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RESEARCH

Black locust stands along railways as novel ecosystems in northeastern Italy: structure, composition and landscape context

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Abstract

Railway corridors contain vegetation that may contribute to habitat availability and landscape connectivity while also creating management constraints related to periodic maintenance and safety requirements. Tree dominated railway vegetation remains poorly described, particularly where it is dominated by alien species. We investigated 42 linear tree strips dominated by black locust (*Robinia pseudoacacia* L.) along four electrified railway lines in northeastern Italy. We quantified stand structure, species richness and plant community composition, and tested whether variation was associated with railway type, track type, adjacent land use and spatial position. The sampled stands were structurally heterogeneous but strongly dominated by black locust, which represented on average 70.5% of live stems. Mean stem density, basal area and volume standardized by canopy projection area were 1,926 stems ha^{-1}, 22.2 m^2 ha^{-1} and 121.3 m^3 ha^{-1}, respectively. Total species richness averaged 15.7 species per 10 m segment. Railway type and track type were associated with some descriptive structural and richness differences, but multivariate composition was more consistently related to adjacent land use and spatial position. Adjacent land use was a more consistent predictor of plant community composition than railway type or track type, both for total vegetation and for the understorey. Railway black locust stands should therefore be interpreted as alien secondary woodlands, vegetation associated with infrastructure and potential novel ecosystems shaped both by environmental filters specific to railway corridors and by the adjacent landscape matrix.

Keywords Alien tree · Invasive species · Linear infrastructure · Novel ecosystem · Understorey vegetation

Introduction

Linear transportation infrastructure verges have been interpreted ambivalently: they can act as habitats or corridors for some organisms, but they may also exacerbate fragmentation, disturbance and biological invasions (Ouédraogo et al. 2020). Besides their transport function, railway corridors often include strips of unmanaged or actively managed vegetation that may contribute to habitat availability, ecological connectivity and landscape heterogeneity, while also creating operational and maintenance constraints (McNab 1986).

Railway corridors also create distinctive abiotic filters. Ballast and embankment substrates are coarse, well drained and frequently exposed to altered thermal and hydrological regimes, while railway operation and maintenance may contribute metals and other pollutants to lineside soils (Wiłkomirski et al. 2011). These persistent anthropogenic conditions mean that railway vegetation includes plant communities assembled under environmental filters specific

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to railways. Where these communities become self sustaining and combine alien, ruderal and woodland species under long term anthropogenic conditions, they can be interpreted within the broader framework of novel ecosystems (Hobbs et al. 2009).

Railway vegetation has often been studied from a floristic or plant community perspective. In central Italy, Filibeck et al. (2012) recorded high vascular plant richness along a high speed railway embankment crossing an intensively farmed landscape, showing that artificial railway structures may host unexpectedly diverse plant assemblages. Recent studies have emphasized the heterogeneity of railway habitats and the role of railway zones, stations, embankments and adjacent land uses in shaping plant community composition (Kutlvašr et al. 2024; Šabić et al. 2026).

Railway vegetation is not only a question of species occurrence. In forest ecosystems, structural attributes such as stem density, tree diameter and height distribution, basal area, stand volume and canopy development are associated with ecosystem functioning, including biomass and carbon storage, light and microclimatic regulation, and habitat provision (McElhinny et al. 2005; Ali 2019). This relationship between vegetation structure and function also applies to linear woody elements. In hedgerows and wooded buffer strips, attributes such as vegetation density, layering, woody biomass, width and structural complexity influence habitat provision and the delivery of regulating ecosystem services, including pollutant retention and microclimatic regulation (Cole et al. 2020; Kratschmer et al. 2024). Tree dominated railway margins can therefore be regarded as functionally analogous to linear woody buffers, although their structure and composition are shaped by the distinctive disturbance regimes, maintenance practices and safety constraints associated with transport infrastructure (Hoerbinger et al. 2020).

From a management perspective, European railways are moving from an herbicide based, zero vegetation paradigm toward integrated, condition based vegetation management. The TransItion STRategy on vegetAtion Management (TRISTRAM) report, edited by the International Union of Railways, stresses the need for locally adapted vegetation control standards, digital monitoring, GIS based planning, and a better understanding of how vegetation growth relates to track category, traffic, infrastructure type and safety requirements (International Union of Railways 2021). Woody vegetation is particularly relevant in this respect. Hoerbinger et al. (2020) developed a large scale assessment of woody vegetation structures for safety along railway corridors, showing that tree and shrub structure can be treated as a measurable railway management variable rather than simply as background vegetation.

Railway corridors serve also as critical pathways for the establishment and spread of alien plants (Hulme 2009; Kutlvašr et al. 2024). Transport infrastructures generate recurrent disturbance, create open substrates and provide long distance connectivity, all of which can favour the spread of ruderal and alien species (Ascensão and Capinha 2017). At broad spatial scales, roads and railway networks act as colonisation corridors for these species (Benedetti and Morelli 2017). For instance, Czech railway stations, yards and junctions serve as sources and reservoirs of alien plants, including species introduced as contaminants, hitchhikers, ornamentals or utility plants (Kutlvašr et al. 2024). These findings suggest that railway vegetation should be interpreted not only as local lineside vegetation, but as an integral part of a wider transport mediated invasion system.

Among alien trees, black locust (*Robinia pseudoacacia* L.) is particularly important in European railway landscapes. Native to North America, it is one of the most widespread alien broadleaved trees in Europe and is now considered invasive across much of the continent. Its fast growth, nitrogen fixation, strong suckering ability and resprouting after cutting make it well adapted to disturbed and repeatedly managed habitats (Cierjacks et al. 2013). These traits help explain both its historical use for erosion control, reclamation and production purposes and its current success in anthropogenic and secondary habitats.

The ecological and management interpretation of black locust is not straightforward. Vítková et al. (2017) described black locust as ‘beloved and despised’ in Central Europe because its economic and cultural uses conflict with its negative impacts on biodiversity and conservation targets. Similarly, Sádlo et al. (2017) argued for site specific management of black locust based on local impacts rather than uniform eradication or acceptance. This perspective is relevant for railway corridors, where black locust may provide canopy cover, slope protection, visual screening and biomass, while also acting as an alien tree capable of altering plant community composition and spreading along disturbed linear habitats.

