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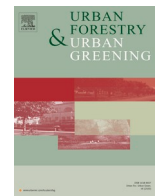
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Schoolyard greening to improve functional connectivity in the city and support biodiversity

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ABSTRACT

Urban greening is increasingly recognized as a nature-based solution (NBS) to address climate adaptation, social equity, and biodiversity conservation challenges. This study explores the innovative potential of schoolyards as key elements of urban green infrastructure (GI) to enhance ecological connectivity and support biodiversity in fragmented urban landscapes. By focusing on four European cities—Barcelona, Brussels, Paris, and Rotterdam—the research combines spatial modeling and ecological network analyses to assess the current and potential contributions of schoolyards to urban functional connectivity for tree-dependent species. The findings reveal marked spatial contrasts, influenced by historical urban planning and vegetation distribution, with schools near large green areas offering the highest connectivity gains. While individual schoolyards yield modest improvements, their dense spatial distribution presents a strategic opportunity to densify urban ecological networks, particularly in vegetation-deficient zones. Beyond their ecological value, green schoolyards provide co-benefits such as urban cooling, enhanced learning environments, and increased social cohesion, embodying the multifunctionality central to NBS frameworks. By integrating biodiversity goals with broader social and climate objectives, this research offers scientific insights to guide urban greening strategies, emphasizing the ecological potential of schoolyards to densify connectivity and support urban biodiversity.

1. Introduction

As cities grow denser and larger, their habitability amidst continuing global warming has become a critical concern (Ward et al., 2016). Projections based on current mortality trends and climate scenarios indicate that nearly all European cities will face rising heatwave-related mortality (Karwat and Franzke, 2021). To make cities more sustainable and livable, urban greening policies are increasing around the world, aligning with frameworks such as Urban Ecosystem Services (UES), Green Infrastructure (GI), and Nature-Based Solutions (NBS) (Haase et al., 2017; Escobedo et al., 2019; Fang et al., 2023; Vasconcelos et al., 2024). These frameworks are integral to addressing the United Nations' Sustainable Development Goal 11, which advocates for sustainable cities and communities (<https://www.globalgoals.org/goals/11-sustainable-cities-and-communities>). At the European level, they align with the EU

Biodiversity Strategy 2030, emphasizing urban greening (e.g., Target 14) and the protection of natural areas through ecological corridors as part of a cohesive Trans-European Nature Network (Target 1).

GI is defined by the European Commission as “a strategically planned network of natural and semi-natural areas with other environmental features, designed and managed to deliver a wide range of ecosystem services, while also enhancing biodiversity”. In urban environments, these services include air quality improvement, recreational space access, temperature moderation, and climate change mitigation. The concept of NBS is more recent and receiving increasing attention. It is defined by the IUCN as “actions to protect, manage and restore natural or modified ecosystems, which address societal challenges, effectively and adaptively, providing human well-being and biodiversity benefits”. Several authors (see for example Dorst et al., 2019; Jones et al., 2022; Fang et al., 2023) have explored the differences and similarities between

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these different concepts, which can be complex given that their definition can fluctuate from one study to another. In general, the authors agree on the systemic, and transdisciplinary approach inherent in these concepts, while at the same time viewing NBS as an umbrella concept that integrates the others (Dorst et al., 2019; Pauleit et al., 2017). The three concepts also have in common the fact that they pursue multi-functional objectives, addressing social, economic and environmental issues simultaneously.

The greening of schoolyards is a flagship example of NBS in the city, combining objectives such as children's well-being, improved learning capacities, increased social diversity in playground usage, and urban cooling (Baró et al., 2022). Among these objectives, the ecological contributions of green schoolyards, particularly their roles in ecological connectivity and biodiversity, remain underexplored (Ignell et al., 2024). Connectivity is crucial for species survival, especially in fragmented landscapes where organisms must traverse urban matrices to reach resource habitats (LaPoint et al., 2015). Given the limited free space in cities and the ecological challenges posed by concrete-dominated environments, the challenge is to build functional and resilient ecological networks with a collection of small vegetation elements that together form corridors connecting larger green spaces (Beninde et al., 2015; Ersoy, 2016). Schoolyards, with their dense and regular spatial distribution in urban areas, present strategic opportunities for enhancing connectivity and biodiversity. Their greening also addresses broader social and health objectives (Flax et al., 2020).

In line with the previous studies on the contribution of schoolyards to GI in European or American cities (Iojă et al., 2014; Baró et al., 2021; Zhang et al., 2022; Gallez et al., 2024), our aim is to assess and compare how schoolyards could contribute to functional connectivity and biodiversity. We extend our focus beyond the structural elements of the GI classically studied (Iojă et al., 2014; Gallez et al., 2024) to examine its ecological functionality for wildlife. Specifically, we assess how schoolyards facilitate wildlife movement through the urban matrix to patches of habitat, with reference to functional connectivity (Taylor et al., 1993). The urban environment is the archetype of a fragmented landscape, where built features constrain species movement between small and isolated habitats. Although a few studies have included empirical data (LaPoint et al., 2015), functional connectivity models have improved our understanding of factors influencing organismal presence and mobility, including plants and animals (Bierwagen, 2005; Beninde et al., 2015).

This study aimed to 1) analyze the current contribution of schoolyards to urban functional ecological networks and 2) assess their potential to enhance urban connectivity. We hypothesized that (H1.1) some schoolyards currently contain sufficient tree cover to act as potential habitats for tree-dependent species; (H1.2) cities with higher vegetation levels exhibit a greater proportion of such schoolyards; and (H1.3) some schoolyards function as stepping stones, i.e., small fragments of habitat patches that facilitate movement between larger habitat patches (Saura et al., 2013). To test these hypotheses, we modeled ecological networks for small tree-dependent fauna and conducted spatial analyses of schoolyards in terms of proximity to potential habitats and corridors. Then, connectivity metrics were calculated to compare schools within and across cities. In addition to assessing their current contributions, we evaluated the potential of schoolyards to improve functional connectivity and reconnect tree habitats within cities. We hypothesized that (H2.1) targeted greening efforts, emphasizing biodiversity, could significantly enhance connectivity. To test this, we conducted simulations to assess the impact of transforming schoolyards into functional habitats, comparing connectivity gains between schools and between cities. Finally, we hypothesized that (H2.2.) city-specific configurations, shaped by historical urban planning, influence connectivity outcomes. We carried out this study in four European cities, Barcelona, Brussels, Paris, and Rotterdam, offering diverse geographical and landscape contexts for analysis.

2. Material and methods

2.1. Study areas

Our study focused on four European cities - Barcelona, Brussels, Paris and Rotterdam (Table 1 and Fig. 1), which are involved in the ERA-NET Coolschools project (<https://coolschools.eu>). Each city has undergone distinct urbanization policies over time, resulting in varied landscape compositions and configurations. Recently, these four cities, like many others in Europe (Reckien et al., 2018), have launched greening and climate adaptation initiatives. These policies aim to integrate nature-based solutions to promote resilience, enhance quality of life, and protect biodiversity in urban environments.

