Nature-based school environments for all children? comparing exposure to school-related green and blue infrastructure in four European cities

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ABSTRACT

Children’s unequal exposure to nature is associated with the uneven distribution of green and blue infrastructure (GBI) in cities, which often disproportionately affects children living in disadvantaged neighbourhoods. School environments are increasingly recognised, both by scientists and policymakers, as priority areas to increase children’s exposure to GBI. However, studies analysing the spatial and temporal patterns of GBI in school environments are still scarce, especially those considering a cross-city and equity perspective. To contribute to the expanding field of urban environmental justice in the context of children’s geographies, our research aims to assess the (un)equal spatial patterns of school-related GBI across four large European cities (Brussels, Barcelona, Rotterdam, and Paris) and over time (between 2006 and 2018). For this purpose, we used EU-comparable green and blue land cover and tree canopy cover data, together with schools’ socio-economic characteristics (median income and educational attainment) based on local neighbourhood-level data. Through geospatial and statistical analyses on 1259 primary schools, our study reveals significant positive correlations between school-related GBI exposure and access and socio-economic variables in Brussels and Rotterdam. In contrast, negative correlations were found in Barcelona and Paris. Overall, the four cities show very distinct patterns of school-related socio-environmental inequities and no substantial GBI gains during the period analysed, suggesting that greening initiatives in and around school environments are still to be upscaled at the city level.

1. Introduction

In our increasingly urbanised world, the uneven distribution of green and blue infrastructure (GBI) components, such as urban parks or street trees, remains one of the main barriers to children’s exposure and access to nature (Beery et al., 2023). As a result, children who have less contact with nature are less prompted to receive the multiple wellbeing and health benefits delivered by GBI (Andersson et al., 2019), such as the reduction of stress and hyperactivity (McCormick, 2017; Squillacciotti et al., 2022; Zare Sakhvidi et al., 2022), enhanced cognitive development (Amicone et al., 2018; Dadvand et al., 2015), improved socio-emotional wellbeing (Pérez-del-Pulgar et al., 2021; Perez-Silva et al., 2023), and more opportunities for physical activity (Akpinar, 2017; Timmons et al., 2012).

The inequitable distribution of urban GBI across different socio-demographic groups has been widely reported by environmental justice scholars (Kabisch et al., 2016; Nesbitt et al., 2019; Rigolon, 2016). In many cities, evidence shows that people (including children) belonging to underprivileged socio-economic groups have access to fewer and smaller green and blue spaces, and often of lower quality (e.g., in terms of biodiversity) (Kuras et al., 2020; Phillips et al., 2022; Rigolon, 2016). Since the 1992 Rio Declaration on Environment and Development, urban greening agendas have been widely adopted by many cities around the world to boost revitalisation, promote public health, and adapt to climate change (Angelovska et al., 2018). In their greening efforts, some cities try to follow the famous “3–30–300” urban forestry rule which promotes that every citizen should at least see 3 trees from their home, have 30 % tree canopy cover in their neighbourhood, and should not have to walk more than 300 m to access the nearest public green space (C. Konijnendijk, 2021).

However, whereas these greening policy agendas and goals have been mainly focused on a residential greening perspective in the past...
years (e.g., the creation of new parks, the introduction of green corridors, and urban gardens), recently scholars also called for greater attention to other key urban infrastructure (e.g. schools, hospitals, health care centres) (Nieuwenhuijsen et al., 2017). These social amenities have the potential to mitigate residential green inequities since some are regularly visited by vulnerable population groups, such as “women and children, older persons and persons with disabilities”, as highlighted in the SGD 11.7 of the 2030 Urban Agenda (United Nations, 2015). For instance, school environments (i.e., school compounds and their surroundings) are a significant part of children’s “daily landscape” since in most European countries, children spend between 156–200 days per year at school (European Commission, 2018).

A few recent studies have adopted a school-based perspective when assessing children’s unequal access and exposure to GBI, including cases in Europe (Baró et al., 2021; Shoari et al., 2021; van Velzen and Helbich, 2023), South America (Fernández et al., 2022; Requia et al., 2022), and North America (Zhang et al., 2022; Zhao et al., 2019). All these studies explored the links between GBI indicators in school environments and variables related to schoolchildren’s socio-economic status, using different methods, data (land and/or vegetation cover), and spatial scales, both at the city or country scale.

However, despite the momentum in school-related greening initiatives in many European cities (Baró et al., 2022), none of these studies have examined to what extent school environments have benefited from urban greening policies across different European cities. Yet, assessing GBI changes in school environments can inform researchers and policymakers on the effectiveness of urban greening policies to ensure equitable access to GBI for children. Moreover, while school environments might have the potential to mitigate residential green inequities (Stevenson et al., 2020), no studies have yet analysed to what extent current school environments are also affected by socio-environmental inequities across different European cities. Yet, comparing cities across countries might be particularly interesting for identifying whether observed school-related GBI inequality patterns are widespread or specific to particular cities, and for understanding the factors that explain these variations (Grove et al., 2014; Kuras et al., 2020).

In this research, we aim to bridge these knowledge gaps and respond to the previously mentioned research questions by assessing the spatial and temporal patterns of school-related GBI across four large cities located in different European countries (Brussels, Barcelona, Rotterdam, and Paris), considering an equity perspective. Our first research objective is to compare the spatio-temporal patterns of school-related GBI across four large cities and temporal patterns of school-related GBI across four large cities. The second objective is to explore the relationships between multiple school-related GBI indicators and schools’ socio-economic characteristics in the four cities. Considering the findings from previous studies, the underlying hypothesis of this study is that school environments located in wealthier neighbourhoods also benefit from greater exposure to green and blue land cover and tree canopy cover compared to those located in disadvantaged neighbourhoods.