In northeastern Italy, black locust has already been studied as a dominant species of alien secondary woodlands. Campagnaro et al. (2018b) investigated black locust secondary forests developing on former grasslands and cultivated land abandoned during the previous 35–40 years, showing that these stands form distinct plant community assemblages. Sitzia et al. (2018) further showed that invasion of abandoned fields by black locust can filter understorey plant functional traits, supporting the interpretation of these stands as novel forest ecosystems rather than merely degraded vegetation. Vítková et al. (2020) extended this perspective to southern Europe by analysing vegetation types dominated by black locust in relation to species composition, invasion history, distribution and management.

Based on this literature, railway black locust stands may be interpreted as a linear infrastructure expression of broader secondary woodland dynamics. Their development is expected to reflect the interaction between the biological traits of black locust and the specific environmental filters of railway corridors, including recurrent cutting, ballast and embankment substrates, safety constraints, traffic intensity, corridor connectivity and edge effects from adjacent land uses. The surrounding landscape matrix is likely to be especially important, because adjacent land use may influence propagule pressure, disturbance, nutrient inputs, edge conditions and the available species pool.

We therefore investigate stands dominated by black locust along railways in northeastern Italy as alien secondary woodlands associated with transport infrastructure and as potential novel ecosystems. Building on the expectation that stand development and plant community composition vary with conditions related to the railway and adjacent land use, we aimed to: (i) describe the main structural and compositional characteristics of railway black locust stands; (ii) assess whether these characteristics vary across railway operational contexts, including traffic intensity class and track type; and (iii) test whether adjacent land use and stand development variables explain additional variation in plant community composition.

Materials and methods

Study area screening and sampling design

Potential sampling areas were first screened in GIS within a 50 m buffer around the regional railway network, using CORINE Land Cover and the regional forest type map of Veneto (Regione del Veneto 2006; Kosztra et al. 2019). This buffer was used to focus the screening on the immediate railway corridor and adjacent land cover context, and to identify railway sections where forest, seminatural land or other land cover contexts could potentially host black locust stands. Candidate areas were then checked in the field to confirm the presence of accessible linear tree strips dominated by black locust and their suitability for distributing the sampling units.

Sampling focused on electrified railway lines to minimise variation associated with traction type. Areas close to major potential pollution sources, including industrial facilities, major roads and intensive livestock farms, were excluded. Candidate stands had to meet three criteria: (i) absence of barriers likely to alter surface runoff between the track and the tree strip; (ii) black locust dominance in the tree layer, structural homogeneity, minimum stand length of 50 m and minimum main stem diameter (DBH) of 5 cm; and (iii) plot spacing of at least 50 m. Historical aerial photos available through the Italian national geoportal were then used to verify that the sampled stands were part of longer established woody strips: woody cover was already visible in 38 plots in imagery acquired between 1984 and 1989 and persisted in subsequent available imagery, while in the remaining four plots the earliest unambiguous evidence of woody cover dated from 1994 to 1996.

A total of 42 plots were established along four electrified railway lines in northeastern Italy (Fig. 1), selected to include both main and subsidiary lines and different operational contexts, such as open line sections and braking zones near stations or junctions, where railway derived metal emissions may vary with traffic and operating conditions (Wiłkomirski et al. 2011). The sampled lines were: the main multi track Padua–Bologna line, electrified since 2006 (A.1: main railway type); the main multi track Treviso–Pordenone–Udine line, electrified since 1960 (A.2: main railway type); the subsidiary multi track Padua–Bassano del Grappa line, electrified since 2020 (B.1: subsidiary railway type); and the subsidiary single track Mantua–Monselice line, electrified since 1997 (B.2: subsidiary railway type). Track type was assigned at the sampled railway section. At the time of data collection, all sampled lines were equipped with concrete sleepers.

At the scale of the sampled railway strips, substrates were generally disturbed and anthropogenic, commonly associated with ballast, embankment fill and other coarse material. According to the regional soil map, the surrounding lowland soils are mainly associated with alluvial or fluvioglacial deposits (ARPAV 2005), within a landscape strongly modified by agricultural and urban land use.

Field data collection

Linear tree strips were surveyed using methods developed for hedges and linear woody vegetation, with minor adaptations to the aims of this study (Defra 2007; Sitzia et al. 2013). Field surveys were carried out between June and July 2023. Plots were 10 m long and oriented parallel to the railway. Plot depth was defined as the maximum horizontal projection of the tree canopy perpendicular to the railway; therefore, canopy projection area was calculated as plot length, fixed at 10 m, multiplied by canopy depth. Stem foot depth was also recorded as the perpendicular distance between the railway edge and the outermost tree stems within the strip (Fig. 2).

For each plot, we recorded aspect, adjacent land use, tree layer composition, vertical structure and presumed origin. Adjacent land use was classified in the field as cropland, seminatural or urbanized. At the midpoint of each plot, the terrain profile was assessed using a clinometer and measuring