Barcelona, located on Spain's northeastern coast, spans 101 km² and is home to approximately 1.6 million inhabitants, with a density of 16,388 residents per km² (Instituto Nacional de Estadística, 2023). The city expanded strongly in the first half of the 19th century following a regular grid plan, composed of square blocks of identical size. Originally, each square block was partially built and was vegetated in the center. However, urban densification has since replaced much of the vegetation with built infrastructure. In 2014 and 2018, Barcelona implemented the "Plan del Verde y de la Biodiversidad" and the "Plan Climat", which include specific measures for greening the city and integrating ecological corridors (Ajuntament de Barcelona, 2018).

Brussels, the capital of Belgium, has a conurbation (named "Bruxelles Capitale") that covers an area of 161 km² with a population of about 1.2 million residents and a density of 7512 residents per km² (Statbel, 2023). Originating in the 11th century along the Senne River, urbanization intensified during the 19th century, with the channeling of the Senne and the densification of surrounding suburbs. To address urban sustainability, the city launched the "Plan Régional Nature" (2016) and the "Plan Régional de Développement Durable" (2018), aiming to expand green spaces, green roofs and walls, and enhance green infrastructures, to improve climate resilience and the quality of life for residents (<https://environnement.brussels>).

Paris, the capital of France, spans 105 km² and has over 2.1 million residents, making it one of the densest cities in Europe, with 20,238 residents per km² (INSEE, 2023). The city underwent a major transformation in the 19th century under Haussmann, who introduced wide tree-lined avenues, squares, and large parks. Since 2011, Paris has implemented a biodiversity plan, complemented by the "Plan Climat de Paris". As part of this strategy, the "OASIS" program was launched to convert schoolyards into cooler, more vegetated spaces with permeable surfaces (<https://www.paris.fr/pages/les-cours-oasis-7389>).

Rotterdam, located in the southwest of the Netherlands, covers an area of 324 km² with approximately 650,000 inhabitants and a low population density of 1986 residents per km² (Centraal Bureau voor de Statistiek, 2023). Due to its location on the Rotte River dike, Rotterdam has long prioritized nature-based approaches in urban planning, addressing challenges such as rising water levels. The "Resilient Rotterdam Strategy 2022–2027" emphasizes climate and ecological resilience (<https://www.resilientrotterdam.nl/en/>). Key measures include creating and enhancing urban parks, installing green roofs, and developing blue infrastructure such as retention basins and canals. The strategy also focuses on improving biodiversity and establishing green corridors to connect natural habitats across the city.

2.2. School and land cover datasets

The school dataset for the four cities studied (n = 2788) includes educational institutions serving children aged 3–18, encompassing nursery, elementary, and secondary schools, both public and private. These datasets were obtained from official government sources in each country (see Table 1). According to the metadata, the datasets are updated weekly and thus reflect the current year's school population. In cases where multiple schools were located on the same site (e.g., a multi-

Table 1

Main characteristics of the four European cities studied, including surface area, population and the number of schools studied. * The number of schools analyzed is less than the total number of schools in the city as schools located on the same site are counted as a single entity.

Cities	Barcelona	Brussels	Paris	Rotterdam
Surface area of the city (km ²)	101	161	105	324
Surface area of the zone studied (city + buffer) (km ²)	289	214	285	498
Inhabitants number (2023)	1.6 million	1.2 million	2.1 million	650,000
Schools number studied*	426	1069	1103	190
Data sources of Inhabitants number	Instituto Nacional de Estadística. (2023). Population and Area Data for Barcelona. https://www.ine.es/	Statbel. (2023). Population and Area Data for Brussels. https://statbel.fgov.be fr	INSEE Institut National de la Statistique et des Études Économiques (2023). Population and Area Data for Paris. https://www.insee.fr/fr/accueil	Centraal Bureau voor de Statistiek. (2023). Population and Area Data for Rotterdam. https://www.cbs.nl/
Data sources of schools' data	https://opendata-ajuntament.barcelona.cat/data/es/dataset/equipament-educacio	https://datastore.brussels/web/urbis-download	https://data.education.gouv.fr/	https://scholenopdekaart.nl/

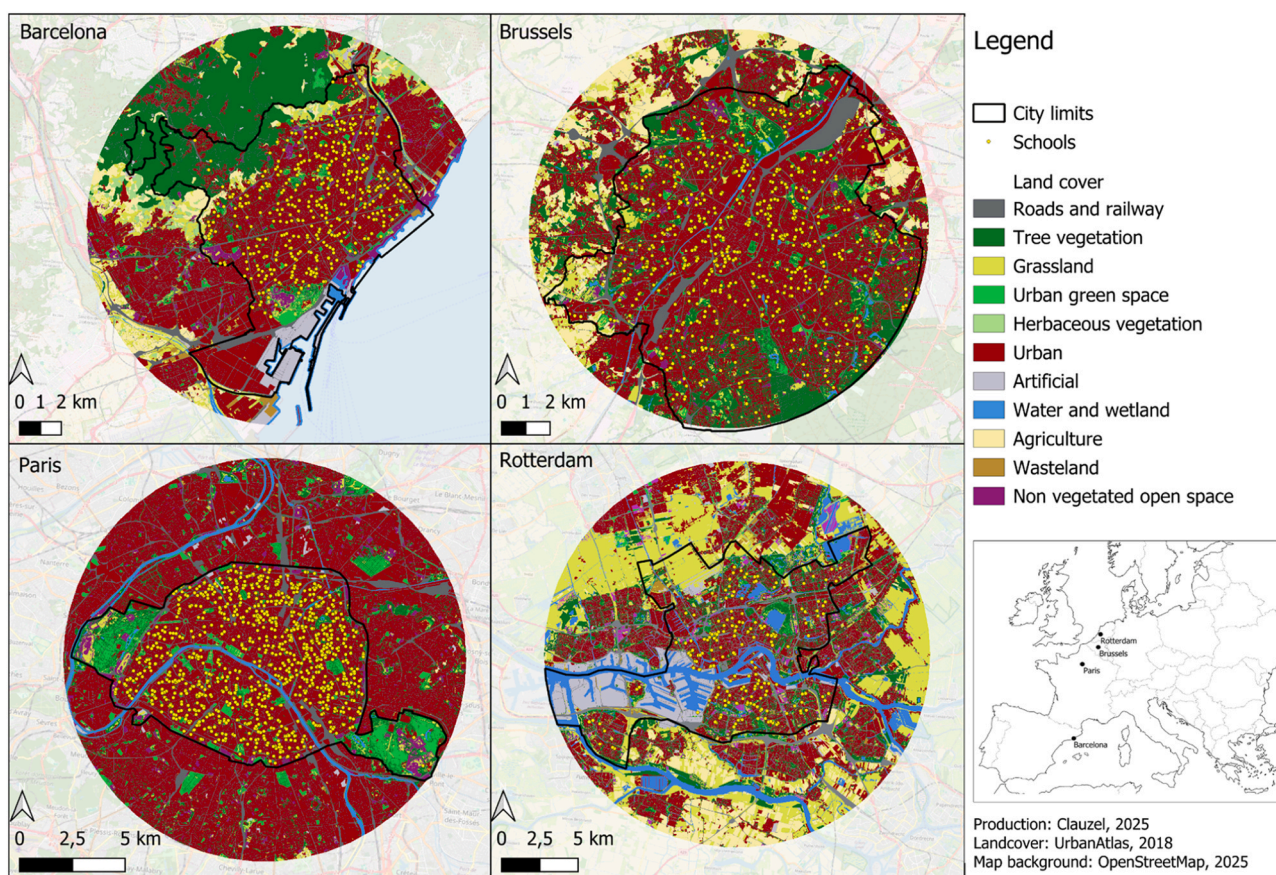


Fig. 1. Land cover at 5-meter spatial resolution and the location of schools included in the study, in four European cities: Barcelona (Spain), Brussels (Belgium), Paris (France), Rotterdam (Netherlands).

level school with both a nursery and an elementary school), only one spatial point was retained, as these schools typically share the same yard. Due to the lack of data on the spatial delineation of the school parcel for some cities, schools are represented as point objects.