2. Data and methods

2.1. Selection of the case study cities

This study encompasses four large European cities: Brussels (Belgium), Barcelona (Spain), Rotterdam (the Netherlands), and Paris (France). These cities are the four case studies of the ERA-NET Cool-schools project (https://www.coolschools.eu) and were selected for the project because of their distinct urban characteristics and GBI distribution, as well as their ambitious urban re-naturing plans, including specific school greening programs.

The four municipalities share relatively similar territorial extents, consisting mostly of urban areas, but show substantially different population densities (Table 1). The extent of “Brussels” includes the 19 municipalities of the Brussels Capital Region, and the extent of Rotterdam encompasses all its districts except the 5 districts of the harbour area (Botlek-Europoort-Maasvlakte, Hoek van Holland, Hoogvliet, Rozenburg, and Vondelingenplant) which we excluded from the analysis due to their meagre population density and low number of schools.

2.2. Case study cities: Urban greening contexts and plans

As shown in Fig. 1, the spatial distribution of green and blue land cover (LC) and primary schools vary between the four cities. To better understand their urban greening context, this section provides more information on the different urban greening policies in the four cities.

2.2.1. Brussels (Belgium)

Initiated in 1996 and integrated into the regional land use plan in 1999, the green and blue ecological network of the Brussels-Capital Region consists of its first urban greening strategy (IBGE, 2000). While the ecological network developed throughout the years, Brussels adopted its first Regional Nature Plan in 2016, to reinforce the network, and chart specific nature conservation and urban greening strategies by 2050 (Brussels Environment, 2016). Key goals of this Regional Nature Plan involve ensuring residents access to green spaces exceeding 1 ha within 400 m and under 1 ha within 200 m of their homes, fostering ecological coherence (Brussels Environment, 2016).

2.2.2. Barcelona (Spain)

The pla General Metropolità has been the main policy instrument for

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Table 1

<table>
<thead>
<tr>
<th>Location</th>
<th>Brussels</th>
<th>Barcelona</th>
<th>Rotterdam</th>
<th>Paris</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total area (km²)</td>
<td>162.4</td>
<td>54.7</td>
<td>101.4</td>
<td>105.4</td>
</tr>
<tr>
<td>Green and blue land cover (km²) (European Copernicus, 2018b)</td>
<td>65.1</td>
<td>114.1</td>
<td>114.1</td>
<td>27.2</td>
</tr>
<tr>
<td>Tree cover (km²) (European Copernicus, 2018a)</td>
<td>33.9</td>
<td>5.6</td>
<td>26.6</td>
<td>9.6</td>
</tr>
<tr>
<td>Total population</td>
<td>1,218,285</td>
<td>1,659,654</td>
<td>651,631</td>
<td>2,145,906</td>
</tr>
<tr>
<td>Population density (inhabitants/km²)</td>
<td>7,501</td>
<td>16,325</td>
<td>2,955</td>
<td>20,359</td>
</tr>
<tr>
<td>Population from 6 to 12 years old</td>
<td>109,912 (9 %)</td>
<td>97,350 (6 %)</td>
<td>52,130 (8 %)</td>
<td>133,213 (6 %)</td>
</tr>
<tr>
<td>Average net income per capita ($) in 2019</td>
<td>28,983</td>
<td>21,010</td>
<td>31,600</td>
<td>33,372</td>
</tr>
<tr>
<td>Number of primary schools</td>
<td>418</td>
<td>337</td>
<td>150</td>
<td>354</td>
</tr>
<tr>
<td>Academic year of the schools' data</td>
<td>2020-2021</td>
<td>2021-2022</td>
<td>2021-2022</td>
<td>2021-2022</td>
</tr>
</tbody>
</table>

1 (Statbel, 2022); 2 (Statbel, 2020); 3 (Statbel, 2019); 4 (Barcelona City Council, 2021); 5 (Barcelona City Council, 2020); 6 (Barcelona City Council, 2019b); 7 (CBS Open Data StatLine, 2021); 8 (CBS Open Data StatLine, 2020); 9 (CBS Open Data StatLine, 2019a); 10 (INSEE, 2020a); 11 (INSEE, 2020b); 12 (INSEE, 2019a).
planning new green spaces in the city for the last 40 years (Anguelovski et al., 2018). The Barcelona Green Infrastructure and Biodiversity Plan was approved in 2013, to set key goals for greenspace and biodiversity by 2020 (Anguelovski et al., 2018). Barcelona’s recent Nature Plan (2021–2030) delineates ambitious green and biodiversity actions for this decade, aligning with the 2018–2030 Climate Plan’s goal to augment greenery per resident by 1 m² by 2030 (Barcelona City Council, 2018, 2021a). Its primary objective is to enhance GBI, maximising its services, especially climate change adaptation, and improving the access of all citizens to urban nature (Barcelona City Council, 2021a).

