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Research paper

Ecological Functions of Siberian Elm (*Ulmus pumila* L.) Forest Belts Along Railway Corridors in Chernihiv, Ukraine

Oleksandr Lukash[1], Yuliia Stupak[1]

ABSTRACT

This study evaluates the multi-functional ecological effects of a protective forest belt dominated by the invasive *Ulmus pumila* L. along a railway corridor in Chernihiv (Ukraine). While protective belts are essential for stabilizing anthropogenic environments, the use of Siberian elm remains controversial due to its invasive potential. This study aims to quantify the belt's efficiency for heavy metal (HM) sequestration, noise attenuation, and dust retention, while analyzing its invasive expansion into adjacent phytocenoses. Geobotanical methods, atomic absorption spectrophotometry, and acoustic measurements were employed to assess these ecosystem services across gradients of increasing distance from the railway.

The results reveal a significant multi-barrier effect. The Siberian elm forest belt facilitated a substantial reduction in HM concentrations; compared to areas closest to the track, concentrations of Ni, Pb, and Zn behind the forest belt decreased by up to 6.0, 4.5, and 2.8 times in leaves, and 4.0, 1.5, and 3.2 times in soil, respectively. The species demonstrated high bioaccumulation capacity, particularly for Cd and Zn. Despite a narrow forest width of only 7 m, the belt achieved a noise reduction of 22 dB(A), a performance attributed to high canopy closure (70%) and dense shrub layers (50%). Furthermore, the leaves exhibited a robust dust retention capacity of 62.23 g/m², supported by specific microstructural surface features. However, the study also noted the progressive invasive expansion of the Siberian elm, which has actively displaced native flora since 2006, leading to floristic poverty in the adjacent phytocenoses.

The study concludes that in heavily contaminated technogenic corridors, the immediate ecosystem services of the Siberian elm outweigh its negative ecological impacts. These findings provide a basis for pragmatic management strategies that prioritize the protective functions of existing belts while implementing containment measures to protect adjacent natural habitats.

Keywords: railway pollution, invasive species, heavy metal mitigation, noise attenuation, dust retention, ecosystem services, *Ulmus pumila* L.

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[1] Department of Ecology, Geography and Nature Management, T.H. Shevchenko National University "Chernihiv Collegium", 53 Hetmana Polubotka Street, Chernihiv, 14013, Ukraine
通訊作者：Oleksandr Lukash, Corresponding author, Oleksandr Lukash, Email: lukash2011@ukr.net
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INTRODUCTION

Green spaces are crucial for the health of cities. Analyzing the landscaping services of the city of Poznań for noise reduction, pollutant filtration and temperature reduction, Łowicki et al. (2025) provided a coefficient of efficiency for filtering pollutants and reducing noise, which decreased in the following order according to land cover type: coniferous forest > mixed forest > deciduous forest > permanent crops (allotment gardens, orchards, and plantations) > single coniferous trees > single deciduous trees > bushes. However, urban green belts were not included in this classification. In contrast, roadside forest belts exhibit high phytomeliorative properties and provide sanitary and ecological functions.

Protective forest belts help minimize negative impacts on adjacent areas, thereby significantly improving the quality of the urban environment (Drebot 2019). In particular, railway forest belts provide key ecosystem services, including heavy metal sequestration, noise attenuation, dust retention, and microclimate regulation, which are all essential for mitigating the environmental impact of transport infrastructure. These forest belts function as natural barriers that reduce noise (Fang and Ling 2003; Ahwaludin et al. 2024; Firnawati 2025; Meng et al. 2025) and improve air pollution by absorbing gaseous pollutants and trapping particulates (Hamad and Jasim 2024; Firnawati et al. 2025), thereby enhancing overall air quality (Smaranda et al. 2014; Chaphekar et al. 2021).

Research has shown a positive logarithmic relationship between noise reduction and the width, length, or height of tree belts (Fang, Ling 2003). Well designed plantings can reduce noise levels by 10–15 dBA (Firnawati 2025), with greenbelt areas showing reductions of approximately 16 dB compared to 11 dB for non-vegetated spaces (Ahwaludin et al. 2024). Furthermore, Meng et al. (2025) found that in 5–15 m wide lanes, the 'Abreast' planting pattern consistently offered greater noise reduction than the 'Taffy' configuration.

Pollutant absorption also varies by species. Among tropical trees, *Mangifera indica* L. exhibits the highest dust absorption capacity (0.531 g/m²), while *Khaya anthotheca* (Welw.) C.DC. shows the lowest (0.212 g/m²) (Firnawati et al. 2025). Similarly, green belts of smooth-leaved species (e.g., *Aesculus hippocastanum* L. and Liriodendron tulipifera L.) are less efficient at reducing pollutants than coarse-leaved species like *Ulmus* L. and *Corylus* L. (Hamad, Jasim 2024).

Forest belts also help mitigate heavy metal pollution. Metal accumulation indices (MAI) ranging from 3.06 to 11.65 in industrial greenbelts, have helped identify species best suited for atmospheric pollution management (Karmakar, Padhy 2019). According to Maksimtsev et al. (2021), the forest litter plays a crucial role in delaying heavy metal migration; thus, linear protective strips of deciduous trees are recommended to maximize this effect along roads. Furthermore, protective afforestation is a key tool for stabilizing microclimates and combating climate change (Potashkina, Koshelev 2022). Along railway tracks, forest plantations protect against adverse climatic factors, reduce various types of pollution, and mitigate aerodynamic effects of passing trains (Bosak et al. 2023).

In the Forest Zone of Ukraine, forest belts have traditionally been established using sustainable local species or the North American *Robinia pseudoacacia* L. However, in the late 1960s, a distinctive forest belt was established in southeastern Chernihiv

(Ukraine) parallel to a railway track using *Ulmus pumila* L. (Siberian elm). This remains the only forest belt composed of *U. pumila* in the northern Ukrainian Forest Zone and it represents a significant component of Chernihiv's green infrastructure (Lukash et al. 2024).

U. pumila is a deciduous tree native to East Asia, valued for its tolerance to urban pollution and resistance to Dutch elm disease (EUFORGEN 2024). However, outside its natural range, the species often exhibits invasive behavior. Recent research has shown that *U. pumila* is capable of significant spread in riparian ecosystems in the western USA (Reynolds et al. 2022), and in Ukraine, it is also classified as an invasive alien species (Kucher et al. 2024). Despite its invasive nature, *U. pumila* is highly valued for specific ecological functions. It is commonly used in Mongolia and China to combat desertification (Park et al. 2016) and is known to improve urban microclimates (Hort et al. 2015). An inter-site comparison of 32 tree species found that Siberian elm exhibited high accumulation rates of heavy metals (Cd, Cr, Cu, Mn, Zn) in both unwashed and washed leaves, ranking third in metal accumulation index (MAI) value (5.72) among roadside tree species in Beijing (Liu et al. 2017).