Land cover in the four cities was mapped using standardized, pan-European data to ensure comparability of results. Specifically, we used the Urban Atlas Land Cover/Land Use 2018 dataset (<https://land.copernicus.eu/en/products/urban-atlas/urban-atlas-2018>) and processed it using QGIS version 3.34.12. The original 17 land cover categories were grouped into broader 9 categories for analytical purposes, and the data were rasterized to 5-meters resolution in the projection system adapted

to each country (Fig. 1). To account for edge effects in the connectivity analysis, the study areas included a 2 km buffer zone around the administrative boundaries of each city. This buffer allows for the inclusion of ecological habitats adjacent to the city, acknowledging that species movements are not constrained by administrative borders.

2.3. Connectivity analysis

For each city, functional connectivity was estimated by modelling ecological networks derived from the corresponding land-cover map using graph theory. Given the resolution of the available land-cover

data, we focused on connectivity of tree-stratum habitats for flying species with medium dispersal capacity ($d=500$ m). These species may include passerine birds or flying insects such as pollinators. The 500-meter distance was chosen based on observations of pollinators (Osborne et al., 2008) and studies on bird species in urban environments (Møller, 2008; Hahs et al., 2023). In line with our emphasis on functional biodiversity at the ecosystem level, our approach is intentionally broad to include various taxa.

Potential habitat patches were defined as contiguous pixels within the “tree vegetation” land-cover category, which formed the nodes of the graph. The minimum surface area of habitat patches is 500 m², corresponding to the minimum size of tree areas represented in Urban Atlas data.

The links between habitat patches were calculated using least-cost paths to integrate the permeability of the landscape matrix. Resistance values were assigned to different land-cover types based on their degree of obstacle to species movement (Appendix 1). Following App et al. (2022) and Zhang et al. (2021), we chose a scale from 1 to 100 to represent some heterogeneity of the landscape matrix. Low resistance values were attributed to tree elements (1) and grasslands (5), which are favorable for species movement. In contrast, high resistance values were assigned to urban areas (100) and transportation infrastructure (50), reflecting the significant barriers posed by these features (e.g., buildings, traffic, noise, human activity). Intermediate resistance values were assigned to other unbuilt elements, such as bitumen-covered areas (20) and vegetated spaces (10). The resulting graph was thresholded at 500 meters, meaning that only links with a cumulative cost distance less than 500 m were retained, indicating that habitat patches within this range were considered connected. For ease of understanding, we have qualified these connections between patches by the technical word “link” when talking about the graph, and the generic word “corridors” when interpreting the results, although it does not refer to a specific width.

To examine the contribution of schoolyards to urban functional ecological networks (Objective 1), we compared their Euclidean distance to the nearest elements of the graph (i.e., nodes and links), and their connectivity values. Local connectivity metrics were computed at both the patch and link levels. We selected the Flux metric (F , Urban and Keitt, 2001) to assess the importance of a patch’s connections with other patches, and the Betweenness Centrality Index (BC ; Bodin and Saura, 2010) to assess the centrality of a focal element. The Flux metric is an indicator of the potential dispersion from a patch i , or to a patch i . For a given patch i , F_i is given by:

$$F_i = \sum_{j=1}^n a_j e^{-\alpha d_{ij}} \quad j \neq i$$

with a_j being the potential recruitment capacity of the patch j . The graph path used is that which maximizes $e^{-\alpha d}$, i.e., that which minimizes the cost distance d between patches i and j .

The Betweenness Centrality Index is an indicator of the ability of a patch or a link to run paths within the graph, as a necessary passage through the network. For a given patch i , BC_i is given by:

$$BC_i = \sum_j \sum_k a_j a_k e^{-\alpha d_{jk}} \quad j, k \in \{1..n\}, \quad k < j, i \in P_{jk}$$

with a_j and a_k being the potential recruitment capacity of the patches j and k , and P_{jk} the set of patches crossed by the least-cost path between patches j and k .

As schools were not necessarily located in a habitat patch or on a link, we interpolated values of these two metrics, initially calculated at the habitat patch (and link for BC) level, in order to measure local connectivity at any point (i.e., pixel) within the study area. The connectivity value for a given point i was derived by averaging the values of the F or BC metric from multiple habitat patches, as outlined by (Tarabon et al., 2022). The weighting function applied was a decreasing exponential function, as described previously. Then, the connectivity

value at a school location was assigned to that school.

To address Objective 2, which assessed the potential of schoolyards in enhancing urban connectivity if greened, global connectivity was evaluated using the Equivalent Connectivity index (EC ; (Saura et al., 2011)), a combined measure of habitat amount and connectivity. The index is derived from the Probability of Connectivity index (PC ; Saura and Pascual-Hortal, 2007), defined as “the probability that two animals randomly placed within the landscape move to habitat areas that are reachable from each other.” The EC index was calculated as follows:

$$EC = \sqrt{\sum_{i=1}^n \sum_{j=1}^n a_i a_j e^{-\alpha d_{ij}}}$$

where n is the total number of patches, a_i and a_j are the areas of patches i and j , and p_{ij} is the maximum probability of potential paths between i and j .

From the initial land-cover map, the algorithm simulated the addition of each school as a habitat patch within the graph and calculated the connectivity gain by comparing the EC value of the original graph with that of the graph incorporating the new patch. This simulation was conducted for each school individually. The resulting values allowed for the ranking of schools based on the potential connectivity gain they would generate if they were greened. The results were subsequently interpreted by considering each school’s location within the urban matrix and its position within the broader ecological network.

Landscape composition and configuration were assessed using metrics of fragmentation and structural connectivity, calculated with the *landscapemetrics* package (Hesselbarth et al., 2019) in RStudio 2024.04.2. The Euclidean distance between schools and the nearest graph elements was calculated with the *sf* package (Pebesma, 2018) and the descriptive statistics (box plots) with the *ggplot* package in the same version of R. Ecological network modeling was conducted using the Graphab 3.0 software (Foltête et al., 2021; <https://sourcesup.renater.fr/www/graphab/>).