2.2.2. Rotterdam (the Netherlands)

Located in the delta of the rivers Rhine and Meuse, the city of Rotterdam is particularly threatened by climate change impacts, such as flood risks and sea level rise. To adapt to climate change, the city adopted two important policy plans in 2007 and 2009, namely the Rotterdam City Vision 2030, and the Rotterdam Climate Proof Adaptation Program (Mees & Driessen, 2011). Later, in 2013, the city adopted the Rotterdam Climate Adaptation Strategy, which is a pivotal component of the Rotterdam Climate Initiative and aims to establish a climate-resilient environment by enhancing green–blue corridors throughout the city by 2025 (City of Rotterdam, 2013). This strategy also encourages citizens to contribute to the corridors by making their gardens greener.

2.2.3. Paris (France)

Since 2007, the urban greening programme of Paris has been one of the main orientations of the Paris Climate and Energy Plan adaptation strategy (IUCN, 2019). In 2015, the greening permit opened doors to citizens’ initiatives in the urban greening strategy of the city (Apur, 2018). Adopted in 2018, the Biodiversity Plan of Paris 2018–2024 underscores the city’s greening objectives, such as the aspiration to achieve 35% permeable green spaces by 2024 (City of Paris, 2018).

2.3. School dataset

The school dataset (n = 1259) used in this research includes almost all primary schools located in each case study city (see Table 1 for detailed numbers per city). All schools provide at least primary education, although some schools in Brussels, Barcelona, and Rotterdam also include other education levels (such as pre-primary or secondary education). Primary education caters to schoolchildren aged 6 to 12 in Brussels, Barcelona, and Rotterdam; and 6 to 11 in Paris. The datasets of the four cities include both public and charter schools; private schools are only included in the cases of Brussels and Barcelona, due to a lack of available data on those schools in Paris and Rotterdam. Data on primary schools, including at least the official school’s name, address, and geographic coordinates of the main entrance were retrieved from various data sources (Table 1).

2.4. GBI indicators

In this study, we defined five school-related GBI indicators measuring exposure to green and blue spaces and urban trees located in school environments (i.e., within and around the schools’ compounds), based on the latest available data from the European Copernicus Urban Atlas dataset (Table 2). We have decided to opt for the Urban Atlas dataset as it is, to date, the sole European dataset which enables us to systematically compare GBI across various European cities, spatially and temporally. It is also a suitable dataset for assessing GBI at the scale of school environments using a buffer approach. Since green and blue cover and tree canopy cover provide different but complementary information on GBI, we assessed them separately. While green and blue land cover include public green and blue spaces (with varying amounts of vegetation cover), tree canopy cover relates to the structural characteristics of GBI in these public green spaces (e.g., parks, forests) but also all other semi-public and private spaces (e.g., streets, schoolyards). Therefore, using both indicators enables to obtain a more reliable and comprehensive assessment of exposure to GBI, and hence to its multiple benefits.

To build our school-related GBI indicators, we opted for two Euclidean buffer distances around the schools’ main entrances, namely 300 m and 500 m. The distance of 300 m was selected because it represents a 5-minute walk for children (UNICEF, 2021) and because the Regional Office for Europe of the World Health Organization recommends a maximum distance of 300 m to the nearest public green space.
4

Table 2
Description of the five school-related GBI indicators and their data sources. MMU = Minimum Mapping Unit.

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Unit, scale, and year(s)</th>
<th>Spatial resolution and MMU</th>
<th>Data sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Green and blue land cover (LC)</td>
<td>% of green and blue LC in a Euclidean buffer of 300 m around the schools’ main entrances in 2018</td>
<td>Resolution: 10 m, MMU: 0.25 ha</td>
<td>Urban Atlas Land Cover (European Copernicus, 2018b)</td>
</tr>
<tr>
<td>Green and blue land cover (LC)</td>
<td>% of green and blue LC in a Euclidean buffer of 500 m around the schools’ main entrances in 2018</td>
<td>Resolution: 10 m, MMU: 0.25 ha</td>
<td>Urban Atlas Land Cover (European Copernicus, 2018b)</td>
</tr>
<tr>
<td>Green and blue tree canopy cover (TC)</td>
<td>% of green and blue TC in a Euclidean buffer of 300 m around the schools’ main entrances in 2018</td>
<td>Resolution: 10 m, MMU: 0.05 ha</td>
<td>Urban Atlas Street Tree Layer* (European Copernicus, 2018a)</td>
</tr>
<tr>
<td>Green and blue tree canopy cover (TC)</td>
<td>% of green and blue TC in a Euclidean buffer of 500 m around the schools’ main entrances in 2018</td>
<td>Resolution: 10 m, MMU: 0.05 ha</td>
<td>Urban Atlas Street Tree Layer* (European Copernicus, 2018a)</td>
</tr>
<tr>
<td>Green and blue land cover (LC) changes</td>
<td>Difference in % of green and blue LC in a Euclidean buffer of 500 m around the schools’ main entrances between 2006 and 2018</td>
<td>Resolution: 10 m, MMU: 0.25 ha</td>
<td>Urban Atlas Land Cover (European Copernicus, 2006, 2018b)</td>
</tr>
</tbody>
</table>

*The Urban Atlas Street Tree Layer mainly represents urban trees in general (not only street trees).

(World Health Organization, 2017). Additionally, 300 m is often used as a reference distance in other studies assessing residential access/exposure to green spaces (Kabisch, 2019). Besides, we also used school buffers with a 500 m radius because this area typically corresponds to the median size of an approximate “school catchment area” in the four cities, often encompassing the surrounding school neighbourhood and potential home-school routes.