Despite a growing body of research on invasive species and environmental mitigation, significant gaps in the literature remain. Specifically, there is a notable lack of field-based studies dedicated to assessing long-established *U. pumila* forest belts growing along railway lines in the distinct environmental context of Eastern Europe. Furthermore, current research rarely employs integrated assessments that simultaneously evaluate both the pollution mitigation potential and the associated invasion dynamics of such established plant communities. This study aims to address these specific shortcomings by providing a comprehensive, integrated analysis of these understudied ecosystems.

To date, no studies conducted in the Forest Zone of Ukraine have comprehensively analyzed both the ecological benefits and the invasive risks of Siberian elm forest belts. This study addresses this gap, testing two main hypotheses regarding the *U. pumila* belt along the railway: (1) it facilitates the spread of an invasive species into adjacent territories; and (2) it provides a significant phytoremediative effect. Consequently, the objective of this study was to identify the primary ecological impacts of the Siberian elm forest belt in Chernihiv.

This study aims to fill these gaps by providing an integrated assessment of long-established *U. pumila* forest belts. Specifically, we investigate their performance in pollution mitigation, including noise reduction, dust deposition, and heavy metal accumulation in soils and plants, while simultaneously evaluating vegetation dynamics to understand their role in local invasion processes.

MATERIALS AND METHODS

Study site description

The studied Siberian elm forest belt is located along a railway in Chernihiv city, in northern Ukraine (51°28' N, 31°15' E). The region is characterized by a temperate continental climate with a mean annual temperature of 8.5–9.0℃ and average annual precipitation of 600–620 mm (DENRCRSA 2026).

The studied forest belt, approximately 1 km long and 7 m wide, is situated 10 m from the railway tracks (Figure 1). Based

on its structure, the belt is classified as a windbreak, featuring high density with almost no gaps, enabling it to intercept the majority of the airflow. A row of one-story buildings is located 25–40 m from the forest belt on the side opposite the railway.

The study site is situated on a flat pine terrace of the Desna River characterized by xerophilous conditions. The forest strip is planted on soils of technogenic origin. The soil texture is sandy loam, with a pH of 5.5 and an organic matter content of 1.5% (DENRCRSA. 2026). These soil properties provide the context for understanding heavy metal mobility and plant growth dynamics in the study area.

Plot establishment and geobotanical methods

Observations of *U. pumila* spread in areas adjacent to the forest belt have been carried out annually since 2001. For the geobotanical study, seven plots (200–300 m² each) were established in the following locations: three plots within the forest belt (200 m apart); three plots along the forest belt near the railway track; and one plot on the ravine slope 100 m from the forest belt, opposite the railway. These locations represent varying degrees of *U. pumila* establishment.

Vegetation field surveys were carried out using standard geobotanical methods (Yakubenko et al. 2018). In particular, vegetation relevés were taken during the peak of the vegetation period (end of May to beginning of June) in the 100 m² areas. Experimental plots were homogeneous in terms of ecological conditions and plant species composition. The contribution of each species to the phytocenosis was assessed using the projective coverage method.

Sample collection

Soil and *U. pumila* leaf samples for laboratory analysis were collected in May 2025 from three zones at different distancesfrom the railway track: 1 m from the railway tracks (in front of the forest belt), 15 m from the railway tracks (in the forest belt)

Figure 1. *Ulmus pumila* forest belt along the railway in Chernihiv city

and 30 m from the railway tracks (behind the forest belt). Samples were collected in dry weather. In each of the three zones, ten plots (10 m² each), spaced 100 m apart, were established for soil and leaf sampling.

Soil samples from each plot were collected using the "envelope" method (Kapanadze et al. 2019) by taking five subsamples from four corner points and at one point in the plot center. Sampling was carried out at a depth of 15–20 cm under the surface at each of the 50 sampling points, with 200–250 g of soil collected per subsample. All 5 subsamples were placed in one container and thoroughly mixed, resulting in composite sample from the site weighing 1–1.5 kg. Stones and roots were removed from the soil samples at the sampling site. A sample from each plot was placed in a clean paper bag. Approximately 100 g of fresh leaf material was collected from each of the 30 plots for determination of heavy metal concentrations.

Dust retention per unit leaf area of *U. pumila* plants was performed according to the method described by Sheng et al. (2024). Leaf samples were collected from 10 plots selected from the previously described 30 plots. Specifically, analysis included the 10 plots located in the belt at a distance of 100 m from the railway. In each plot, 100 leaves were selected from different trees, resulting in a total of 1,000 leaves for analysis. Leaf area was measured in the field on intact plants using a portable AM350 (ADC BioScientific Ltd, UK) .

Leaves were collected from the upper third of the tree crowns (Rautio et al. 2020) at heights ranging from 2 to 8 m above ground level, depending on the tree height. An aerial platform (basket lift) was used to collect samples from tall trees. Sampling was performed uniformly from all sides of the trees, including from portions facing both the railway and the residential area, to ensure a representative and homogeneous samples. Immediately after collection, samples were stored in clean paper bags and kept cool (Rautio et al. 2020).

Noise level measurement

Noise characteristics associated with railway traffic were measured on-site. The research was conducted on dry and windless days in May 2025, when the Siberian elm trees were in full growth. Noise levels were measured using an SL824 digital sound level meter (Shenzhen Handsome Technology Ltd, China). Ten representative sites, located 100 m apart, were selected for the study. At each of the ten sites, noise levels were measured at four points at a distance of 1, 10, 15 and 25 m from the track.

For all measurements, the noise level was measured from the same regional passenger electric train, which was 160 m long and consisted of two electric locomotives and six passenger cars. At each of the four points in each of the 10 sites, four sound level meters—previously tested for equivalence of their readings—were used simultaneously to measure noise during the passage of the electric train. Data collection took 10 days. In one day, measurements were taken at one site per day, with noise levels recorded at each of four points in four replicates, corresponding to the train's four daily passages near the forest belt (at 06:15, 12:30, 14:30 and 20:45). The duration of noise level measurement at each point was 15 seconds, reflecting the average time required for the train to pass each section.

Sample preparation for laboratory analysis

For determining the concentration of heavy metals, all selected soil samples were dried in a drying stove at a temperature of 105℃ for 24 h. Foreign impurities (small

stones, plant roots and leaves, etc.) were removed by sifting through a stainless steel sieve with a mesh aperture of 3 mm. Following the recommendations of Rautio et al. (2020), the leaves were thoroughly washed with distilled water before drying, then dried in a drying stove at a temperature of 70℃, then crushed and homogenized. The homogenization of the samples was carried out using a special laboratory mill. Mineralization was carried out by dry ashing: soil samples were incinerated at 450–550℃ for 24 hours, and plant samples were incinerated for 48 hours. After natural cooling of the furnace, the inorganic ash was converted into a liquid form for analysis by adding concentrated HNO_3 and gently heating the mixture on a hot plate. Finally, the solution was filtered through Whatman Grade 42 filter paper (2.5 μm) and diluted with distilled water up to a fixed volume of 25 mL in a volumetric flask.

