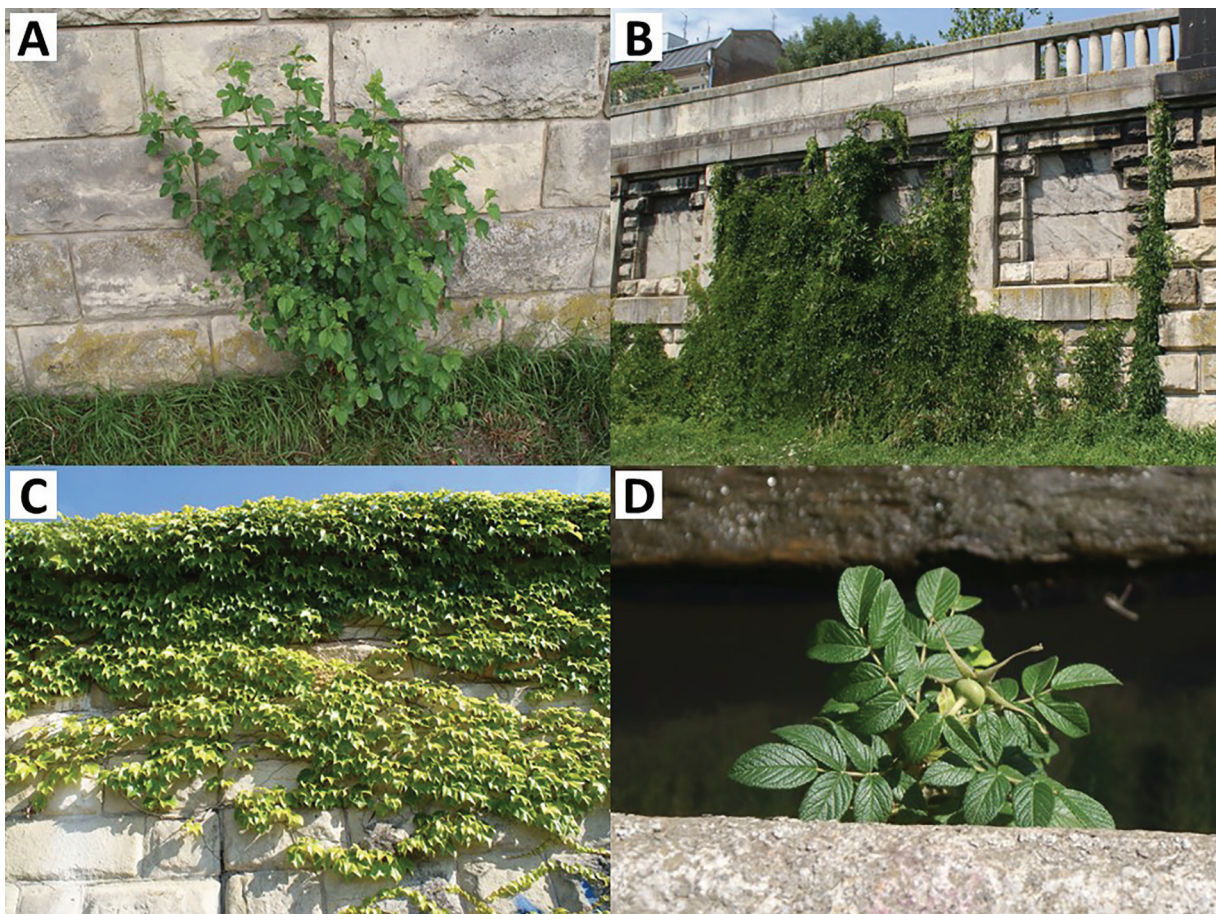


Fig. 3. Examples of alien woody plants inhabiting the retaining walls of the Vistula boulevards in Kraków, southern Poland: A – *Morus alba* at the foot of the upper wall of Kurlandzki Boulevard, B – *Parthenocissus quinquefolia* on the upper wall of Kurlandzki Boulevard, C – *Parthenocissus tricuspidata* on the upper wall of Rodła Boulevard, D – *Rosa rugosa* on the lower wall of Wołyński Boulevard (photos by A. Pliszko)

toric buildings (Nedelcheva, 2011; Dahmani et al., 2020; Celesti-Grapow & Ricotta, 2021). Therefore, the selection of alien trees and shrubs to be planted in Kraków, especially in the historic part of the city and its vicinity, should be consulted with the conservation services as suggested by Muras (2016).

Due to their history and important anti-flood function, the retaining walls of the Vistula boulevards in Kraków require regular monitoring. Particular attention should be paid to woody plants growing on the walls or at the very base of the walls so that they are removed as soon as possible. Cutting shoots is not an effective method of eliminating alien woody plants. During field observations, I saw an individual of *Acer negundo*, which, despite cutting (it had the scars indicating the cutting), still grew between the stones of the upper retaining wall (Fig. 2 A). It was visible that the plant's roots undermined the block of the wall. As a part of the cooperation between the management of urban green areas in Kraków and the provincial office for the protection of monuments, it seems necessary to develop more effective methods of protecting the retaining walls of the Vistula boulevards from the adverse effects of woody plants. It appears that the low abundance of phanerophytes will continue in the future if the technical condition of the retaining walls does not deteriorate (i.e. if there are no numerous cracks or cavities in the mortar, where trees and shrubs can grow). For further research, it is worth monitoring changes in the life stages and abundance of alien trees and shrubs at regular intervals (e.g. every five years) as well as checking their preferences about the material from which the wall is made or the height of the wall, using statistical analyses. Finally, the invasion of alien trees and shrubs may also affect retaining walls in other cities in Poland. Therefore, it is essential to continue research and take appropriate action on a wide scale.

CONCLUSIONS

The retaining walls of the riverbanks can serve as a habitat for alien woody plants that escape from cultivation in urban areas. The low abundance of trees and shrubs confirms the general pattern that the walls are difficult to colonise by phanerophytes and indicates the good technical condition of most of the examined retaining walls. Nevertheless, regular removal and monitoring of trees and shrubs are recom-

mended to prevent damage to the historic retaining walls of the Vistula boulevards in Kraków.

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