As presented in Table 2, the five indicators were built on GBI data from 2018. Regarding the green and blue land cover changes indicator, we have opted for the period between 2006 and 2018, because based on the available Urban Atlas dataset of 2006, 2012, and 2018, we have prioritized the longest time period, namely 12 years (2006–2018) to depict the eventual land cover changes in school environments. Moreover, most European cities started adopting urban greening strategies in the early 2000’s (Anguelovski et al., 2018), which explains why 2006 can be chosen as the baseline year. Given the relatively low resolution of this data (10 m), we opted for a 500 m radius to increase the likelihood of LC change detection. We did not apply the temporal assessment for tree canopy cover because, considering that the first available year for the Urban Atlas Street Tree Layer was 2012, no substantial changes in tree cover were expected in this short 6 years-period.

2.5. Spatial analysis

The spatial patterns of the five school-related GBI indicators were then analysed comparatively across cities through visual comparison of maps and descriptive statistics. The spatial analysis was conducted in the ArcGIS Pro 3.1.2 software. The descriptive statistical analysis consisted of a boxplot analysis, displaying median values and interquartile ranges (due to the non-normal distribution of the variables). Additionally, we tested for each indicator if differences between cities were significant, by using the non-parametric Kruskal-Wallis test by ranks and the Dunn-test pairwise comparison with Holm correction, in the R Studio 2023.03.0 software.

Akin to other studies investigating equitable access to nature, our cross-city spatial analysis was based on the famous “3–30–300” urban forestry rule, proposed by C. Konijnendijk (2021).

The recent version of this rule advocates for a minimum of 3 visible trees from the window (home, work or school), 30 % GBI cover in every neighbourhood, including around schools, and a minimum of 300 m to the nearest public green space (Konijnendijk, 2023). This rule is increasingly gaining the attention of scientists, urban planners and the wider public (Croser et al., 2024; Nieuwenhuijsen et al., 2022; Zheng et al., 2024). Since our analysis focuses on school environments, we have used the “30 %” threshold as a key threshold value to evaluate to what extent the four cities comply with this part of the rule (around their schools). As recommended by scholars, we evaluated this “30 %” threshold using high-resolution land cover maps (Browning et al., 2023).

2.6. Socio-economic indicators and equity analysis

Following methods from similar studies in the field of school-related environmental inequities in Europe (Baro et al., 2021; van Velzen and Helbich, 2023), we distinguished the socio-economic position of schools based on two commonly used neighbourhood-level indicators, median income level per capita and educational attainment. The definition of the median income level indicator varies among case studies but generally corresponds to the median income per capita per year (Table 3). The educational attainment indicator was defined as the proportion of the population over a certain age whose highest level of education achieved is equivalent to the university level (bachelor or above) (see Table 3 for variations between cities).

Due to the lack of consistent data on socio-economic positions at the school-level across all cities, we opted to assign neighbourhood-level socio-economic data to schools. This method has been used in earlier studies (Baró et al., 2021; van Velzen and Helbich, 2023).
neighbourhood level was deemed the most suitable spatial scale for the comparative analysis because it generally corresponds to the spatial extent of school catchment areas (geographical area served by a school), and because the number and size of neighbourhoods were relatively consistent across all cities (Table 3, Supplementary Data Appendix G). In practice, each school point (main entrance) was assigned the socio-economic data of the neighbourhood within which it was located. However, in Brussels and Paris, socio-economic data was only available at smaller spatial units (statistical sector and IRIS level, respectively). Consequently, these statistical sectors and IRIS-level data were first aggregated at the neighbourhood level before being assigned to the schools. Exceptionally, six schools in Brussels, and one in Paris, were assigned data from the nearest adjacent neighbourhood because they were located in neighbourhoods lacking statistical data (primarily due to low population densities).

To identify potential correlations between the school-related GBI indicators and the socio-economic indicators, we first conducted a bivariate correlation analysis for each variable (Baró et al., 2021; Fernández et al., 2022; van Velzen and Helbich, 2023; Zhang et al., 2022). Due to the skewed distributions of all our variables, we utilized a non-parametric Spearman’s rank correlation test using the RStudio 2023.03.0 software.

Secondly, we followed the approach from similar studies (Baró et al., 2021; Lu et al., 2024) by supplementing the correlation analysis with a cluster analysis, in order to consider all the indicators together (unlike the bivariate analysis) and identify groups or clusters of school environments sharing similar characteristics in terms of GBI and socio-economic profile. We generated spatial clusters of primary schools.

Fig. 2. Spatial and statistical distribution of the school-related green and blue land cover (LC) indicator expressed in percentages in Brussels, Barcelona, Rotterdam, and Paris (2018). Classification method: natural breaks (on the entire school dataset over the 4 cities). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
sharing similar GBI and socio-economic values using the k-means clustering algorithm in ArcGIS. To ensure comparability between cities, we first normalized all variables on a 0 to 1 scale using the minimum–maximum method. This method linearly transforms the values of each variable into a range from 0 to 1. For this cluster analysis, we ran the Multivariate Clustering tool based on the normalized variables in each city separately, first without specifying a fixed number of clusters in the parameters. The pseudo-F statistics, which determines the optimal number of clusters between 2 and 30 based on 100 iterations of the k-means procedure, indicated 2 as the optimal number of clusters for Brussels and Rotterdam, and 3 as the optimal one for Barcelona and Paris. However, for the sake of comparability between cities, we forced the Multivariate Clustering tool to create 3 clusters in each city. As provided in other similar studies (Baró et al., 2019, 2021; Hamann et al., 2015), the mean values of all indicators in each cluster were summarized in star plots to illustrate the commonalities and differences between the school clusters in the four cities.