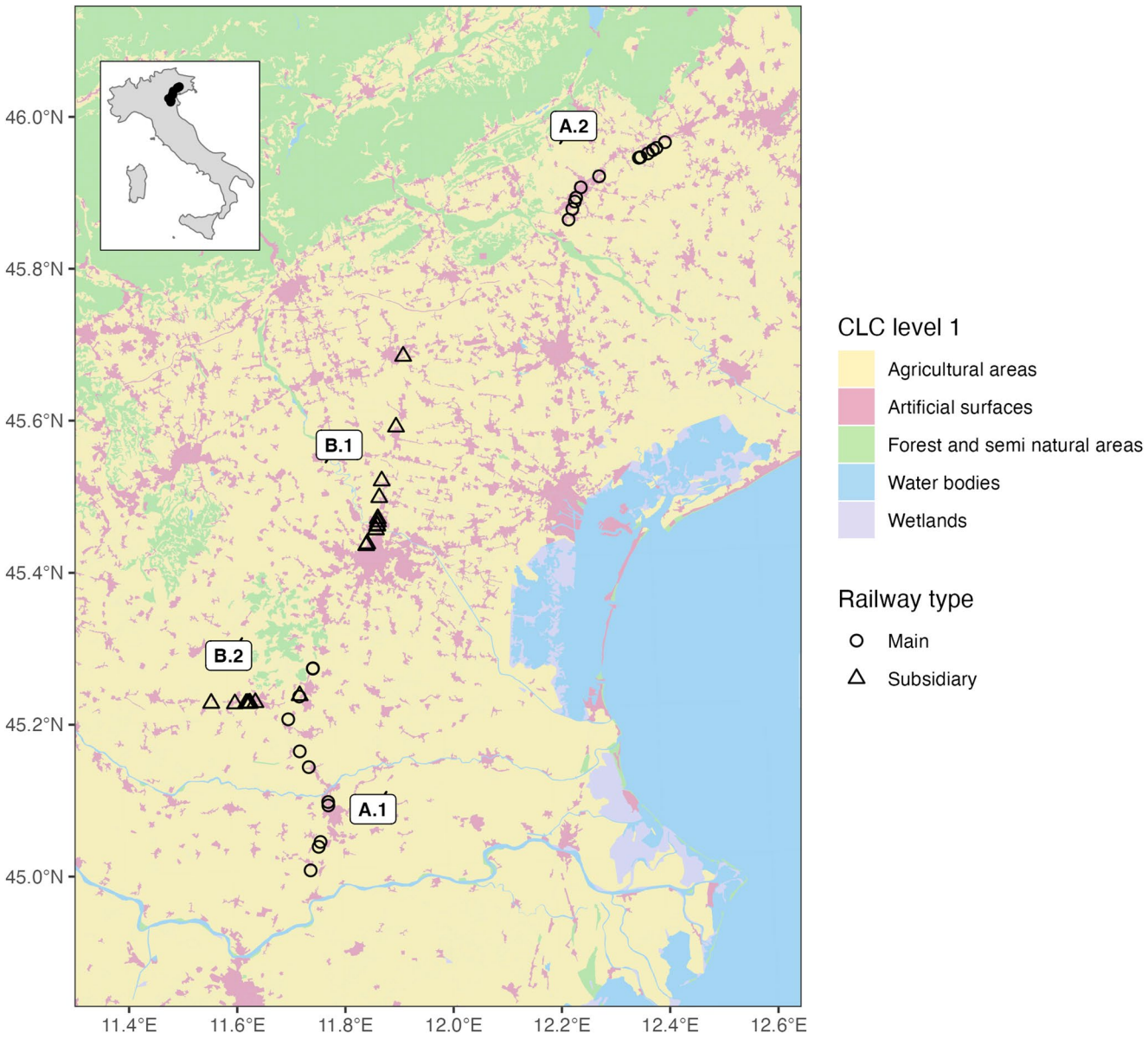

Fig. 1 Study area and sampling design. Location of the 42 sampled black locust dominated railway stands in northeastern Italy. The background shows CORINE Land Cover (level 1) 2018. Open symbols indicate sampling units, with circles representing main railway lines and triangles representing subsidiary railway lines. Labels identify the four sampled railway lines: A.1, Padua–Bologna; A.2, Treviso–Pordenone–Udine; B.1, Padua–Bassano del Grappa; and B.2, Mantua–Monselice. The inset shows the location of the study area within Italy

tape. Percentage cover was visually estimated separately for the ground (herb) layer (≤1 m), shrub layer (1–5 m) and tree layer (≥5 m). Vascular plant species were identified in each layer. In the ground and shrub layers, species cover was assigned using Braun-Blanquet cover abundance classes (Braun-Blanquet 1964) and converted to percentage cover values using the corresponding Braun-Blanquet values reported by van der Maarel (1979): + = 0.1%, 1 = 5%, 2 = 17.5%, 3 = 37.5%, 4 = 62.5%, and 5 = 87.5%. For the tree layer, total visually estimated cover was apportioned among tree species according to their proportional basal area (species basal area/total plot basal area), using relative basal area as a surrogate for proportional canopy contribution (Gawler and Cutko 2018).

All live trees with diameter at breast height (DBH) ≥ 5 cm were measured. For each tree, species, DBH and height were recorded. DBH was measured using tree callipers, and height using a TruPulse 200 laser rangefinder.

Increment cores were collected from 106 black locust stems in 36 plots. Within each plot, stems were selected among individuals with DBH ≥ 5 cm, as close as possible to the railway and preferentially among the larger stems,

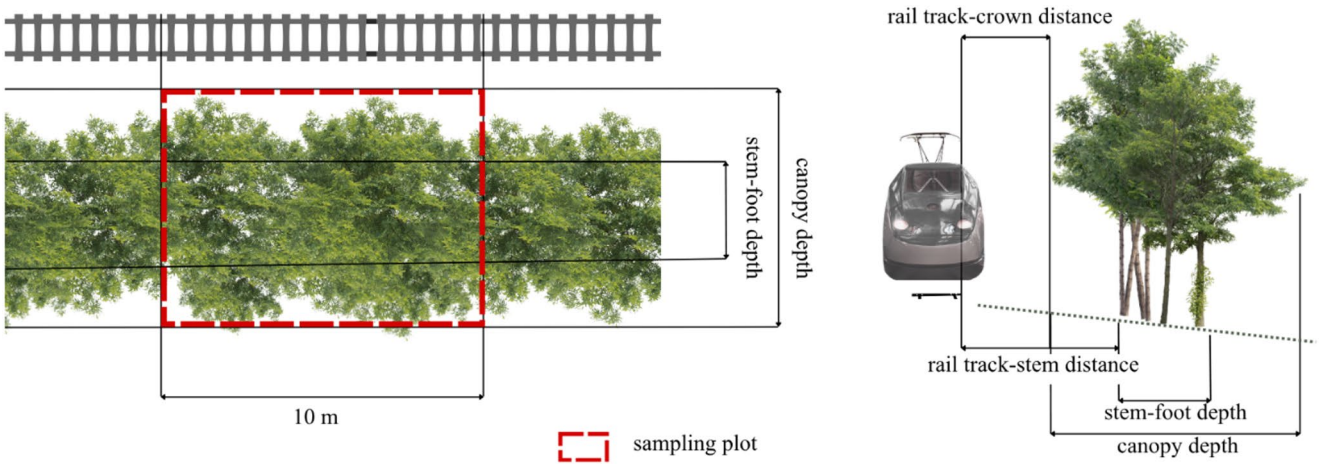

Fig. 2 Plan and section of the sampling plot. The canopy depth (maximum horizontal projection of the tree canopy perpendicular to the railway), the stem foot depth (perpendicular distance between the railway edge and the outermost tree stems within the strip), the distance from the tracks to the crown, and from the tracks to the stem are highlighted. The perimeter of the sampling plot is shown in red (10 meter length and variable width based on the canopy depth)

to characterise the age and recent diameter growth of the dominant current above ground cohort.