3. Results

3.1. Land-cover composition and configuration

The land-cover maps reveal significant variation in landscape composition across the four cities, particularly in terms of tree vegetation and urbanized areas (Appendices 1 and 2). Paris exhibits the most homogeneous landscape, with urbanized areas dominating at 60 % and the lowest proportion of tree vegetation (16 %). In contrast, Rotterdam’s landscape is the most diverse, with relatively balanced proportions across land-cover categories: 28 % urbanized areas, 23 % grasslands, and between 11 % and 13 % for tree vegetation, water, and transport infrastructure. Barcelona and Brussels fall into an intermediate category. Both cities have high vegetation densities (24 % in Barcelona and 19 % in Brussels), although the distribution of vegetation varies considerably between them. Barcelona features a large patch of tree vegetation in the northwest, corresponding to the Collserola Natural Park, which covers 5.8 % of the study area. However, the rest of the city, particularly the downtown area, has sparse vegetation. Brussels, on the other hand, contains a few large vegetation patches to the south and north of the city (though much smaller than Barcelona’s) and numerous small patches throughout the rest of the study area.

3.2. Functional connectivity at the initial state

The graphs modelling functional ecological networks show considerable variations (Fig. 2). Barcelona has the highest global functional connectivity value, with the Equivalent Connectivity (EC) metric being 4–9 times higher than in the other three cities (Appendix 2). This high connectivity is primarily due to the substantial amount of tree

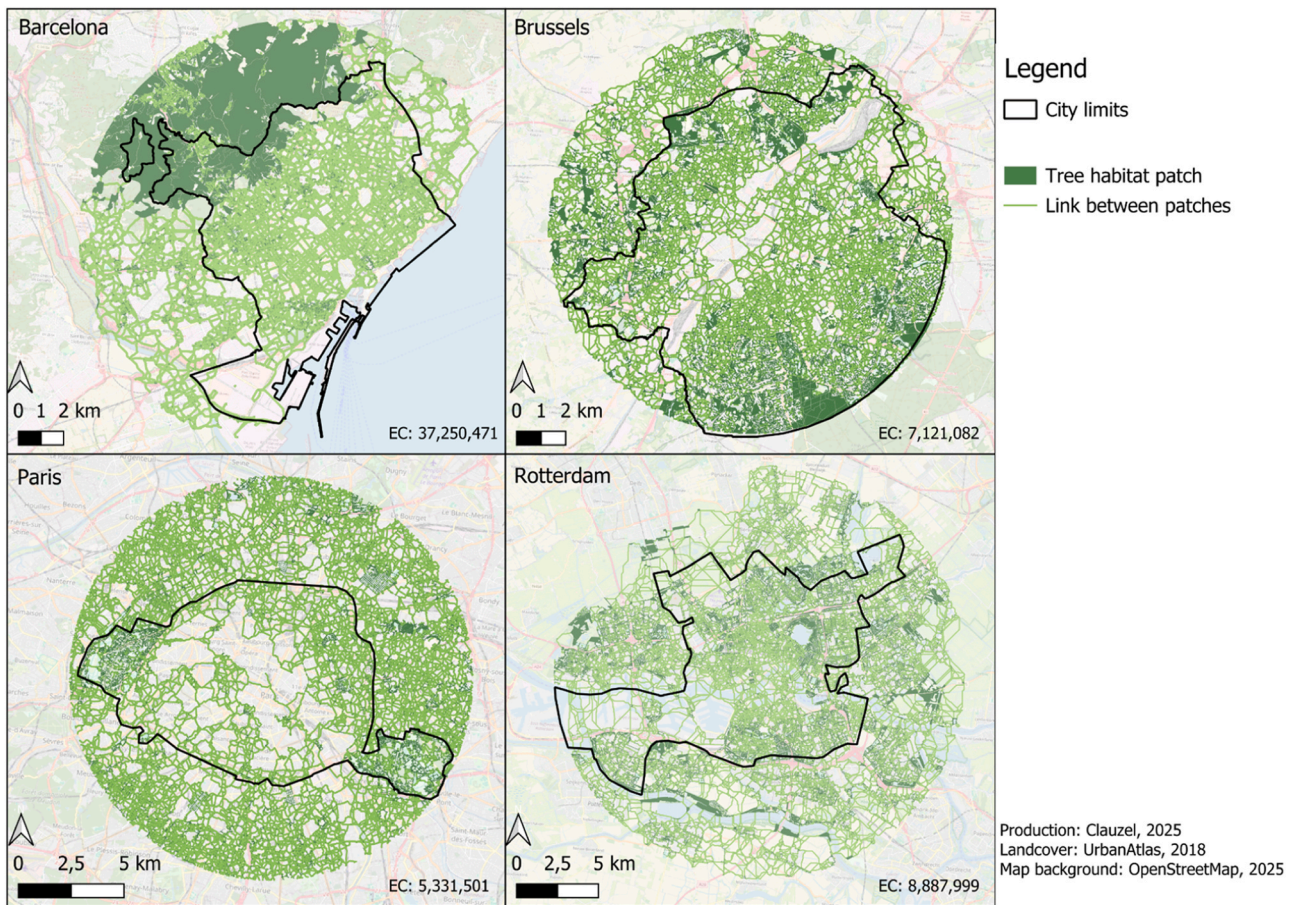


Fig. 2. Ecological networks modeled from tree vegetation habitat patches in Barcelona, Brussels, Paris and Rotterdam, with global connectivity estimated using the Equivalent Connectivity (EC) metric.

vegetation in the area. However, this global metric does not reflect the highly uneven spatial distribution of vegetation previously described. The low number of patches (6840) and the large standard deviation in patch sizes compared with the other cities highlight this imbalance, as shown in Figs. 2 and 3. Rotterdam has the second-highest functional connectivity value, driven by the large number of tree vegetation patches (21,623) and numerous links in the graph. This suggests that many habitat patches are connected, meaning they are located within the dispersal range of the species in question and within a landscape conducive to movement, without significant barriers. Brussels has a slightly lower functional connectivity value than Rotterdam, but its ecological network differs significantly. Although the number of habitat patches is lower (7202), the average patch size is twice as large. While the ecological network is fully connected (all patches are linked to at least one other), it consists of two sub-networks located to the east and west of the city, with minimal connectivity between them due to the dense urban development in the city center and along the canal. Finally, Paris has the lowest global connectivity value. Despite having a large number of habitat patches (17,148), these patches are small on average (5680 m²). The center of Paris contains very few tree vegetation patches, and the landscape is generally unfavorable to species movement due to the high density of buildings and limited herbaceous or shrubby vegetation.

3.3. Contribution of schools to current landscape connectivity

The spatial intersection of schools and habitat patches reveals that 7 % (30 out of 426) of the schools in Barcelona currently contribute to connectivity by acting as tree habitat patches. The number and

proportion of schools serving as habitat in the other three cities are much lower: around 1 % in Rotterdam (2 out of 190), and less than 1 % in Paris (7 out of 1103) and Brussels (5 out of 1069).

The Euclidean distance between schools and the nearest elements of the modeled ecological network is relatively low, though considerable variability exists among the cities, and, in some cases, among schools within the same city (Fig. 4). Rotterdam exhibits the lowest distances, with schools located on average about 30 m from the nearest habitat element. In contrast, Paris has the highest average distances, around 150 m. Barcelona and Brussels have similar average distances (approximately 65 m), although Brussels displays higher maximum distances, with some schools located up to 500 meters from a habitat, compared to a maximum of 300 m in Barcelona. Paris notably differs from the other cities with a very large standard deviation in distance values, with maximum distances exceeding 800 m between a school and a habitat patch or corridor. The most remote schools are found in central Paris and the southwestern part of the city, areas characterized by high urban density and limited vegetation.