3. Results

3.1. Spatio-temporal patterns of school-related GBI indicators

The spatial analysis of the green and blue LC indicator within the 300-meter school buffer (Fig. 2) reveals that an overwhelming majority of primary schools (92.6 %) across the four cities have a nearby environment covered by less than 30 % green and blue LC. Paris has the highest percentage of schools (99 %) with a green and blue LC value below 30 %, while Brussels exhibits the lowest proportion among the four cities (90 %). However, these percentages remain relatively consistent across all four cities. In Brussels, Barcelona, and Paris,

![Spatial and statistical distribution of school-related tree canopy cover (TC) indicator expressed in percentages in Brussels, Barcelona, Rotterdam, and Paris (2018). Classification method: natural breaks (on the entire school dataset over the 4 cities).](image-url)

Fig. 3.
schools with lower levels of green and blue LC tend to be clustered in the more central and compact areas of the city whereas schools located in the outskirts generally have greener environments (Fig. 2). In contrast, Rotterdam does not display a clear urban core-periphery gradient; instead, schools with lower LC values are randomly distributed throughout the city. These random patterns in Rotterdam are confirmed by the low Global Moran’s Index of 0.06 and z-score of 0.16 (Supplementary Data Appendix F). The spatial patterns observed with the 500 m buffer are similar, although the indicator values are slightly higher (see Supplementary Data Appendix B).

The percentage of schools with TC values below 30 % across the four cities is nearly equivalent to the previous indicator concerning green and blue LC (92.3 %) (Fig. 3). Remarkably, all schools in Paris fall within this category, while Rotterdam has the lowest percentage of schools (78 %) with TC values below 30 %. In Brussels and Barcelona, the overall distribution of schools based on their TC values aligns with the urban core-periphery gradient, with schools having lower TC values predominantly clustered in central areas (and along the coast in Barcelona). Although schools in Rotterdam do not seem to be spatially clustered according to their TC value on the map, the spatial autocorrelation did not provide strong evidence of random spatial patterns (Global Morans’ Index = 0.94, z-score = 0.34, p-value = 0.02) (Supplementary Data Appendix F). Zooming in on the lower value ranges, we found that 82 % of schools in Paris have a TC value lower than (or equal to) 6 % in their environment (300 m). The map in Fig. 3 highlights this threshold value and shows an uneven spatial pattern across Paris, where primary schools with more than 6 % TC are mostly located in the Northern areas. In contrast, only seven schools show TC values below (or equal to) 6 % in Rotterdam. The descriptive statistics confirm the primary position of Rotterdam compared to the three other cities in terms of median values for all school-related GBI indicators (Supplementary Data Appendix D and E). The spatial patterns identified with the 500 m buffer closely resemble those of the smaller buffer, albeit with slightly higher values (Supplementary Data Appendix C).

The analysis of school-related green and blue LC changes (2006–2018) indicates minimal changes, with most values (89 %) ranging between −1% and + 1% (Fig. 4). Only 11 % of all schools exhibit values below or above 1 %. This threshold (1 %) was considered a “significant” LC change given the accuracy constraints of the Urban Atlas land cover layer; namely its low resolution (10 m) and large Minimum Mapping Unit (0.25 ha). Among the four cities, Brussels records the highest percentage of schools (9.8 %) that experienced a loss of green and blue LC (between −1% and −23.9 %) — mostly located in the periphery —, and the lowest percentage of schools (3.8 %) that have seen an increase in green and blue LC (between + 1 % and + 4.7 %), primarily clustered around the Brussels Canal (Fig. 4). On the contrary, Paris has a higher percentage of schools that witnessed an increase of green and blue LC (5.4 %) compared to those which experienced a decrease (0.8 %). Yet, the magnitude of LC changes is particularly low, with all values lying between −1.3 % and + 1.9 %.

Barcelona and Rotterdam exhibit more balanced scenarios, with similar percentages of schools that lost or gained green and blue LC in the period analysed (around 6 %). In Barcelona, 6.5 % of schools experienced an increase in green and blue LC (between + 1 % and + 18.8 %), predominantly located in the coastal and eastern neighbourhoods, whereas in Rotterdam those schools (representing 6 % of the city schools’ dataset) are mostly located in the city centre (with values lying between + 1 % and + 24 %).

3.2. Inequalities in exposure to school-related GBI

The bivariate analysis delineates two distinct groups of cities with similar correlation patterns between socio-economic and school-related GBI indicators (Table 4). Brussels and Rotterdam exhibit predominantly positive and significant coefficients, while Barcelona and Paris predominantly show negative ones.

Specifically, Brussels shows stronger positive correlation coefficients between the socio-economic and GBI indicators (0.26 ≤ ρ ≤ 0.64) in comparison to Rotterdam (ρ = 0.25). Rotterdam only demonstrates significant positive associations between median income level and TC at...
300 m. Both Brussels and Rotterdam display stronger correlation coefficients between the socio-economic and TC indicators than between the socio-economic and LC indicators.

Conversely, Paris underscores strong negative significant coefficients between the socio-economic and almost all school-related GBI indicators ($0.46 \leq \rho \leq -0.15$). As for Brussels and Rotterdam, stronger coefficients are observed with the TC indicators. Comparatively, Barcelona presents a more nuanced scenario that portrays both negative correlation coefficients ($\rho = -0.20$) between the socio-economic and LC indicators, and positive coefficients between median income level and TC indicators ($\rho = 0.15$).