Derived variables and statistical analyses

For each plot, we calculated stem number, number and proportion of black locust stems, tree species richness, DBH and height descriptors, basal area, volume, stem density, canopy depth and stem foot depth. Basal area was calculated from DBH as $\pi(DBH/200)^2$, where DBH is in centimetres and basal area in square metres. Tree volume was recalculated from species, DBH and height using the Italian species specific volume equations of Tabacchi et al. (2011). For *Quercus robur* L., we used an updated equation based on Marchi et al. (2016). Because stands were linear strips with variable width, density, basal area and volume were expressed both per plot and per canopy projection area.

Stem age was estimated from the core chronology and interpreted as the age of the current above ground stem or shoot. Mean annual diameter growth was calculated as the total diameter increment from 2019 to 2023 divided by five. Stem age and mean annual diameter growth were summarised descriptively and were not used as explanatory variables in the community models. In these periodically coppiced and resprouting black locust strips, tree size and stand structure variables can be interpreted as descriptors of recent above ground stand development and, indirectly, of the time elapsed since the last major cutting or resprouting event. Stand development in the community analyses was therefore represented by measured structural variables, including DBH, height, basal area, volume and canopy cover. To support this interpretation, Spearman correlations were calculated between plot level mean stem age and selected structural variables.

Species richness was interpreted as richness per 10 m railway stand segment rather than as species density per unit area, because all plots had the same length, and variation in canopy depth was considered a structural feature of the sampled linear stands. Total richness and richness by layer were calculated for each plot. To check whether variable strip width influenced richness, we tested the relationships between total, layer specific and understorey richness and canopy projection area, canopy depth and stem foot area using Spearman correlations and linear models. For community analyses, cover values were summed across layers by plot and species to obtain a total composition matrix. Additionally, an understorey matrix was constructed by excluding the tree layer, allowing shrub and herb composition to be analysed independently from black locust canopy dominance.

Analyses were performed in R (R Core Team 2025). Descriptive statistics were calculated by railway type, track type at the sampled section, adjacent land use and railway line. Univariate differences in selected structural and richness variables were tested using Kruskal-Wallis tests. The results were interpreted as exploratory because group sizes were small and several predictors were partly confounded. Descriptive summaries and Kruskal-Wallis test results are reported in Tables S1 and S3.

Plant community composition was analysed using Hellinger transformed cover matrices, an approach suitable for ordination of species abundance data (Legendre and Gallagher 2001), and Bray-Curtis dissimilarities. Non-metric multidimensional scaling (NMDS) was used for ordination. Compositional differences were tested with

PERMANOVA using the adonis2 function in the R package vegan, with 999 permutations (Oksanen et al. 2025). Models were fitted for total composition and understorey composition, first testing railway type, track type, adjacent land use and spatial coordinates separately, and then testing a full model including railway type, track type, adjacent land use and centred kilometre scale x and y coordinates. To address the possible role of stand development, additional sensitivity PERMANOVA models tested tree cover, basal area per canopy projection area, volume per canopy projection area and maximum height, both alone and together with railway, land use and spatial predictors. Homogeneity of multivariate dispersion was checked using the betadisper function in vegan (Oksanen et al. 2025). Indicator species analysis was performed using the multipatt function with the IndVal.g association function in the R package indicspecies, with 999 permutations (De Cáceres and Legendre 2009). Additional exploratory analyses, including environmental fitting of stand variables, PCA of stand descriptors, comparison with diagnostic species of southern European *Robinia* vegetation types sensu Vítková et al. (2020) and understorey clustering, are reported in the Supplementary Material.

Results

Sampled stands and stand structure

The 42 sampled black locust stands included 23 plots along main railway lines and 19 plots along subsidiary railway lines; railway type and line identity were not independent. Adjacent land use included cropland (19 plots), seminatural land (14 plots) and urbanized land (9 plots). Full plot distribution by railway type, track type, adjacent land use and line is reported in Table S2.

The stands were structurally heterogeneous. Mean canopy projection area was 123.8 m^2 (range: 50.0–209.0 m^2), while mean area defined by stem foot depth was 56.9 m^2 (range: 10.0–119.0 m^2). Tree cover was generally high (mean: 77.6%; median: 80.0%) and the mean number of live stems per plot was 22.5 (range: 9–50). Mean plot level DBH was 11.8 cm (range: 6.1–24.6 cm), mean tree height was 9.9 m, and maximum height reached 22 m. The diameter class distribution is reported in Fig. S2. Mean basal area was 0.27 m^2 per plot and mean volume was 1.53 m^3 per plot. When standardized by canopy projection area, mean stem density was 1,926 stems ha^{-1}, mean basal area was 22.2 m^2 ha^{-1} and mean volume was 121.3 m^3 ha^{-1}.

Black locust was present and structurally dominant in all sampled plots by design. On average, it represented 70.5% of live stems, and its median contribution to basal area and volume was 100%. This indicates that many stands were structurally almost pure black locust stands, even where other woody or herbaceous species occurred in the vegetation layers.

Increment cores were available for 106 black locust stems in 36 plots. The sampled above ground stems ranged from 3 to 26 years old. At plot level, mean stem age ranged from 4.7 to 21.3 years, with most plots concentrated between 5 and 15 years. Mean annual diameter growth averaged 8.35 mm yr^{-1} (median 7.86 mm yr^{-1}; range 1.90–17.94 mm yr^{-1}). Plot level mean stem age was positively correlated with mean DBH (Spearman's $\rho = 0.54$, $p = 0.001$), mean height ($\rho = 0.38$, $p = 0.024$), plot volume ($\rho = 0.53$, $p = 0.001$) and volume per canopy projection area ($\rho = 0.41$, $p = 0.012$), and negatively correlated with mean annual diameter growth ($\rho = -0.58$, $p < 0.001$), supporting the interpretation of tree size and stand structure variables as descriptors of recent above ground stand development and, indirectly, time since the last major cutting or resprouting event.