Analytical methods

The concentration of mobile forms of copper (Cu), zinc (Zn), nickel (Ni), cadmium (Cd), and lead (Pb) was determined using the atomic absorption spectrophotometry method (SSU 2025) using a Spectr AA 240Z Varian AA DUO (Agilent Technologies, USA) atomic absorption spectrophotometer. Extraction was conducted using a buffer solution of ammonium acetate (1 mol L^{-1} at pH 4.8) at a soil:solution ratio of 1:10, shaken for 2 hours. Quality control measures included analysis of reagent blanks, duplicate samples (relative standard deviation < 5%), and certified reference materials of soil composition to verify the analytical accuracy of the recovery rates.

For dust retention analysis under laboratory conditions, the collected leaves were fully submerged in distilled water for 4 hours. The remaining dust suspension was then filtered through pre-weighed Whatman Grade 42 (2.5 μm pore size) filter paper. The filtered papers with dust were then dried at 60℃ for 24 h and weighed. Dust retention per unit leaf area (G) was determined by the formula:

$$G = \frac{W_2 - W_1}{S}$$

where:
W_2 is the weight of the filter paper after filtration and drying,
W_1 is the weight of the filter paper itself, and
S is the total area of the collected leaves.

Statistical analysis

All statistical analyses were performed using STATISTICA 13.3 (TIBCO Inc., Palo Alto, CA, USA). The results are expressed as mean ± standard deviation (SD).

In the study of heavy metal mitigation effect, two-way ANOVA was used to evaluate the effects of two main factors: Distance (1, 15, and 30 m from the railway tracks) and Medium (leaves vs. soil). Before running the analysis, normality and homogeneity of variance were checked using the Shapiro-Wilk test and Levene's test, respectively (Sokal, Rohlf 2012). Tukey's HSD post-hoc test was applied to identify specific significant differences among sampling locations.

The obtained noise level data and dust retention capacity were analyzed using One-way ANOVA to determine the significance of noise reduction at different distances from the source. The background noise level (ambient noise) was measured before each train passage to ensure it did not interfere with the primary data. In all cases, statistical significance was set at $p < 0.05$.

RESULTS

Vegetation structure and invasion

As shown in Table 1 (relevé 1), *U. pumila* trees in the forest belt reach 10–12 m in height and feature well-developed crowns (with 70% coverage area). The share of other trees is insignificant. In addition, *U. pumila* dominates (40%) in the shrub layer. The herb layer is floristically poor; it is dominated by shade-tolerant weed species, primarily *Galium aparine* and *Ballota nigra*.

The relevés 2–4 (Table 1) present the composition and structure of phytocenoses in areas with different projective cover and different durations of *U. pumila* invasion into phytocenoses next to the track. Phytocenoses with *U. pumila* occur along the entire trackside opposite the forest belt. The invasive species spreads both by seed reproduction and vegetatively (Figure 2). It should be noted that these phytocenoses are periodically mowed: as a result, the height of the shrub layer in all areas does not exceed 1.5 m.

Relevé No. 2 (Table 1) records the result of the successful spread of *U. pumila*: the species has firmly established itself in the phytocenosis – it has a projective cover in the shrub and herb layers of 10%. The average diameter at the root collar (ADRC) of *U. pumila* shrubs in this area is 3.5 cm.

In the area, where the relevé No. 3 (Table 1) was carried out, *U. pumila* projective coverage in the shrub layer is 15%, and 30% in the herb layer. However, the dominant role (30%) in the phytocenosis belongs to the natural species *U. laevis*. This area is the most floristically rich compared to the others. In the relevé No.3 the ADRC of *U. pumila* shrubs is 5.5 cm.

In the fourth relevé, *U. pumila* cover increased to 35% in the shrub layer, and 20% in the herb layer. The ADRC of *U. pumila* shrubs is 6.7 cm. In this area, the appearance of *U. pumila* along the railway track was registered for the first time in 2006.

In the fifth relevé (Table 1), on the slope of a ravine on the opposite side of the railway, the phytocenosis is composed of *U. pumila* trees of similar age and height to those found in the forest belt. In contrast to the forest belt, on the slope of the ravine, *U. pumila* co-dominates with *Robinia pseudoacacia*. The herbaceous layer is also floristically poor, and is dominated by the shade-tolerant ruderal species *Galium aparine*.

Heavy metal accumulation

Statistical analysis using two-way ANOVA confirmed that both sampling distance and the type of medium (leaves vs. soil) significantly influenced heavy metal concentrations (Table 2). ANOVA and subsequent Tukey's HSD post-hoc tests revealed a statistically significant reduction in the concentration of all studied heavy metals as distance from the railway increased ($p < 0.05$).

A total of 30 soil and 30 leaf samples were analyzed. The soil and *U. pumila* leaf samples taken at different distances from the railway track were slightly contaminated with Cu, Zn, Ni, Cd and Pb (Table 3).

Compared to samples taken from the area closest to the railway, the content of Cu, Zn, Ni, Cd and Pb in samples behind the forest belt was lower by 1.26, 2.8, 6, 1.82 and 4.5 times in the *U. pumila* leaves and by 1.44, 3.25, 4, 2 and 1.53 times in the soil, respectively.

The most substantial drop was observed for Pb and Cu. Specifically, foliar Pb levels decreased from 0.545 mg/kg at 1 m from the railway tracks to 0.152 mg/kg within the forest belt (by 72%). Similarly, soil Cu levels