The four cities display strong and significant correlations between the two socio-economic variables (median income and educational attainment) ($0.78 \leq \rho \leq 0.92$).

The multivariate clustering analysis (k-means) identifies four distinct groups of school environments – three in each city – sharing similar socio-economic and GBI characteristics (Fig. 5), all of them being spatially clustered, with a Global Moran’s index value $\geq 0.34$ and a z-score $\geq 10.88$ (Supplementary Data Appendix F).

The first cluster is characterized by “grey and underprivileged” school environments (in red in Fig. 5). These schools ($n = 605$ out of 1259) are distinguished by low levels of both GBI and socio-economic indicators (Fig. 6). This cluster contains the largest number of schools in the four cities (second largest in Paris), representing 48% of the entire school dataset. In Brussels and Rotterdam, these schools are mostly located in the urban cores, whereas in Barcelona and Paris, they are mainly located in the outskirts.

The second cluster includes “grey and wealthy” school environments (in blue in Fig. 5). This cluster, found in all cities except Rotterdam, includes schools ($n = 407$ out of 1259) that have relatively low values of school-related GBI indicators (in general lower than in the first cluster except for Brussels) but are located in neighbourhoods with the highest socio-economic levels (Fig. 6). Although containing fewer schools than the first cluster, it still represents 36% of all schools in the four cities. In Barcelona and Paris, primary schools included within this cluster are located in central areas, whereas in Brussels, they are mainly found in the southeast area.

The third cluster is characterized by “green and wealthy” school environments (in green in Fig. 5). This cluster, found in all cities except for Brussels, includes schools ($n = 407$ out of 1259) that have relatively low values of school-related GBI indicators (in general lower than in the first cluster except for Brussels) but are located in neighbourhoods with the highest socio-economic levels (Fig. 6). Although containing fewer schools than the first cluster, it still represents 36% of all schools in the four cities. In Barcelona and Paris, primary schools included within this cluster are located in central areas, whereas in Brussels, they are mainly found in the peripheral areas.

The fourth cluster encompasses schools characterized as “green and
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Schools and is only found in Rotterdam and Paris. These schools (underprivileged) are located to the periphery of Paris, closely located to the “grey and underprivileged” schools, but randomly spread in Rotterdam.

4. Discussion

4.1. Low exposure to GBI in most school environments and no major changes since 2006

Our analysis revealed that 93% of all schools in Brussels, Barcelona, Rotterdam, and Paris were surrounded by less than 30% green and blue LC and TC in 2018. Hence, a vast majority of primary schools do not yet seem to comply with recommended standards concerning GBI exposure, such as the 3–30% urban green space rule of thumb advocating for a minimum of 30% tree canopy cover in all neighbourhoods, including school catchment areas (Konijnendijk, 2023).

Similar findings are reported for schools in the Netherlands (van Velzen & Helbich, 2023) and in Brazil, where 75% of schools were found to be in areas with lower greenness levels (Requia et al., 2022). Given the important beneficial effects of urban green spaces on children’s health and development (Kabisch et al., 2017; UNICEF, 2021), our findings highlight the need for upscaling nature-based interventions within and around schools.

Besides, no major green and blue LC changes were found between 2006 and 2018, except for very few school environments. These results might be explained by the limited resolution of our GBI data, and/or by the chosen timeframe. Indeed, given the relatively densely built environment of the four cities, some urban greening interventions can be quite limited in terms of total GBI coverage, and might therefore not be well represented in the Urban Atlas Land Cover dataset, which has a resolution of 10 m and minimum mapping unit of 0.25 ha. Besides, most urban greening strategies, although initiated in the 2000s, have been reinforced by Cities’ Climate Action Plans after the 2015 Paris Agreement (see section 2.2) (Reckien et al., 2018). Hence, the effects of these policies might only be seen after 2018. For instance, many school-related greening initiatives have emerged since 2018 (Baro et al., 2022). These include schoolyard greening programs such as the 2019–2021 “Cours Oasis” (Oasis schoolyards) and “Refugis Climatics” (Climate Shelters) programs in Paris and Barcelona (Barcelona City Council, 2021b; UIA-initiative, 2019), the 2021–2024 “Opération-Récération” and 2019 “Groenblauwe schoolpleinen” (Green-Blue Schoolyards) programs in Brussels and Rotterdam (Brussels Environment, 2021; Overheid.nl, 2023), as well as initiatives in school surroundings like “Rues scolaires” (school streets) or “Protegim les Escoles” (Protecting schools) in Brussels and Barcelona, respectively (Barcelona City Council, 2022; Perspective.Brussels, 2022). However, these initiatives remain scarce, small-scale, and project-based, rather than fully integrated into long-term urban greening strategies. A systematic incorporation of school environments in urban greening policies is therefore needed.

Moreover, we observed that about half of all the schools (48%) in Brussels, Barcelona, Rotterdam, and Paris are grouped in the “grey and underprivileged” cluster, illustrating inequitable patterns of access to school-related GBI, also revealed by our correlation analysis (see section 2.2 and 2.3). The fact that many schools located in more disadvantaged neighbourhoods tend to have lower levels of GBI is also reported by other studies (Baro et al., 2021; Fernández et al., 2022; Shoori et al., 2021; van Velzen and Helbich, 2023), which shows that currently school environments mostly do not yet mitigate residential green inequalities, as reported by various scholars (Nesbitt et al., 2019; Rigolon, 2016).