Variation across railway and land use contexts

Subsidiary railway plots had higher mean stem number, basal area, volume and species richness than main railway plots. Mean volume was 1.92 m^3 per plot in subsidiary stands and 1.20 m^3 per plot in main line stands, while mean total richness was 17.4 and 14.3 species per plot, respectively. Kruskal-Wallis tests indicated significant differences between railway types for basal area ($H(1) = 5.12$, $p = 0.024$) and volume ($H(1) = 4.24$, $p = 0.039$), both standardised by canopy projection area, as well as in total richness and non black locust richness (both $H(1) = 5.99$, $p = 0.014$), and shrub layer richness ($H(1) = 4.56$, $p = 0.033$; Fig. 3 and Table S3). However, these differences must be interpreted cautiously because railway type was confounded with line identity and spatial position.

Track type showed fewer differences and was interpreted as exploratory because single track plots were fewer and spatially clustered. Single track plots had higher mean volume and shrub layer richness than multi track plots, and Kruskal-Wallis tests were significant for volume per canopy area ($H(1) = 3.91$, $p = 0.048$) and shrub layer richness ($H(1) = 4.31$, $p = 0.038$; Table S3). Adjacent land use was associated with clearer structural contrasts: seminatural plots had the largest mean DBH and tallest trees, whereas urbanized plots had the highest stem density and the lowest mean species richness. Tests by adjacent land use were significant for maximum height ($H(2) = 9.85$, $p = 0.007$), stem density per canopy area ($H(2) = 7.29$, $p = 0.026$) and median DBH ($H(2) = 6.66$, $p = 0.036$; Table S3).

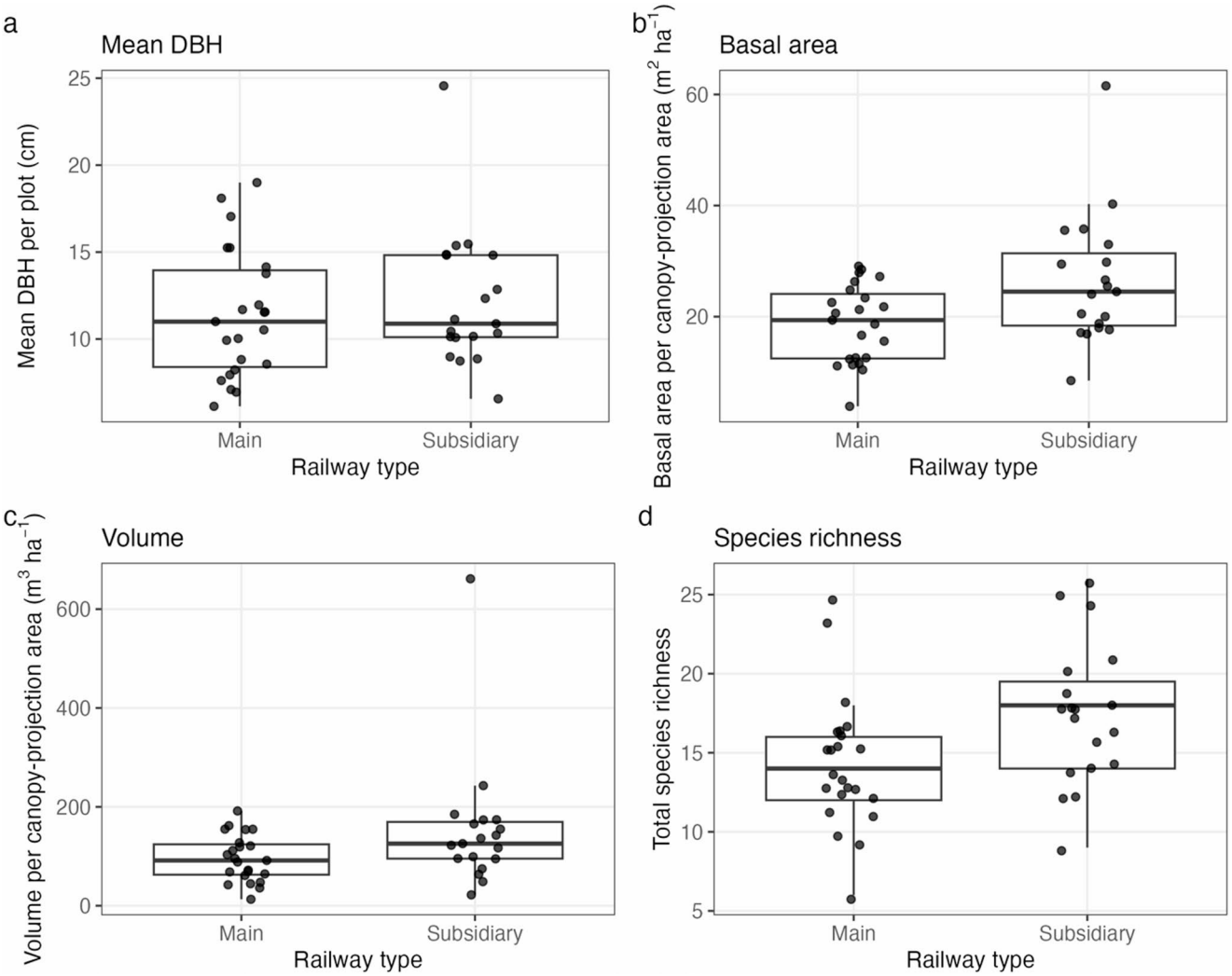

Fig. 3 Stand structure of black locust dominated railway tree strips. Variation in selected structural and compositional descriptors of the 42 sampled railway stands. Panels show mean DBH per plot, basal area standardized by canopy projection area, volume standardized by canopy projection area, and total species richness per 10 m railway stand segment. Basal area and volume are expressed per canopy projection area, whereas species richness is retained as richness per sampled 10 m segment. Points represent individual plots; boxes show median, interquartile range and whiskers

Plant community richness and composition

A total of 113 vascular plant species was recorded across the 42 plots. Total species richness averaged 15.7 species per plot and ranged from 6 to 26 species. Most richness was concentrated in the herb layer, which averaged 14.0 species per plot. Shrub layer richness averaged 4.0 species per plot, and tree layer richness averaged 2.5 species per plot. Understorey richness, calculated from shrub and herb layers, averaged 15.3 species per plot. Black locust was present in the understorey in many plots, but its mean relative understorey cover was low (11.5%). Gamma diversity and plot level richness summaries are reported in Table S1. Total, layer specific and understorey richness were not significantly related to canopy projection area, canopy depth or stem foot area, supporting the interpretation of richness as richness per 10 m railway stand segment.