The analysis of connectivity values, whether using the F or BC metric, at school locations, reveals two contrasting patterns (Fig. 5). The first pattern is observed in Rotterdam and, to a lesser extent, in Brussels, where schools are generally situated in areas with high connectivity, although there is considerable variance. The second pattern is found in Barcelona and Paris, where most schools are located in areas with very low connectivity. These differences can likely be explained by the spatial distribution of schools and tree vegetation within the cities. In Rotterdam and Brussels, schools are more evenly distributed between the city center and the periphery, which results in a higher likelihood of schools being located near habitat patches. In contrast, in Barcelona and Paris,

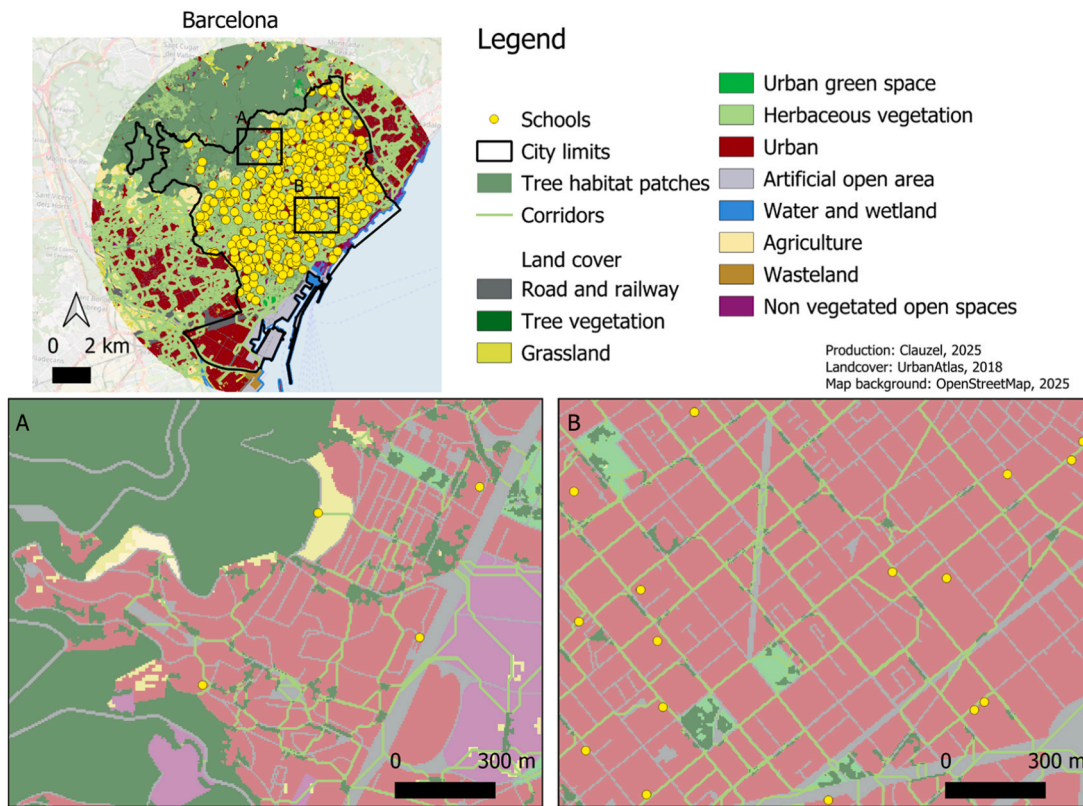


Fig. 3. Examples of landscape composition and ecological networks in two sectors of Barcelona, illustrating areas with high connectivity (A: Sant Genís dels Agudells) and low connectivity (B: La Sagrada Família).

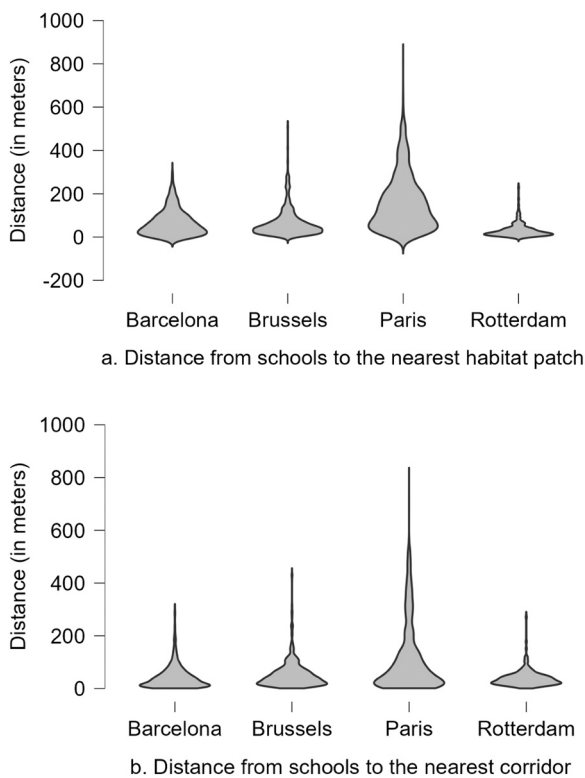


Fig. 4. Distribution of Euclidean distances from each school to the nearest patch of tree habitat (a) and to the nearest corridor (b).

schools tend to be concentrated in the city centers, areas that are

characterized by a lower presence of tree vegetation. The more vegetated peripheries of these cities (e.g., the Bois de Boulogne and Bois de Vincennes in Paris) have fewer schools.

3.4. Potential of schoolyards to improve functional connectivity

The simulation was conducted only for schools that are not already habitat patches in the ecological network model. When considering all schools as potential habitats, global connectivity increases by 0.0011 % in Barcelona and 3.7 % in Paris. The spatial distribution of connectivity gains from the transformation of each school into a habitat patch shows marked variation across the cities (Fig. 6). Schools that generate the greatest connectivity gains are typically located near existing wooded areas, often on the city peripheries. Conversely, schools in sparsely vegetated areas show lower connectivity gains, as the addition of a single school does not significantly densify the existing network.

Despite the relatively small gains in connectivity at the level of individual schools or at the overall city scale, transforming all schools into habitat patches would substantially increase the density of tree habitats and corridors, particularly in the dense city centers of Paris and Brussels. These areas are currently poorly vegetated and lack sufficient corridors (Fig. 7).