Table 1. Phytocenoses including *U. pumila* participation in Chernihiv city

Relevé number	1	2	3	4	5
Tree layer (a) cover [%]	70	.	.	.	80
Shrub layer (b) cover [%]	50	10	15	40	50
Herb layer (c) cover [%]	30	100	100	100	40
Acer campestre (b)	5	.	.	.	.
Acer negundo (b)	7	+	3	5	5
Acer platanoides (b)	8	.	.	.	.
Achillea submillefolium	.	+	+	.	.
Ambrosia artemisiifolia	.	10	.	.	.
Arrhenatherum elatius	.	.	+	.	.
Artemisia scoparia	.	.	+	.	.
Artemisia vulgaris	.	.	+	.	+
Asparagus officinalis	.	.	+	.	.
Asperugo procumbens	.	+	+	.	.
Ballota nigra	10	+	.	+	20
Berteroa incana	.	1	2	.	+
Calamagrostis epigejos	.	.	+	.	.
Carex hirta	.	.	+	.	2
Chelidonium majus	1	.	.	.	1
Cichorium intybus	.	+	.	.	.
Cirsium arvense	.	.	1	.	.
Convolvulus arvensis	.	.	1	.	.
Crataegus sp. (b)	.	.	.	.	10
Dactylis glomerata	.	+	.	.	.
Daucus carota	.	.	+	.	.
Echium vulgare	.	+	+	.	.
Elymus repens	.	90	80	70	.
Equisetum arvense	.	20	+	.	.
Erigeron strigosus	.	+	+	.	.
Fraxinus excelsior (b)	.	.	+	.	3
Galium aparine	15	.	.	.	20
Humulus lupulus	.	+	.	15	.
Oenothera biennis	.	.	+	.	.
Plantago lanceolata	.	.	+	.	.
Potentilla argentea	.	+	+	.	.
Robinia pseudoacacia (a)	5	.	.	.	35
Robinia pseudoacacia (c)	5	.	.	.	.
Setaria glauca	.	+	+	.	.
Sisymbrium orientale	.	.	.	.	+
Tanacetum vulgare	.	.	+	.	.
Taraxacum officinale	.	.	+	+	+
Tragopogon major	.	1	7	+	.
Ulmus laevis (a)	.	.	.	.	7
Ulmus laevis (b)	.	1	30	10	10
Ulmus pumila (a)	70	.	.	.	50
Ulmus pumila (b)	40	10	15	35	30
Ulmus pumila (c)	1	10	30	20	3
Urtica dioica	.	.	.	+	.

Note: Location of relevé (plot): 1 – forest belt, 2-4 – along the forest belt near the track, 5 – ravine slope (100 m from the forest belt, opposite the railway). Values represent projective coverage (1–100%); '+' indicates coverage < 1%; a dot ('.') indicates the species was not detected. Symbols (a), (b), and (c) refer to the tree, shrub, and herb layers, respectively; unmarked species are assigned to the herb layer. Projective cover for each species within a layer was estimated independently, allowing for interspecific overlap.

Figure 2. *Ulmus pumila* spread along railway corridor environments (trackside)

Table 2. Two-way ANOVA results for heavy metal content

Metal	Source of Variation	*df*	*F*-value	*p*-value	Significance
Cu	Distance (zones)	2	12.45	< 0.001	***
	Medium (leaf/soil)	1	284.12	< 0.001	***
	Interaction	2	8.15	0.004	**
Zn	Distance (zones)	2	34.21	< 0.001	***
	Medium (leaf/soil)	1	52.60	< 0.001	***
	Interaction	2	11.08	< 0.001	***
Ni	Distance (zones)	2	48.15	< 0.001	***
	Medium (leaf/soil)	1	18.22	0.001	***
	Interaction	2	9.44	0.002	**
Cd	Distance (zones)	2	22.10	< 0.001	***
	Medium (leaf/soil)	1	68.34	< 0.001	***
	Interaction	2	5.12	0.018	*
Pb	Distance (zones)	2	62.45	< 0.001	***
	Medium (leaf/soil)	1	84.19	< 0.001	***
	Interaction	2	14.28	< 0.001	***

Note: *df*, degrees of freedom. Significance levels, $p < 0.05$ (*), $p < 0.01$ (**), $p < 0.001$ (***).

Table 3. Heavy metal content in soil and *Ulmus pumila* leaves (mg/kg dry weight) at various distances from the railway tracks

Metal	Medium	1 m (Location 1)	15 m (Location 2)	30 m (Location 3)
Cu	Soil	$0.361 \pm 0.034^{a,A}$	$0.256 \pm 0.013^{b,A}$	$0.251 \pm 0.011^{b,A}$
	Leaf	$2.735 \pm 0.281^{a,B}$	$2.192 \pm 0.213^{b,B}$	$2.173 \pm 0.212^{b,B}$
Zn	Soil	$0.013 \pm 0.001^{a,A}$	$0.010 \pm 0.001^{b,A}$	$0.004 \pm 0.001^{c,A}$
	Leaf	$0.042 \pm 0.004^{a,B}$	$0.024 \pm 0.001^{b,B}$	$0.015 \pm 0.001^{c,B}$
Ni	Soil	$0.008 \pm 0.001^{a,A}$	$0.003 \pm 0.000^{b,A}$	$0.002 \pm 0.000^{b,A}$
	Leaf	$0.012 \pm 0.001^{a,B}$	$0.007 \pm 0.000^{b,B}$	$0.002 \pm 0.000^{c,A}$
Cd	Soil	$0.008 \pm 0.001^{a,A}$	$0.005 \pm 0.001^{b,A}$	$0.004 \pm 0.000^{b,A}$
	Leaf	$0.031 \pm 0.005^{a,B}$	$0.018 \pm 0.001^{b,B}$	$0.017 \pm 0.001^{b,B}$
Pb	Soil	$0.815 \pm 0.094^{a,A}$	$0.528 \pm 0.042^{b,A}$	$0.534 \pm 0.041^{b,A}$
	Leaf	$0.545 \pm 0.046^{a,B}$	$0.152 \pm 0.013^{b,B}$	$0.121 \pm 0.014^{b,B}$

Note: Data are presented as *mean* ± *SD*. Different superscript lowercase letters ($^{a, b, c}$) indicate significant differences among distances within the same medium ($p < 0.05$). Different superscript uppercase letters ($^{A, B}$) indicate significant differences between soil and leaf at the same distance ($p < 0.05$).

showed a significant decrease from 0.361 mg/kg at the railway edge to 0.256 mg/kg within the forest belt, with no further significant reduction observed at 30 m from the railway tracks ($p > 0.05$). Zn exhibited a pronounced reduction in leaf tissues, dropping from 0.042 mg/kg at 1 m from the railway tracks to 0.024 mg/kg within the forest belt, a total decrease of 43% ($p < 0.05$). Soil Zn levels followed a similar significant downward trend ($F = 34.21$). In all locations, Zn concentrations in *U. pumila* leaves remained 2.4 to 3.7 times higher than in the soil, highlighting the species' role as a bioaccumulator. The filtering effect was particularly evident for Ni. Foliar concentrations decreased from 0.012 mg/kg at 1 m from the railway tracks to 0.007 mg/kg at the forest belt, eventually reaching minimal levels of 0.002 mg/kg at 30 m from the railway tracks ($p < 0.001$). Concentrations of Cd in the *U. pumila* leaves decreased from 0.031 mg/kg to 0.018 mg/kg within the forest belt, indicating that heavy metal accumulation was also highly sensitive to distance from the pollution source.