Beyond black locust, the most frequent species across the sampled stands were *Hedera helix* L. (90.5% of plots), *Rubus ulmifolius* Schott (83.3%), *Sambucus nigra* L. (64.3%), *Galium aparine* L. (54.8%), *Cornus sanguinea* L. (50.0%), and *Acer campestre* L. and *Quercus robur* L. (both 47.6%). *Hedera helix* and *R. ulmifolius* also showed the highest mean cover across plots in the herb layer (25.3% and 17.3%, respectively), whereas *R. pseudoacacia* and *S. nigra* had the highest mean cover in the shrub layer (11.8% and 8.8%, respectively).

Total plant community composition (Fig. 4) differed significantly among railway types when tested alone (R^2 = 0.041, p=0.036). Adjacent land use explained a larger

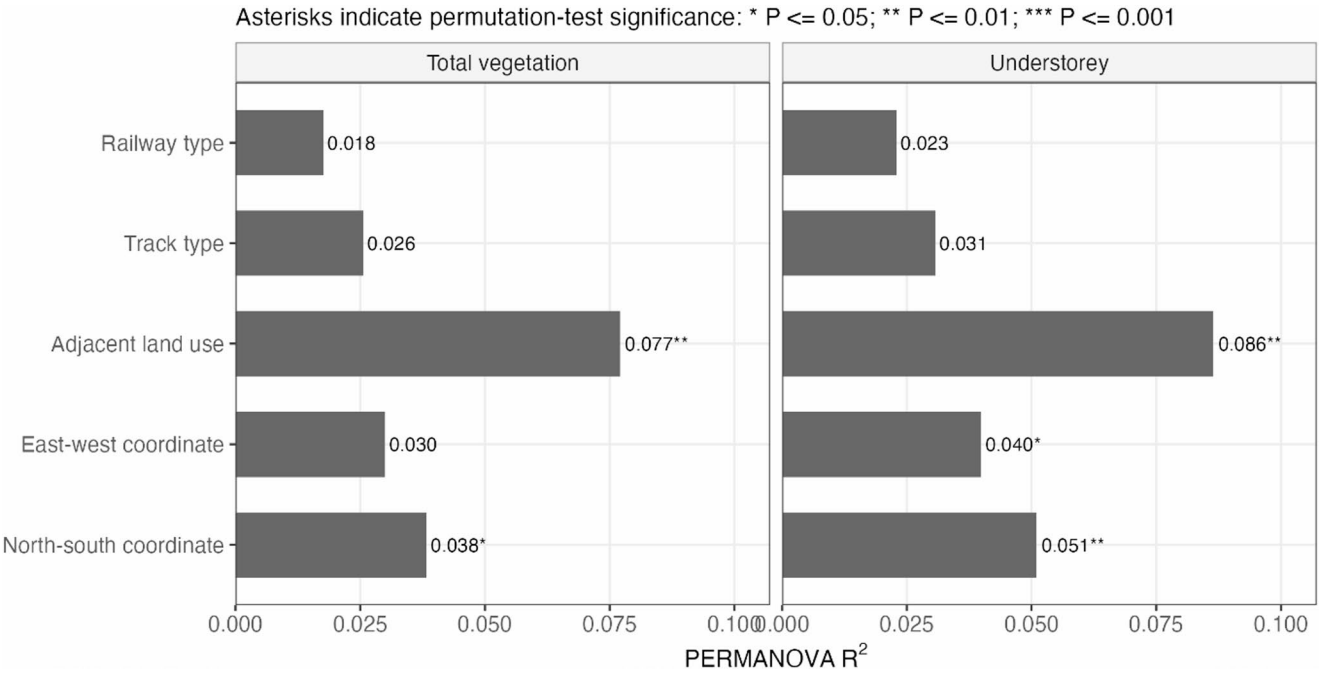

Fig. 4 Relative explanatory power of railway context, adjacent land use and spatial position on plant community composition. Marginal PERMANOVA effect sizes for total vegetation composition and understorey composition. Bars show the proportion of variation explained by each predictor, expressed as R^2, in models including railway type, track type, adjacent land use and centred spatial coordinates. Significance levels are based on 999 permutations. The figure highlights the stronger and more consistent contribution of adjacent land use and spatial position compared with railway type and track type

proportion of variation (R^2 = 0.077, p=0.012), and spatial coordinates explained 10.2% of variation (p=0.001). Track type alone was not significant. In the full model including railway type, track type, adjacent land use and coordinates, only adjacent land use (R^2 = 0.077, p=0.007) and the north south coordinate (R^2 = 0.038, p=0.039) remained significant. Railway type and track type did not retain significant independent effects after accounting for land use and spatial position.

For total composition, tests of multivariate dispersion were not significant for railway type, track type or adjacent land use (all $p \geq 0.144$), indicating that the significant land use effect in PERMANOVA was unlikely to be explained by unequal within group dispersion. These results indicate that the apparent compositional difference between railway types was reduced after accounting for adjacent land use and spatial position.

Understorey composition

Understorey composition showed a similar but clearer pattern (Fig. 5). Railway type alone was not significant (R^2 = 0.036, p=0.088), and track type alone was not significant (R^2 = 0.026, p=0.363). Adjacent land use (R^2 = 0.091, p=0.002) and coordinates (R^2 = 0.102, p=0.001) were significant predictors. In the full model, adjacent land use remained significant (R^2 = 0.086, p=0.004), as did both the east west coordinate (R^2 = 0.040, p=0.022) and the north south coordinate (R^2 = 0.051, p=0.004). Railway type and track type were not significant in the full model.

For understorey composition, dispersion differed significantly by railway type and track type, but not by adjacent land use. Therefore, apparent understorey differences associated with railway or track category may partly reflect differences in compositional heterogeneity, whereas the land use effect is more robustly interpretable as a difference in community composition.