4. Discussion

Greening policies in cities have become increasingly important in recent years as a response to social, health and climate challenges (Bowler et al., 2010; Singh et al., 2020; Pereira and Baró 2022). Whereas in the early years few cities explicitly integrated biodiversity conservation into their initial greening policies (Feng and Tan, 2017), some European cities (e.g., Berlin, Barcelona, Lisbon) have made progress since 2014 by developing new planning instruments and biodiversity policies (Hansen et al., 2023). Our four cities studied have each drawn

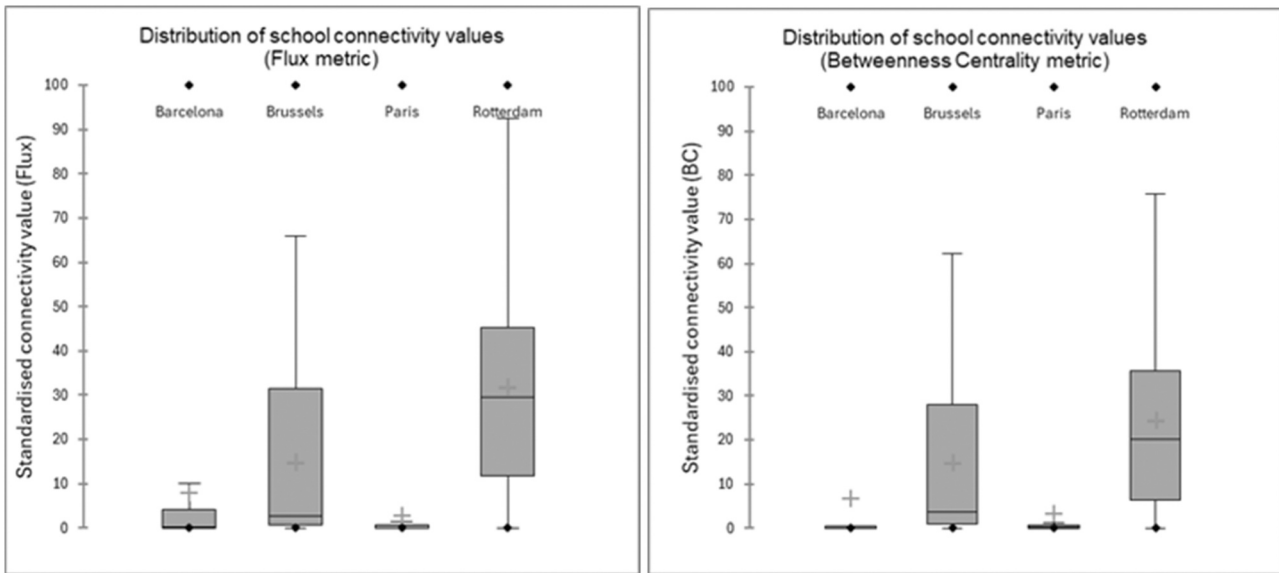


Fig. 5. Distribution of connectivity values at school points, estimated using the Flux (F) metric (left) and Betweenness Centrality (BC) metric (right), both standardized for comparability across the four case study cities.

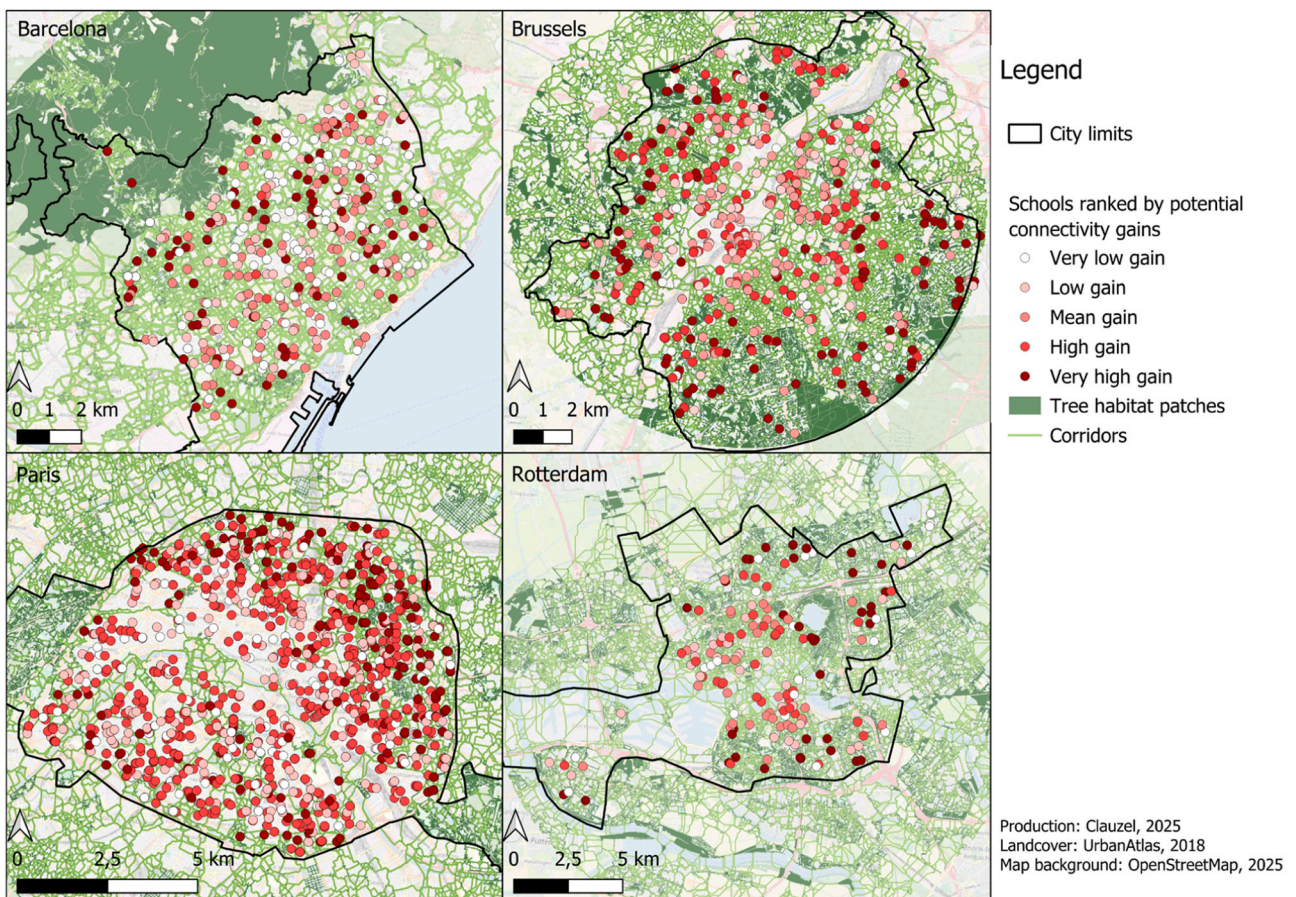


Fig. 6. Spatial distribution of connectivity gains from transforming each school into potential tree habitat.

up biodiversity and climate plans aimed at developing new green spaces of various types (parks, squares, walls, and corridors). Despite these advancements, these plans give little methodological guidance on the creation of an effective corridor or on monitoring the contribution of these spaces to connectivity.