As stated in the EU Strategy on the rights of the child, “each child has the right to an adequate standard of living, and to equal opportunities, from the earliest stage of life” (European Commission, 2021). Hence, to reduce children’s health inequities, school-related GBIs should be equally accessible and school greening initiatives should therefore prioritize schools located in disadvantaged neighbourhoods, in which children already suffer from a lack of residential GBI.

Fig. 6. Star plots summarizing the normalized mean indicator values in the three school clusters of the four cities. “TC3” corresponds to tree canopy cover (500 m), “LC5” corresponds to green and blue land cover (500 m). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

underprivileged” (in orange in Fig. 5). This cluster represents 9% of all schools and is only found in Rotterdam and Paris. These schools (n = 117 out of 1259) have relatively high values of GBI indicators (as high as the “grey and wealthy” school cluster in Rotterdam) and low levels of socio-economic indicators (lowest in Rotterdam, but still higher than the “grey and underprivileged” school cluster in Paris) (Fig. 6). These schools are mostly spatially clustered in the periphery of Paris, closely located to the “grey and underprivileged” schools, but randomly spread in Rotterdam.
4.2. School-related luxury effect in Brussels and Rotterdam?

Our findings show evidence of pronounced inequities in exposure to GBI around schools in Brussels and, to a lesser extent, in Rotterdam.

In Brussels, we found strong positive and significant correlations between schools’ socio-economic status levels and school-related GBI. These correlations were even stronger with TC than with green and blue LC indicators. Previous studies showed similar results from a residential perspective, highlighting that the uneven distribution of GBI in Brussels tends to disfavour the most socio-economic underprivileged households, generally located in central and compact areas of the city (Phillips et al., 2022; Rodriguez-Loureiro et al., 2021; Van de Voorde, 2017). This situation is reflected in the distribution of the “grey and underprivileged” school cluster: these are mostly found in the dense city centre, compared to “green and wealthy cluster” school cluster, mainly located in the greener outskirts of Brussels. This inequitable pattern according to which wealthier families tend to have more opportunities to live in areas with higher biodiversity (often measured in terms of plant diversity but also vegetation cover, such as our TC indicators) is usually referred to in the literature as the “luxury effect” and has been found in many other cities worldwide (Kuras et al., 2020; Leong et al., 2018).

Our research also shows patterns of school-related inequities in Rotterdam, but to a lesser extent than in Brussels, and again particularly strong with the TC indicators. These findings align with a study on access to green space around all schools in the Netherlands which found positive associations between high-income households and school greenness (van Velzen & Helbich, 2023). Hence, the school-related luxury effect is also observed in Rotterdam, although less strong than in Brussels. School environments in Rotterdam benefit generally from higher levels of green and blue LC and TC compared to the three other cities, and the school-related GBI distribution is more evenly spread across the municipality. Nonetheless, it is important to stress the impact of the large urban blue spaces in this outcome, otherwise the results might have been more similar to the Brussels case.

4.3. School-related haussmann paradox in Paris and Barcelona?

Our findings provide evidence of “reverse” socio-economic inequalities – a term notably used in the health inequalities research fields (Mackenbach et al., 2008) – in exposure to GBI around schools in Barcelona and Paris, generally favouring those situated in more underprivileged neighbourhoods.

In Paris, our results show that the distribution of GBI tends to favour the most underprivileged school children, with stronger negative correlations for TC than for LC indicators. This pattern might be explained by the “Haussmann paradox”, referring to the fact that affluent populations prioritise denser areas with limited exposure to green and blue LC, a term originally referring to the historical urban renewal of Paris in the 19th Century (Cohen et al., 2012; Kuras et al., 2020). Parisian peripheral neighbourhoods have indeed a higher number of green spaces as the post-war redevelopment projects (1945–1955) prioritized the creation of multiple public green spaces when building dense social housing districts (“grands ensembles”). Industrial wastelands located in these areas were also converted into public green spaces from 1980 onwards (Apur, 2018). In contrast, the richest neighbourhoods are located in the dense and greyer city centre of Paris, a pattern probably explained by historical (monuments), and modern amenities (theatres, museums) (Brueckner et al., 1999; Lemoy et al., 2013).

In Barcelona, schools located in more privileged neighbourhoods tend to be surrounded by a lower proportion of green and blue LC cover but a higher proportion of TC cover in their school environments. Similar results were found by Baró et al., 2021, who detected negative associations between socio-economic variables and public green spaces around schools (i.e., comparable to our green and blue LC indicator although based on different data, i.e. local data), but positive associations between socio-economic variables and surrounding vegetation cover (i.e., comparable to our TC indicator although based on different data, i.e. NDVI). In Barcelona, wealthier residents predominantly reside in the compact and central neighbourhoods, as well as in the north-western peripheral neighbourhoods (see Supplementary Data Appendix G). These areas exhibit higher vegetation cover (mostly attributable to street trees and private green spaces), albeit fewer public green spaces (Fig. 1 and Supplementary Data Appendix A). Conversely, less privileged neighbourhoods such as the Old Town or northeastern peripheral neighbourhoods have more limited space for extended vegetation cover due to their urban compactness but offer a higher number of public green spaces (often small parks), resulting in elevated levels of green and blue LC. These patterns are reflected in the distribution of school-related GBI and its relationship with socio-economic variables. These results suggest that Barcelona also follows to a certain extent the so-called “Haussmann paradox” (Kuras et al., 2020). However, this pattern only applies to the distribution of the green and blue LC indicator (linked to public green and blue spaces), not to TC.