Stand gradients and supplementary compositional analyses

Supplementary ordination analyses showed that plant community composition was associated with stand development gradients. Environmental fitting results are reported in Table S4. The strongest fitted variables were volume per canopy area, basal area per canopy area, stem density per canopy area, maximum height, tree cover and the north south coordinate. The PCA of these stand descriptors supported the interpretation of a primary structural gradient ranging from smaller, less developed stands to stands with greater biomass, larger trees and higher basal area (Fig. S1; Table S5). Sensitivity PERMANOVA models confirmed that stand

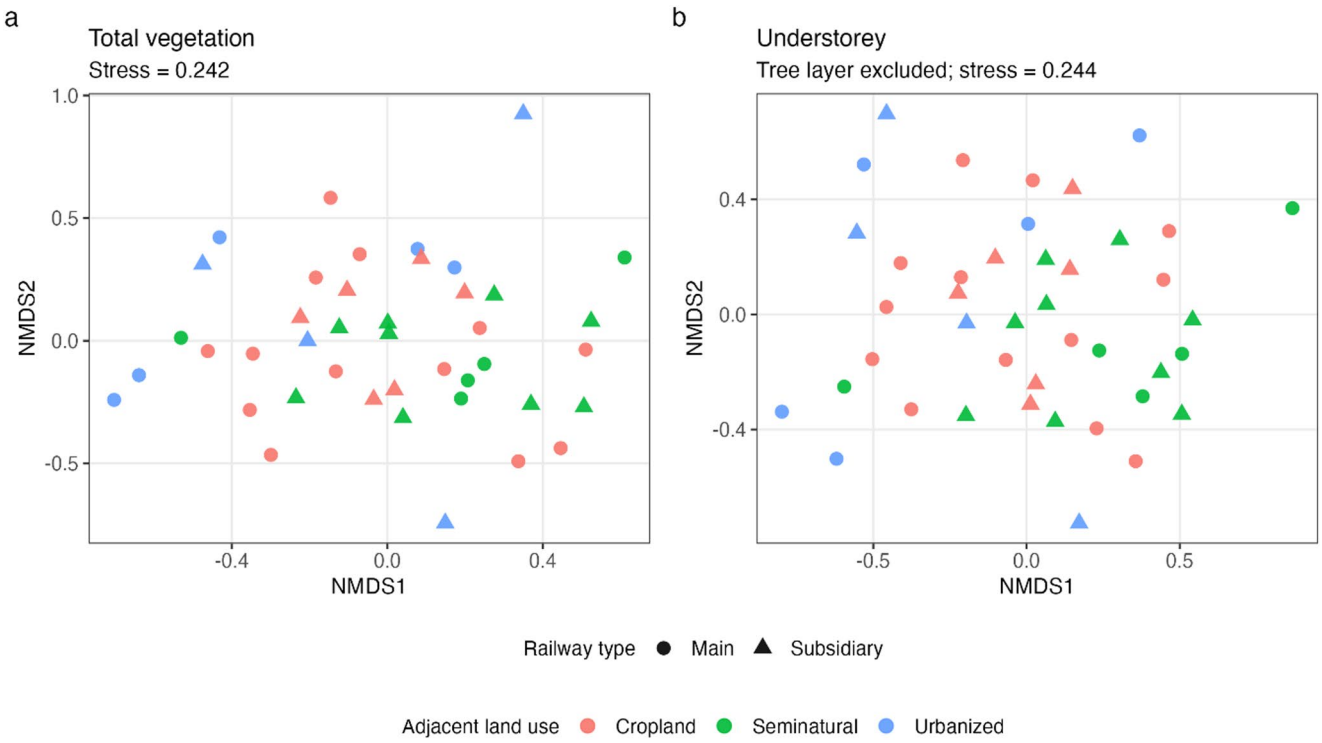

Fig. 5 Plant community composition of railway black locust stands. Nonmetric multidimensional scaling ordinations based on Bray-Curtis dissimilarities of Hellinger transformed species cover data. Panel a shows total plant community composition, including all vegetation layers. Panel b shows understorey composition after excluding the tree layer. Point colour indicates adjacent land use, and point shape indicates railway type. Stress values are reported in each panel

structure contributed to compositional variation (Table S9). In structure only models, volume per canopy projection area and maximum height were significant for total composition, while basal area, volume and maximum height were significant for understorey composition. In models including railway type, track type, adjacent land use, spatial coordinates and stand structure variables, adjacent land use remained significant, and volume per canopy projection area retained an independent effect for both total vegetation and understorey composition.

Indicator species analyses identified several species associated with sampled railway contexts, although these associations should be interpreted cautiously because railway type, track type, line identity and spatial position were partly confounded (Table S6).

The supplementary comparison with southern European black locust dominated vegetation types sensu Vítková et al. (2020) showed that many plots had affinity with dry ruderal or mesic nitrophilous black locust vegetation types (Figs. S3, S4; Table S7). Exploratory understorey clustering provided an additional descriptive grouping of plots, whose distribution by railway type is shown in Fig. S5 and Table S8. Overall, the sampled stands combined ruderal, nitrophilous, alien and woodland affinity components, indicating that they were not compositionally uniform black locust strips but understorey assemblages with different affinities to known *Robinia* dominated vegetation types.

Discussion

The combination of strong black locust dominance, developed woody structure and heterogeneous understorey composition supports the interpretation of these railway strips as linear alien secondary woodlands associated with transport infrastructure.

The structural dominance of black locust was expected given the study selection criteria, but its degree of dominance is nevertheless important. In many plots, black locust accounted for most stems, basal area and volume, indicating that these railway strips can be interpreted as narrow, linear expressions of black locust secondary woodland rather than as scattered tree rows. This is consistent with the broader ecology of the species, which is well adapted to disturbed sites because of its fast growth, resprouting ability, clonal spread and nitrogen fixation capability (Cierjacks et al. 2013; Vítková et al. 2017). In railway corridors, these traits are likely to be favoured by recurrent cutting, edge conditions, embankment substrates and repeated disturbance.