The leaf concentrations for Cu, Zn, Ni, and Cd were consistently higher than soil concentrations across all locations, whereas Pb soil concentrations remained higher than those in the leaves. Two-way ANOVA indicated a highly significant difference ($p < 0.001$) between heavy metal content in *U. pumila* leaves compared to soil for Cu, Zn, Ni, and Cd. Furthermore, concentration in *U. pumila* leaves was significantly higher than in soil across all belts, with the most pronounced difference observed for Cu ($F = 284.12$, $p < 0.001$). Specifically, at 1 m from the railway tracks, leaves contained 2.735 mg/kg compared to only 0.361 mg/kg in the soil, representing a 7.5-fold higher concentration in the plant biomass. Similarly, the leaf-to-soil heavy metal concentration for Zn remained consistently above 1.0 (e.g., 3.2 at 1 m from the railway tracks), confirming that *U. pumila* effectively contributes to heavy metal mitigation. Similar accumulation patterns were observed for Ni and Cd. The

concentration of Ni in *U. pumila* leaves at the railway edge (1 m from the railway tracks) was 1.5 times higher than in the soil, while for Cd, the leaf-to-soil ratio reached 3.8. There was also significant interaction between Distance and Medium ($p < 0.05$).

In contrast, Pb showed a distinct distribution pattern; while Pb concentrations in leaves were significantly higher 1 m from the railway tracks (0.545 mg/kg), soil levels remained elevated across all sampling sites, ranging from 0.528 to 0.815 mg/kg. This discrepancy resulted in a leaf-to-soil ratio of less than 1.0 for Pb. These results underscore different sequestration dynamics for different heavy metals.

In summary, the results demonstrate a consistent and statistically significant gradient in heavy metal concentrations across the three belts (sampling zones). The Siberian elm forest belt serves as a primary functional barrier, resulting in an average reduction of metal content in leaves by 40–70% compared to location 1 (in front of the forest belt). The high significance levels ($p < 0.001$) for the *Medium* factor across all elements confirms that *U. pumila* leaves act as more sensitive bioindicators of technogenic pressure than the soil substrate. These results provide robust evidence for the protective ecosystem service provided by the forest belt in mitigating pollution originating from railway activity.

Noise reduction

Noise level measurement indicators are presented in Table 4.

The results of acoustic measurements showed a significant decrease in noise levels as distance from the tracks increased ($p < 0.001$). At 1 m from the railway tracks, the peak noise level from the regional train averaged 93.0 dB. Upon entering the forest belt (15 m from the railway tracks), the noise level dropped by 9.0 dB (reaching 84.0 dB), and behind the belt (25 m from the railway), the measured noise level reduced to 71.0 dB. The dense structure of the *U. pumila* canopy, with its 70% projective cover, provided additional noise attenuation of approximately 6–9 dB compared with open areas, effectively bringing noise levels closer to sanitary standards for residential zones.

Table 4. Noise levels near the railway track and forest belt, dB(A)

Plots	Point 1 (1 m from the track)	Point 2 (10 m from the track)	Point 3 (15 m from the track)	Point 4 (25 m from the track)
1	95±0.9	90±0.8	82±0.9	75±1.1
2	93±1.1	90±1.4	86±1.4	73±0.7
3	93±0.8	90±0.8	86±1.1	75±1.4
4	91±0.8	87±0.5	82±1.1	69±1.2
5	93±0.4	90±1.4	85±0.9	70±1.1
6	92±1.5	90±1.2	87±0.6	72±0.4
7	95±0.6	91±0.6	87±0.7	75±0.8
8	95±0.8	92±0.6	85±1.4	71±1.1
9	95±0.9	92±0.6	83±0.7	69±1.4
10	92±1.4	87±0.9	82±0.4	64±0.7
Average value	93±0.9	90±1.0	84±0.9	71±0.9

Note: Data are presented as *mean* ± *SD*.

Dust retention

The minimum *U. pumila* leaf size in the selected samples was 2.7 cm × 1.6 cm, and the maximum was 6.3 cm × 2.4 cm. The area of the smallest leaf was 3.187 cm², the area of the largest leaf was 10.324 cm². The dust retention capacity of *U. pumila* (G) showed consistency across the ten study plots, with an average value of 62.23 ± 2.84 g/m². The total dust mass collected from the leaf surface area of 0.7856 m² (the total area of 1000 leaves) amounted to 48.888 g. As seen in Figure 3, variation between plots (ranging from 58.45 to 66.12 g/m²) was statistically insignificant ($p > 0.05$), indicating a uniform distribution of particulate matter deposition along the forest belt edge.

DISCUSSION

Facilitation of invasion effect

Active distribution of *U. pumila* has been observed in the Steppe Zone of Ukraine since 1970 (Kucher et al. 2024). The Siberian elm forest belt along the railway became the center of distribution of this invasive species in the northern Forest Zone of Ukraine. *U. pumila* has spread from the forest belt to adjacent territories.

The average diameter of the root collar (ADRC) of *U. pumila* shrubs in anthropogenic areas can be used to determine the age of the plant invasion (Lykholat et al. 2019). According to Lykholat et al. (2019), as well as our observations, the age of *U. pumila* colonization in herbaceous plant communities in sites 2, 3, and 4 is 4–5, 8–10, and 18–20 years, respectively.

The invasiveness of alien plants is determined by a complex set of functional features (Fedenko 2024). For herbaceous plants, the impact on trait composition of invaded communities is linear and positive with increasing invasive plant cover (Fenesi et al. 2023). The *U. pumila* invasion began with the capture of herbaceous phytocenoses (Figure 2). The invasiveness of the shrub and tree species often (but not always) depends

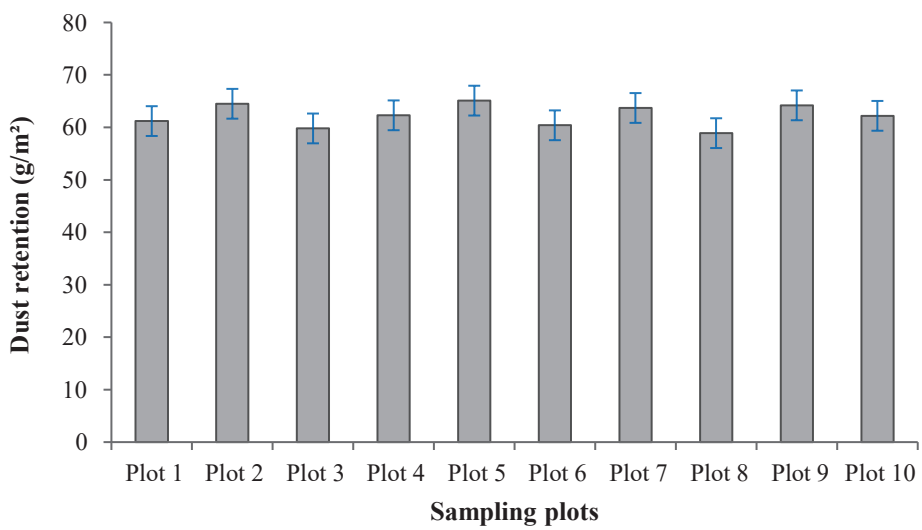

Figure 3. Dust retention per unit leaf area (g/m²) of *Ulmus pumila* across ten sampling plots. Data are presented as *mean* ± *SD* (*n* = 100) leaves per plot. Average retention value is 62.23 g/m².

consistently on projective coverage in a consistent way. High projective coverage (abundance) often increases the detrimental impacts of an invasive species on a native plant community, particularly affecting species richness and diversity (Hejda et al. 2009; Barney et al. 2013). However, these effects can be non-linear and may only appear after a certain abundance threshold is reached (Fenesi et al. 2023). Moreover, specific impact is influenced by the invasive species' traits, such as its life form and height, as well as characteristics of the invaded ecosystem (Pyšek et al. 2012). In northern Ukraine, *U. pumila* is a potentially aggressive species capable of active invasion in xerophilic conditions. It is photophilous, has a deep root system, and does not tolerate wet soils (Ghelardini 2007). The ecological conditions of the areas adjacent to the forest belt, where *U. pumila* invades, are xerophilic which contributes to the spread of this invasive species.