Our study sheds light on the fact that school-related GBI cover (and especially TC) is generally lower in Barcelona and Paris compared to Brussels and Rotterdam, implying that upscaling school greening initiatives at various scales is even more important in these cities. Yet, although the distribution of GBI around schools in Barcelona and Paris tends to favour the most underprivileged, it is important to keep in mind that higher-income families usually have more capacities to compensate for the lack of nature in their neighbourhoods (and around their children’s school), notably by bringing children to outdoor natural areas during the weekend or holidays (Cohen et al., 2012). For this reason, the transformation of “grey and underprivileged” schools should remain a priority in school greening programs in these two cities as well. Moreover, given the more robust correlations found between schools’ socio-economic profile and school-related TC in the four cities, and the numerous health benefits provided by urban trees to children (e.g., reduction of asthma, reduced risk of heat stroke, skin cancer, reduced hyperactivity) (Lanza et al., 2021; Wolf et al., 2020), our findings suggest that nature-based interventions in schools should mainly focus on increasing the tree cover.

4.4. Limitations, strengths, and future research

In this study, our focus was directed towards broader school environments, including both school premises and their surroundings, which we deemed to be the most suitable scale for comparative analysis, based on the only comparable data available (the European Copernicus Urban Atlas data). However, given the emergence of ambitious schoolyard greening programs in many cities (including the four case studies here), we encourage future investigations to analyse the effectiveness of urban greening policies in mitigating socio-environmental inequities, at a more detailed scale (e.g., considering schoolyard transformations).

Currently, the low resolution (10 m) and high Minimum Mapping Unit of the Urban Atlas Land Cover data (0.25 ha) did not allow accounting for small patches of green and blue land cover potentially located within school compounds. Similarly, the large Minimum Mapping Unit (0.05 ha) and relatively low resolution (10 m) of the Urban Atlas Street Tree layer likely resulted in an underestimation of the TC in school environments across the four cities. Moreover, these LC data limitations also resulted in the identification of a lot of small changes (below 1 %) for which it is not possible to verify if they represent real changes in green and blue LC. Consequently, we emphasize the pressing need for the development of higher-resolution vegetation cover datasets within the next edition of the Urban Atlas, to support more fine-grained analyses (e.g., to detect vegetation changes in schoolyards across cities).

Another limitation of our research is the allocation of neighbourhood-level data to schools, assuming that these data reflect schoolchildren’s socio-demographic characteristics. It is important to acknowledge that schools located at the limits between two (or more) neighbourhoods probably have pupils living on both sides, and that not
all children attend proximate schools located in their neighbourhood due to divergent school enrolment systems across the studied cities. In Brussels for instance, the proximity criterion (geographical distance from a child’s residence to the primary school) is not as important in the enrolment process as in the other cities. Hence, children may not always attend schools within their neighbourhoods (Perspective.Brussels, 2019). In contrast, in Paris, parents must enrol their children in a primary school located in the same neighbourhood where they reside (Ministry of National Education, 2023). Consequently, we advocate for future research in this domain to consider the utilization of school-level socio-economic data. However, in the context of cross-city comparisons akin to our study, we found major limitations due to data unavailability or the use of different methodologies in generating such data.

The main strength of our study is that it is the first to compare school-related disparities in exposure to GBI across four large cities located in different European countries. It considers both spatial and temporal patterns related to school GBI, a facet not yet addressed in previous academic research. As schools increasingly emerge as focal points for urban greening initiatives, investigating the GBI dynamics within these environments is particularly relevant to assessing such policies’ efficacy (Stevenson et al., 2020). Hence, we encourage scholars in this field to adopt a temporal approach in their future endeavours, especially considering the ongoing and prospective developments of school greening projects.

Methodologically, our study also underscores the added value of employing diverse GBI indicators, distinguishing between green and blue LC and TC. This approach facilitates a more nuanced comprehension of the urban landscape, as exemplified by our findings in Barcelona. However, while spatial and statistical analyses provide a quantitative overview of socio-environmental inequalities, understanding the actual use and non-use of GBI within school environments through more qualitative approaches remains important. Some studies have already assessed children’s use and perceptions of school-related GBI through surveys and interviews (Van Truong et al., 2022; Zwierzchowska & Lupa, 2021), but further research is still needed to thoroughly understand the various factors enabling or limiting contact with nature, particularly among disadvantaged children.

5. Conclusions and policy recommendations

This study contributes to the fields of urban ecology and environmental justice by comparing exposure to school-related green and blue infrastructure across four European cities. Through spatial, bivariate and cluster analyses on 1259 primary schools, we discovered that most primary school environments had less than 30 % green and blue land cover and tree cover in 2018, and no major green and blue land cover changes were found between 2006 and 2018. These findings demonstrate that school environments did not benefit extensively from urban greening policies across European cities (until 2018). Moreover, our study revealed that school environments are affected by socio-environmental inequities in most cities, except in Paris – and to a lesser extent in Barcelona. Therefore, to address the school-related socio-environmental inequities found in this study, we encourage urban planners and policymakers to incorporate school environments as priority places into current and future urban greening strategies, and thereby upscale the process of school-based greening, from the schoolyard level to the surrounding neighbourhoods. To ensure health benefits for all children, cities should follow recommended standards, targeting, for instance, 30 % GBI cover (and especially tree cover) in schoolyards and school surroundings by 2030. During this upscaling process, we recommend policymakers prioritise the most underprivileged schools, as school environments have the potential to ensure equitable exposure to nature-based solutions for all children.