At the same time, the sampled stands differed from typical black locust secondary forests on abandoned fields, as they were strictly constrained by the linear geometry and management context of the railway infrastructure. Previous studies in northeastern Italy have shown that black locust can form recognisable alien secondary woodland communities on abandoned agricultural land and former grasslands (Campagnaro et al. 2018b; Sitzia et al. 2018). The present results suggest that railway black locust strips belong to the same broad phenomenon of novel alien secondary woodland, but under a different set of environmental and management filters. Their narrow shape, strong edge exposure, ballast and embankment substrates, recurrent maintenance and proximity to agricultural, urban and seminatural land uses probably increase the influence of the surrounding species pool and local disturbance regime.

The association between adjacent land use and plant community composition is central to the interpretation of this study. Railway type and track type did not retain significant independent effects after accounting for land use and spatial coordinates, whereas adjacent land use remained significant for both total vegetation and understorey composition. This suggests that the vegetation of railway black locust stands reflects the surrounding landscape matrix rather than railway infrastructure variables alone. The association may arise through differences in propagule availability, disturbance and edge conditions. Local edaphic variation may provide an additional filter: soil chemical properties can vary at fine spatial scales along railway corridors because of substrate characteristics and railway related inputs (Wiłkomirski et al. 2011) and may contribute to plant community composition independently of the broader soil setting.

This result is consistent with studies showing that railway vegetation reflects the heterogeneity of both railway habitats and surrounding landscapes. Floristic studies of railway embankments and railway associated habitats have shown that artificial transport corridors can host species rich assemblages and that composition varies among railway microhabitats, yards, embankments and adjacent land uses (Filibeck et al. 2012; Kutlvašr et al. 2024; Šabić et al. 2026). Our results extend this perspective to tree dominated railway vegetation by showing that adjacent land use also affects the understorey of black locust strips. The railway corridor should therefore be considered not as an isolated habitat, but as a linear element deeply embedded within a broader landscape context. In intensively managed or poorly wooded landscapes, such strips may also function as refugia for forest and shrub associated plant species and, potentially, as cover or stepping stone habitat for animal movement, although animal use was not directly tested here.

The structural patterns were more complex. Subsidiary railway plots contained greater basal area, volume and richness per sampled segment than main railway plots, while single track plots showed higher volume and shrub richness than multi track plots. These differences may reflect management history, line identity, spatial position or surrounding landscape context, but the present sampling design does not allow these effects to be separated. In this dataset, the apparent railway type signal may partly reflect differences among railway lines, regional gradients or surrounding landscapes, rather than the direct effect of traffic intensity. This interpretation is supported by the multivariate models, where railway type lost explanatory power once land use and spatial coordinates were included.

The association between stand development variables and plant community composition suggests that structure and composition are linked. Environmental fitting showed that volume, basal area and stem density per canopy projection area, together with maximum height and tree cover, were among the strongest variables associated with ordination patterns. This indicates that the development of the woody layer may influence the understorey through shading, litter input, root competition, nitrogen enrichment and microclimatic buffering. Conversely, more open or recently disturbed stands may allow greater persistence of ruderal or light demanding species. Thus, stand structure is not merely a management descriptor; it also functions as an ecological filter for plant community composition.

This point is relevant for railway vegetation management. European railway management is transitioning from a zero vegetation paradigm (McNab 1986) toward more integrated and condition based approaches, where vegetation monitoring, local standards and risk assessment become increasingly important (International Union of Railways 2021). For this reason, structural variables such as stem density, tree height, basal area, volume and canopy development are critical because they characterize the amount and spatial arrangement of woody vegetation along the infrastructure. In the case of black locust, two management issues are especially important: vigorous resprouting after cutting, which can maintain repeated maintenance cycles, and the potential risk of stem or tree failure on embankments and line sides as stands age or develop larger stems. These risks must be balanced against possible ecological functions such as shading, habitat provision, visual screening and local connectivity.

The structural data also support a cautious interpretation of possible ecosystem functions. The sampled stands contained substantial woody biomass and canopy cover, but pollutant interception, carbon storage, thermal regulation and habitat value cannot be inferred from structure alone. These possible functions depend on stand position, species composition, management frequency, local pollution levels and landscape context, and should therefore be tested directly in future work.

Additionally, the alien status of black locust introduces complexity to the interpretation of management strategies. Black locust is an invasive tree capable of altering plant communities and soils and of spreading in disturbed habitats (Campagnaro et al. 2018a; Sádlo et al. 2017; Vítková et al. 2017; Wohlgemuth et al. 2022). This raises concerns in nearby areas along railways, which may represent potential hotspots for further invasion. On the other hand, its historical use for erosion control and reclamation illustrates that black locust can also provide structural functions in disturbed sites (Cierjacks et al. 2013; Vítková et al. 2017). This dual role supports site specific management based on local impacts, conservation value, safety requirements and landscape context rather than a uniform eradication or acceptance approach (Sádlo et al. 2017).

Some limitations should be considered. First, the study was observational, and the sampling design was constrained by the distribution of suitable strips dominated by black locust along electrified railway lines. As a result, railway type, line identity and spatial position were not fully independent, and effects attributed to railway category should be interpreted cautiously. Second, soil conditions were not directly measured. Soils close to railways may vary in substrate composition and metal contamination, and such variation could contribute to local differences in plant community composition and stand structure. Third, vegetation surveys were conducted only in June–July, so some early spring species, particularly geophytes, may have been underrecorded, and seasonal or interannual variation was not assessed.

Further work should address these limitations by sampling a larger number of railway lines to obtain a more balanced representation of railway type, traffic intensity, track type and landscape context. Repeated surveys would provide a more reliable assessment of seasonal and interannual variation in the understorey species pool and of the effects of maintenance activities (Schultz et al. 2014). Future studies should also integrate structural measurements with site specific soil chemistry.

Railway black locust stands should be interpreted as alien secondary woodlands, infrastructure associated vegetation and potential novel ecosystems embedded within the surrounding landscape matrix. Their management should consider both railway operational requirements and the environmental context in which these linear stands occur.

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Data availability The dataset required to reproduce the above findings is available on the GitHub repository of Tommaso Sitzia (https://github.com/TommasoSitzia/robrailw).

Code availability The R code used for the above analyses is stored in the GitHub repository of Tommaso Sitzia (https://github.com/TommasoSitzia/robrailw).

Declarations

Conflict of interest The authors declare no conflict of interest.

Ethical approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

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