Several scientific studies have recently analyzed the potential contribution of new urban green areas to landscape connectivity, such as business green sites (Serret et al., 2014), green roofs (Louis-Lucas et al., 2022), private gardens (App et al., 2022; Mimet et al., 2020) or multi-family residential plots (Bourgeois et al., 2024). Specifically on

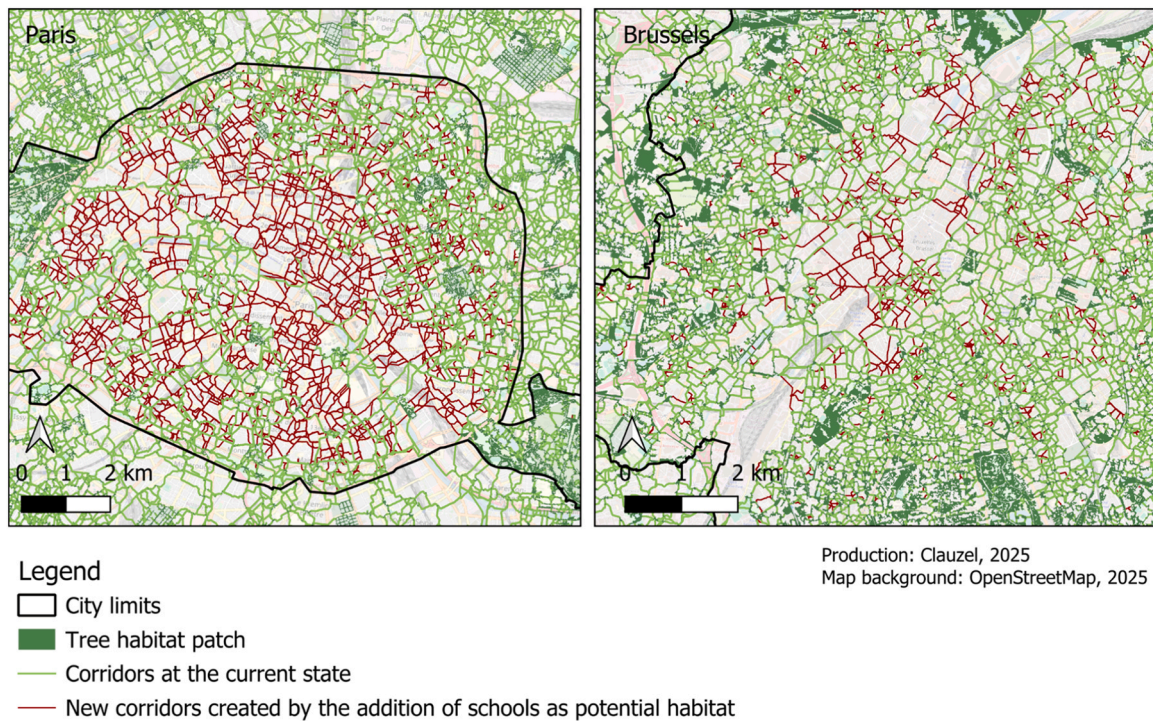


Fig. 7. Graph links between habitat patches in the initial state (green) and the simulated (red) state, in which all schools were converted into habitat patches, with examples from Paris (left) and Brussels (right).

schoolyards, existing studies (e.g., Iojă et al., 2014; Haase et al., 2017; Gallez et al., 2024) focus more on accessibility of green spaces or the amount of added vegetation than on connectivity per se.

The added value of our study lies in assessing the contribution of school greening operations at the ecosystem level. Greening schoolyards could help create small, functional ecosystems that can potentially support communities of plants and animals, fostering exchanges with other habitats throughout the city (Flax et al., 2020). Our methodology, grounded in graph theory and landscape ecology, enables us to analyze the position of schools within ecological networks and their contribution to functional connectivity in a multi-scalar perspective.

The comparison of the four European cities reveals significant spatial contrasts, not only between cities but also within cities, confirming the influence of the historical urban planning (H2.2). These contrasts are indeed largely explained by the landscape composition and configuration of cities, inherited from centuries of planning, where the place of nature in urban planning varied according to cultural and historical contexts (Alexandre, 2013). For example, in Paris and Barcelona, the historic center has been heavily densified over the centuries, resulting in a loss of vegetation. This explains why schools located in the city center tend to have very little surrounding greenery, a pattern confirmed by previous studies (Gallez et al., 2024).

The results on the contribution of schools to current connectivity show that a very small proportion of schools provide habitat for tree-related species, which weakens our hypothesis H1.1. Only Barcelona, which also has a much higher connectivity than the other three cities, has a higher percentage (7 %) of this type of school. This could support our hypothesis H1.2 that there is a city-wide link between the overall vegetation density and the percentage of schools that constitute a potential habitat. However, it is important to note that the small proportion of schools being habitats may be exacerbated by the resolution of the land cover data used. Urban Atlas data only represent tree canopy areas larger than 500 m², which likely underestimates the true extent of vegetation. While high-resolution data are available, they are country-specific and do not allow for comparisons between the four cities. Another limitation of our study, as with many large-scale studies, is its

reliance on vegetation as seen from above, which maps only the tree canopy. This does not account for what exists beneath the trees, where the surface of bitumen or a grass layer provides different ecological functions. Due to this limitation and to reduce potential bias, we choose to focus only on the connectivity of tree habitats. To refine the analysis, Light Detection and Ranging (LiDAR) data could offer a more detailed understanding of vegetation cover, including spatial arrangement and vertical structure (Caynes et al., 2016; Bourgeois et al., 2024). Another perspective would be to verify the real contribution of schoolyards to connectivity by cross-checking the results with empirical data. This requires enough protocol data representative of the taxa present, which can be an important challenge (Lookingbill et al., 2022). While this has not been specifically studied in schools to our knowledge, some studies have demonstrated the effectiveness of corridors in urban contexts for garden shrews (Vergnes et al., 2013), moths and passerines (Balbi et al., 2021), and hedgehogs (App et al., 2022).

The analysis of BC value distributions reveals that for two cities (Rotterdam and Brussels), some schools act - if they themselves are habitats - as stepping stones, i.e., small intermediate habitat patches that facilitate movements between larger habitat patches, partially confirming the hypothesis H1.3. The two selected connectivity metrics refer to different contributions of a habitat patch to connectivity. While the BC is an indicator of centrality within the network, the Flux puts more emphasis on the density of habitat connected nearby. These two metrics are therefore complementary indicators for categorizing the role of each green space in the urban ecological network and thus for designing targeted greening operations.