Different invasive plant species have varying impacts on native communities, even when they achieve high projective coverage (Sun, Junod 2017). In the studied area, the projective coverage of *U. pumila* in a particular phytocenosis layer increases with the increase in the time of entry of this species from the forest belt. At the stage of establishment in the phytocenosis (Table 1, relevé No.2), *U. pumila* projective coverage was 10% in both the herbaceous and shrub layers. Over time, the participation of the invasive species in each layer increases, and later projected coverage in the shrub layer increases to 35% (Table 1, relevé No.4) and in the tree layer to 70% (Table 1, relevé No.5). In areas near the Siberian elm forest belt, we observed the invasive effect of *U. pumila*, which may reflect a different mechanism of competition, where low projective coverage of native plant species promotes invasion by providing alien species with favorable conditions for growth and development. *U. pumila* spread from the forest belt corresponds to the case noted by Hejda et al. (2009), where traits such as the life form of the species and the aggressiveness of the species play a significant role in the fact that a dense canopy of invasive species can significantly reduce the diversity of native species. Invasive phytocenoses are highly depleted in natural species, represented only by *Achillea millefolium*, *Arrhenatherum elatius*, *Calamagrostis epigejos*, *Dactylis glomerata*, *Daucus carota*, *Elymus repens*, *Fraxinus excelsior*, *Ulmus laevis*, and *Viola odorata*.

Despite this reduction in local biodiversity, the structural transformation of these communities highlights the high invasive potential and ecological resilience of *U. pumila* in the railway corridor. Since its first recorded appearance in 2006, the species has demonstrated a progressive increase in projective cover (up to 35% in the shrub layer) and biomass. While categorized as an invasive threat, in heavily contaminated railway peripheries, its rapid growth provides an immediate ecosystem service. The formation of monodominant stands creates a dense "living wall" that enhances the sequestration of heavy metals, effectively compensating for the floristic poverty of the herb layer. This aggressive expansion, driven by its opportunistic ecological strategy, allows the species to maintain high projective coverage where less resilient native species fail to establish.

Heavy metal mitigation effect

It is well-established that the concentration of heavy metals decreases with increasing distance from railways (Brtnický et al. 2022;

Dimitrijević et al. 2024). Our findings strongly support this trend, as two-way ANOVA confirmed that the sampling distance had a highly significant effect on the concentrations of all studied heavy metals ($p < 0.001$). Heavy metals, particularly in dust and particulate form from railway operations (e.g., wheel-track abrasion, brake wear), are intercepted by the *U. pumila* forest belt. Our findings align with the observations of Hrotkó et al. (2021), who emphasized that urban tree foliage serves as a primary interface for the removal of atmospheric pollutants through the deposition of foliar dust. This is further corroborated by Liu et al. (2017), who demonstrated that plant leaves play a crucial role in removing airborne dust and associated heavy metals, particularly in high-traffic roadside environments. Their research highlights that the accumulation of metals on leaf surfaces is directly linked to the dust-capturing capacity of the species, which explains the high efficiency of the *U. pumila* belt in localizing contaminants near the railway source. Our results show that proximity to the tracks is a critical factor, with the highest contamination localized at the 1 m mark (in front of the forest belt). This is consistent with Safadoust et al. (2025), who demonstrated that distance plays a decisive role in soil contamination patterns. In this context, our results also align with El-Amier and Alghanem (2018), who emphasized that tree leaves are not merely passive receptors but effective bioindicators reflecting pollution from both soil and ambient air. This dual-source accumulation explains why foliar concentrations in our study remained higher than soil levels even as distance from the railway increased.

Most released metals are particles emitted by friction processes with iron (Burkhardt et al. 2008). Railway transport is one of the main sources of Cu, Zn, Ni pollution, which enters the surrounding areas due to the abrasion of railway infrastructure components; Pb comes mainly from exhaust gases (Brtnický et al. 2022). Railways can be a significant source of cadmium pollution. Cadmium is released into the environment from the abrasion of railway tracks and wheels, the corrosion of metallic infrastructure, and from activities like the storage and use of creosote-impregnated railway sleepers (Dimitrijević et al. 2024). Thus, sources of heavy metals are closely linked to the operation of railways and the functioning of rail transport. It is practically impossible to eliminate them. Therefore, the effect of heavy metal mitigation, provided by the Siberian elm forest belt is of great importance for area adjacent to the railway, primarily single-story residential buildings. Phytoremediation using afforestation species, including *U. pumila*, represents a cost-effective strategy for heavy metal mitigation. These trees demonstrate exceptional remediation potential through extensive green coverage and substantial biomass (Baidourela et al. 2025).

The results obtained showed that *U. pumila* in the forest belt vegetation, along with the soil in the forest belt, can filter out heavy metal particles carried by wind from the railway tracks. Samples taken from the area behind the forest belt show lower concentrations of Pb, Zn, Ni, and Cd compared to samples taken closest to the railway, as forest belts act as a natural barrier that can trap and prevent the transport of airborne particulate matter containing these heavy metals. Baidourela et al. (2025) established the *U. pumila* metal accumulation hierarchy: bark > root > leaf > branch. It is likely that elm leaves contained only a portion of the accumulated heavy metals, with the highest concentrations localized in the bark or root tissues. However, our study

demonstrates that leaves alone provide a vital filtration service. Two-way ANOVA confirmed that the medium (leaves vs. soil) had a significant impact on metal levels ($p < 0.001$), with leaves acting as a primary sink for Cu, Zn, Ni, and Cd. Specifically, leaf-to-soil ratios reached values as high as 3.2 for Zn and 3.8 for Cd, indicating that *U. pumila* effectively accumulate these elements from the atmosphere. The high *F*-values obtained in our statistical analysis provide robust evidence that the Siberian elm forest belt is not merely a passive barrier but also an active component of phytoremediation in railway-adjacent territories. Essentially, the forest belt acts as a buffer zone, trapping and containing contaminants closer to the source (the railway) thus reducing the amount of pollutants that reach areas further away.