At a broader scale, the overall connectivity gain from transforming all schoolyards into potential tree habitats is very small, challenging the hypothesis H2.1. This is due to the limited surface area of schoolyards (only one pixel) compared to larger green spaces, such as parks or gardens. One way forward would be to develop scenarios for the greening of courses that consider the actual size of the schoolyards. This would increase the gain in connectivity but, above all, would add nuance to the results between schools. However, this requires spatial data for school plots, which were not available for the four cities. Although all yards are

considered equivalent in size, the ranking of schools based on the connectivity gains highlights strong spatial contrasts. As for the greening scenarios in multi-residential plots (Bourgeois et al., 2024), schools with the greatest gains in connectivity are located near already densely vegetated areas. This is explained by the connectivity metric used for prioritization which gives more weight to these areas and suggests that other metrics or indicators should be used if, for example, vegetation is to be prioritized in vegetation-poor areas. Indeed, areas that are highly deficient in green spaces (e.g., Paris center) show minimal gains from greening a single school, as other habitat patches are too far away to be connected. In these areas, it is crucial to green multiple schools in close proximity to each other to create interconnected networks of vegetation patches, thereby enhancing local connectivity, as shown in Fig. 7. This strategy aligns with the importance of greening areas currently lacking vegetation to mitigate the urban heat island effect and improve urban living conditions (Bowler et al., 2010; Gallez et al., 2024). But the greening of schoolyards raises feasibility issues because of their primary function as a recreational space for children and a sports ground for physical activities (Mårtensson et al., 2014). This can therefore lead to a competition between uses and functions. Cunningham et al. (2024) showed for example a negative relationship between the sports field size and the number of large trees in schoolyards. The greening strategy may also be limited by reluctance on the part of school staff, particularly about management constraints, which have not always been adapted to the characteristics of the new yard (management of wood chips, protection against mud and dirt, etc.) (Delaunay et al., 2021). To fully realize the benefits of greening operations, urban policies must shift from viewing vegetation as simple street furniture to recognizing it as part of a functional ecosystem (Hansen et al., 2023). Integrating ecological, social, economic, and health considerations into urban greening efforts requires coordinated efforts from stakeholders, including ecological experts, landscape architects, green space maintenance teams and teaching staff (Costadone and Vierikko, 2023). Our approach goes beyond purely ecological concerns by aligning with the *One Health* (Castañeda et al., 2024) and *Nexus* (Babí Almenar et al., 2021) frameworks. These frameworks recognize the interconnections between ecosystem health, human health, and biodiversity. By enhancing connectivity through greening schoolyards, we are not only addressing landscape fragmentation but also supporting public health by improving air quality, reducing the urban heat island effect, and providing spaces for recreation and well-being. Schoolyards serve as prime examples of the multifunctionality of nature-based solutions. Numerous studies have shown that green schoolyards reduce conflict between children, improve their well-being and learning abilities, and increase physical activity (Bates et al., 2018; Browning and Rigolon, 2019; Bikomeye et al., 2021; Sanz-Mas et al., 2025). Moreover, greening schoolyards, especially in underserved neighborhoods, can foster social equity and resilience by providing greater access to nature, which is particularly beneficial for children in densely built environments (Haase et al., 2017; Pereira and Baró 2022). This can also promote social equity in deprived areas, as seen in Brussels and Rotterdam (Gallez et al., 2024). However, it is noteworthy that low-density green spaces do not always correlate with economically deprived neighborhoods. Gallez et al., (2024) demonstrated this in Paris and Barcelona, where central districts, despite being deficient in vegetation, are privileged areas. Regardless of socio-economic factors, greening dense urban areas is essential for reducing negative urban externalities, such as the urban heat island effect, flooding, and air pollution. It is precisely in these vegetation-deficient areas that greening actions are vital to enhance urban resilience to global change (Demuzere et al., 2014).

5. Conclusion

This study aimed to assess the potential contribution of schoolyards in enhancing ecological connectivity in four European cities. Our results show that, despite their small size, some schoolyards can play a stepping stone in urban ecological networks, particularly in Rotterdam and Brussels. However, there is only a small proportion of schoolyards currently providing tree habitat for the target species, except for Barcelona, where denser city-wide vegetation seems to favor this function.

On a broader scale, the conversion of all schoolyards into tree-covered habitats results in only a limited gain in connectivity and highlights the relative importance of these areas compared with larger green infrastructures. Transforming schoolyards into green spaces would therefore play a crucial role in enhancing biodiversity, a function that is largely unrealized today (Harvey et al., 2020). Schoolyards should not be overlooked in city greening strategies, as small patches of green space can have similar species richness to larger ones (Strohbach et al., 2013; Vega and Küffer, 2021). On the other hand, the spatial analysis of the potential benefits highlights important intra- and inter-urban contrasts, revealing the influence of the legacy of historic urban planning that structures the current opportunities for renaturation.

Thus, while schoolyards alone cannot transform urban ecological networks, their potential to complement other green spaces, particularly in deficit areas, makes them relevant levers for targeted and equitable greening strategies. Our study provides methodological and empirical bases for guiding these strategies, integrating spatial and functional constraints specific to urban contexts.

CRedit authorship contribution statement

Tanguy Louis-Lucas: Writing – review & editing, Methodology, Formal analysis, Conceptualization. **Céline Clauzel:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Funding acquisition, Formal analysis. **Nathalie Blanc:** Writing – review & editing, Resources, Project administration. **Sarah Bortolamiol:** Writing – review & editing, Visualization, Investigation, Conceptualization. **François Bouteau:** Writing – review & editing, Resources, Investigation. **Etienne Grésillon:** Writing – review & editing, Resources, Investigation. **Patrick Laurenti:** Writing – review & editing, Resources. **Joanne Clavel:** Writing – review & editing, Validation, Resources, Investigation, Formal analysis.

Declaration of Competing Interest

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Appendix 1. Proportion (%) of each land-cover category in the four cities studied, calculated from the land-cover map produced, and resistance values for species movements

Land cover categories	Barcelona	Brussels	Paris	Rotterdam	Resistance values
Road and railway	13,10	13,47	16,08	10,50	50
Wooded vegetation	23,97	19,23	7,47	12,68	1
Grassland	6,21	6,89	1,41	23,15	5
Urban green spaces	4,19	2,55	6,22	2,06	10
Urban	38,52	47,39	62,78	27,54	100
Artificial open areas	5,93	1,68	3,46	6,47	20
Water and wetland	2,66	0,89	2,44	11,32	10
Agriculture	4,51	7,88	0,05	5,54	10
Wasteland	0,92	0,01	0,11	0,74	10

Appendix 2. Characterization of the landscape of the four cities studied by fragmentation, structural connectivity (using *landscapemetrics* R package) and functional connectivity (using Graphab 3.0). The * beside the metrics in the categories “Fragmentation” and “Structural connectivity” indicates that the calculation was performed on the class “Tree vegetation” only. The absence of * indicates that the calculation has been carried out on the whole land cover map and therefore characterizes the overall landscape

		Barcelona	Brussels	Paris	Rotterdam
Fragmentation	Patch Density*	0.000130	0.000192	0.000468	0.000345
	Largest Patch Index*	5.810	0.934	0.414	0.275
	Mean Patch Size*	0.765	0.519	0.210	0.290
	Mean Euclidean distance between patches*	25.305	30.935	29.223	17.515
	Shannon Diversity Index	1.798	1.535	1.338	1.934
	Simpson Diversity Index	0.768	0.708	0.602	0.825
Structural connectivity	Evenness	0.750	0.667	0.581	0.807
	Landscape Division Index	0.424	0.363	0.161	0.251
	Contagion Index	54.5	56.9	61.6	50.7
Functional connectivity	Patch Cohesion Index*	99.4	97.6	97.4	97.1
	Habitat patch number	6840	7202	17148	21623
	Mean patch area	8064	5680	2223	2920
	Total habitat surface	55,157,950	40,902,775	38,123,035	63,145,575
	Standard deviation	236,852	35,443	19,509	21,916
	Link number	12,583	14,590	33,183	38,502
	Global EC metric	37,250,471	7121,082	5331,501	8887,999

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