Therefore, the *U. pumila forest* belt serves as a critical biogeochemical barrier that effectively immobilizes heavy metals within the immediate vicinity of the railway. By reducing the spatial migration of Cu, Zn, Ni, Cd, and Pb, this "green shield" prevents the toxicological loading of adjacent territories and safeguards the long-term integrity of the soil profile and residential buildings located near the railway. Special attention must be paid to the monitoring of Cd and Pb, as their high toxicity and persistence require stringent control within these buffer zones. Our findings demonstrate that the mitigation effect is achieved through a combination of spatial containment and biological sequestration, highlighting the forest belt as a functional tool for environmental risk management in northern Ukraine. Ultimately, the strategic preservation of these Siberian elm corridors is essential for transforming railway peripheries into resilient zones of phytoremediation, ensuring that heavy metal contaminants are sequestered before they can pose a threat to the surrounding ecological and residential environments. Further research is needed to systematically analyze the accumulation and mitigation effectiveness of *U. pumila* in different plant communities.

Noise reduction effect

Our results confirm the well-established pattern that noise levels gradually decrease with increasing distance from railway tracks; however, the presence of a forest belt plays a decisive role in noise attenuation. Traffic green belts are an important part of the urban ecosystem and play a role not only in traffic noise reduction but also provide ecosystem services, such as creating a natural landscape and retaining dust. Establishing road shelter forests is a key method to reduce traffic noise pollution (Liu et al. 2024). The difference in noise attenuation is due to both minor variations in terrain configuration (track above/below the surrounding terrain) and attenuation by vegetation (Kragh 1979). The *U. pumila* forest belt behind Chernihiv is at approximately the same elevation as the railway track. Therefore, noise absorption is due to the vegetation of the forest belt. Crown shape, tree density, visibility, height, width of the tree belt, height of the receiver and noise source, distance between the noise source and the receiver and noise frequency all positively affect noise attenuation (Fang, Ling 2003; Fang, Ling 2005; Liu et al. 2024).

Liu et al. (2024) identified the width of the forest strip as the main factor affecting noise reduction. We agree with this opinion. But our research shows that an equally important factor in noise reduction is canopy closure (projective coverage) of tree and shrub layers in the forest belt. With a width of only 7 m, but with a dense tree (70%) and shrub (50%) layers the *U. pumila* forest belt reduces noise by 22 dB(A). For comparison,

a 60 m wide forest strip of mixed coniferous and broad-leaved forest reduced additional noise from urban transport by 6.6 dB(A), and the average additional noise reduction achieved by pure road shelter forests was 6.3 dB(A) (Liu et al. 2024).

The total noise reduction observed in our study is exceptionally high. This efficiency translates to a noise attenuation rate of approximately 3.1 dB per meter of forest belt width, which significantly exceeds the standard attenuation values reported for typical roadside shelterbelts.

This high efficacy is clearly illustrated by the acoustic gradient observed across the study area: noise intensity decreases by approximately 3 dB(A) (4%) in the first 10 meters of open space. However, within the dense plantations, a sharper reduction of 9 dB(A) (about 10%) is achieved over a much shorter distance (5 m). Near the residential area (at a distance of 25 m from the railway track), the cumulative effect of the forest belt contributes to a total noise reduction of 22 dB(A), or more than 23%.

Liu et al. (2024) showed that mixed and conical crown shapes were the most effective in noise attenuation, while inverted conical and almost spherical crown shapes had lower median values. In the forest belt, *U. pumila* trees mostly have dense mixed crown shapes. This likely contributes to the good noise-absorbing capacity of the Siberian elm forest belt. Our results highlight that the effectiveness of a *U. pumila* forest belt in noise reduction is influenced by its distance from the noise source and its location relative to sensitive areas like residential building.

The structure of the wood of a particular tree affects its sound-absorbing properties (Guiman et al. 2023). It is obvious that the structure of *U. pumila* wood affects noise absorption. There is no information in the literature on the dependence of the noise absorption properties of *U. pumila* on the structure of its wood. Therefore, this issue requires further research.

Dust retention effect

Plants play an important role in reducing particulate matter air pollution and improving air quality (Lü et al. 2016). Trees, with their larger leaf surface area and distinctive physical properties, can function as biological filters, proficiently removing a greater quantity of airborne pollutants and thereby enhancing air quality in polluted regions (Sheng et al. 2024). The dust retention per unit leaf area of the *U. pumila* trees of the forest belt (62.23 g/m²) compared to the available data for trees in conditions of dry and dusty mining areas (Zhu et al. 2022; Sheng et al. 2024) indicates satisfactory performance. The amount of dust retained on the leaves directly reflects the pollution of the surrounding air. It is likely that the substantial dust retention capacity observed in our study is one of the mechanisms for the mitigation of heavy metal pollution.

In a dusty environment, species reflect their adaptability through changes in morphology and biomass allocation (Zhu et al. 2022). Features of the microsurface of plant leaves affect dust retention (Zhang et al. 2017; Li et al. 2021; Tan et al. 2022; Sheng et al. 2024).

U. pumila leaves have a number of morphological and microstructural features that increase their dust-retention capacity, specifically: a wavy leaf surface, micro-grooves, prominent primary veins, sunken stomata, and the presence of trichomes (Figure 4). These features allow *U. pumila* to intercept and trap particulate matter more effectively than smooth-leaved species. In urban environments, this results in a

Figure 4. Microrelief of an *Ulmus pumila* leaf blade that increases its ability to retain dust

significant improvement in air quality, as such leaf structures act as a biological filter. For instance, studies in similar railway corridors show that species with high surface roughness, like *U. pumila*, can capture 1.5–2 times more dust than species with smooth cuticles, such as *Populus* or *Betula* species (Sæbø et al., 2012). However, when excessive particulate matter covers the leaf surface, the retention efficiency of the microstructure decreases (Sheng et al. 2024). Seasonal variations also play a critical role; dust accumulation peaks during dry periods and before leaf senescence, while rain events partially 'reset' the filtration capacity by washing particles into the soil (Prajapati 2012).

The study of factors affecting the ability of the *U. pumila* leaves to retain dust currently requires further research. However, it is known that dust accumulation on leaves negatively affects physiological processes in plants by reducing light absorption, interfering with gas exchange, blocking stomata, and sometimes increasing leaf temperature, ultimately hindering photosynthesis, transpiration, and overall plant health and productivity (Zia-Khan et al. 2015; Meravi et al. 2021).

The Siberian elm forest belt itself creates a denser environment, slowing down wind speed and reducing the distance dust particles travel. Under high wind conditions, the complex surface of *U. pumila* leaves minimizes particle re-suspension back into the atmosphere compared to smooth-leaved trees, making it a superior choice for protective belts along transport arteries.

Management implications and balancing ecological impacts

The findings of this study highlight the dual role of *U. pumila* in the railway ecosystem, acting as a highly effective multi-functional barrier while simultaneously posing an invasion risk. To balance these contrasting impacts, we propose a management framework organized around monitoring, containment, and gradual replacement.

First, regular monitoring of *U. pumila* dispersal beyond the 30-meter buffer zone is essential, especially in areas where environmental stress is lower and native flora could potentially establish. This should be followed by a containment-based control strategy for technogenic corridors. Given its superior tolerance to pollution (Vaz et al. 2017; Sladonja et al. 2018), *U. pumila* serves as a functional utility species in heavily disturbed zones. The containment

strategy should specifically target the removal of spontaneous saplings in nearby natural areas to prevent their establishment in sensitive habitats, while maintaining the integrity of the established forest belt. Such a targeted approach ensures that the protective functions of the belt are preserved without compromising the local biodiversity of adjacent ecosystems. In such degraded landscapes, a pragmatic approach is required: the immediate ecosystem services, such as noise mitigation and heavy metal retention, currently outweigh the ecological costs of its invasive status (Potgieter et al. 2022).

Finally, long-term transition strategies should focus on the gradual diversification of these forest belts. Future management efforts should prioritize the introduction of native species with similar functional traits, such as high leaf area index and stress tolerance, to achieve a more sustainable and balanced ecosystem (Sheng et al. 2024; Baidourela et al. 2025).

CONCLUSIONS

This study demonstrates that *Ulmus pumila* forest belts along railway corridors in northern Ukraine function as functional barriers for heavy metal sequestration (72% reduction in foliar Pb), noise attenuation (22 dB(A)), and dust retention (62.23 g/m²). These ecosystem services result from the species' growth strategy and high biomass density, which contribute to the protection of adjacent residential areas from technogenic pressures. However, the observed expansion of *U. pumila* into neighboring phytocenoses presents a management challenge. We recommend a pragmatic approach that prioritizes the maintenance of these protective belts within contaminated transport corridors while implementing containment strategies to limit seed dispersal into natural habitats. Future research should focus on the long-term sequestration capacity of various plant tissues and the correlation between wood microstructure and acoustic absorption. In summary, the strategic management of Siberian elm belts represents a useful, though complex, tool for urban planning and environmental risk mitigation in degraded landscapes.

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研究報告

烏克蘭切爾尼戈夫鐵路廊道榆樹(*Ulmus pumila* L.)防護林帶之生態功能與環境效益

Oleksandr Lukash[1], Yuliia Stupak[1]

摘　要

研究背景

都市環境中的綠色基礎設施(green infrastructure)具有提供關鍵生態系服務的重要功能，然而特定道路或交通廊道旁林帶在土地覆蓋效率評估中的貢獻，往往被低估。鐵路廊道屬於複合型環境壓力來源，不僅會因基礎設施磨損而釋放重金屬(heavy metals)，亦會產生高強度噪音污染。

1960年代後期，烏克蘭切爾尼戈夫(Chernihiv)於鐵路廊道沿線建立了一條以榆樹(*Ulmus pumila* L.)為優勢種的特殊林帶。儘管榆樹在烏克蘭森林地帶被視為入侵物種，但該物種對污染物展現出顯著耐受性。本研究旨在評估該林帶的多功能生態效益，並驗證以下兩項假設：

(1) 該林帶會促進潛在入侵物種向鄰近區域擴張；

(2) 該林帶對化學污染與噪音污染具有顯著的植物修復與防護效能。

材料與方法

本研究於一條長1公里、寬7公尺、距離鐵軌10公尺的榆樹林帶進行。研究團隊利用植群樣區調查法(vegetation relevés)分析植物群落的組成與結構，並追蹤自2006年以來該物種的擴張動態。

重金屬檢測項目包括銅(Cu)、鋅(Zn)、鎳(Ni)、鎘(Cd)及鉛(Pb)，研究透過原子吸收光譜法(atomic absorption spectrophotometry)，分析三個不同距離帶，即1公尺、15公尺及30公尺處的土壤與葉片樣本。統計可靠性則透過雙因子變異數分析(two-way ANOVA)及 Tukey's

[1] Department of Ecology, Geography and Nature Management, T.H. Shevchenko National University "Chernihiv Collegium", 53 Hetmana Polubotka Street, Chernihiv, 14013, Ukraine
通訊作者：Oleksandr Lukash, Corresponding author, Oleksandr Lukash, Email: lukash2011@ukr.net
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HSD 事後檢定進行驗證。

噪音監測方面，研究設置10個代表性樣點，在電聯車通過期間，進行現地噪音量測，單位為dB(A)。此外，葉片滯塵能力方面，則以1,000片葉片進行重量分析法(gravimetric analysis)測定，並透過影像紀錄葉片表面的微細結構特徵。

結果與討論

研究結果證實，該榆樹防護林帶具有顯著的「綠色屏障」(green shield)效果。重金屬濃度隨距離增加而顯著降低，統計上達高度顯著差異($p < 0.001$)。在距離鐵路15公尺範圍內，也就是林帶內部，葉片中的鉛含量下降了72%。

榆樹展現出優異的生物累積能力，其中鋅與鎘的葉片／土壤濃度比值分別達到3.2與3.8，顯示其對部分重金屬具有良好的吸收與累積潛力。

在噪音防護方面，這條寬度僅7公尺的林帶可達到22 dB(A)的減噪效果，相當於每公尺林帶寬度可衰減約3.1 dB，其減噪效率，明顯優於部分更寬的原生林分。此一高減噪效率可能與其70%的高樹冠鬱閉度，以及50%的緻密灌木層覆蓋度有關。

葉片滯塵能力分析顯示，此榆樹具有良好的粉塵截留能力，達62.23 g/m²。此能力可能受到葉片表面特徵的影響，如：突出的葉脈及下陷型氣孔(sunken stomata)，均有助於粉塵附著與保留。

然而，本研究也證實榆樹具有明顯的入侵性。該樹種的投影覆蓋度逐漸增加，並排擠原生植物，進而導致鄰近植物群落出現植物相貧乏的現象。

結論

本研究顯示，榆樹防護林帶具有多功能生態屏障效益，可有效發揮重金屬攔截、粉塵滯留與噪音衰減等功能。因此，在受到嚴重污染的人為污染廊道中，榆樹防護林帶所提供的即時生態系服務，包括降低噪音、截留粉塵及吸收重金屬等，其效益顯然超過其入侵特性所造成的負面生態衝擊。

因此，本研究提出務實的治理建議：在維持烏克蘭北部現有榆樹林帶防護功能的同時，應實施嚴格的控制措施，以防止其種子擴散至敏感的原生生態棲地。

未來研究，應優先探討木材微細結構與聲音吸收能力之間的關係，以及不同植物組織中重金屬長期固定與累積的情形。

關鍵詞：鐵路污染、外來入侵種、重金屬緩解、降噪、滯塵能力、生態系統服務、榆樹(*Ulmus pumila* L.)

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